Pediatric Trauma
Pathophysiology, Diagnosis, and Treatment

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Pediatric Trauma
Injuries cause more than half of all deaths among children in the United States. The spectrum of causes varies with age, but blunt forces cause the overwhelming majority of injuries. Children are not just small adults. They differ in many ways from adults. Many of the differences in behavior, risk exposure, anatomy, and physiology have a direct bearing on trauma care. In recent years, this reality has been widely accepted in the field. The Committee on Trauma of the American College of Surgeons has specifically addressed the needs of injured children in its resources document and in the curriculum of its Advanced Trauma Life Support® course. The Committee on Trauma recommends at least six hours of pediatric trauma–related continuing medical education for all surgeons providing pediatric trauma care, and many states have established specific requirements for hospitals receiving injured children. Across the United States, children’s hospitals, pediatric surgeons, and pediatric emergency physicians have focused on the needs of injured children and established pediatric-specific benchmarks in the management of solid organ injuries, neurotrauma, fractures, and numerous other types of trauma.

But there is a problem. There are just not enough children’s hospitals or pediatric trauma specialists to meet the needs of all injured children in the United States. Much, if not most, pediatric trauma care is provided in general hospitals by non-pediatric specialists. This book is intended for all physicians and surgeons who treat children with life- and limb-threatening injuries. The primary target audience includes general surgeons, trauma surgeons, and emergency physicians experienced in trauma care who want to expand their knowledge of pediatric trauma. The content relates primarily to direct patient care, excluding such topics as prevention, organ procurement, and medical legal and legislative issues. The emphasis is on injuries caused by blunt and penetrating mechanical forces to the exclusion of burns and scald injuries and drowning.

The book is divided into four sections. The first deals with trauma systems for children, including epidemiology and preparations for pediatric trauma care. Section two covers general principles of resuscitation and supportive care relevant to all pediatric trauma patients. Section three covers the management of specific injuries. Section four deals with rehabilitation and long-term outcomes and how to effectively communicate with families, particularly when the outcome is not good.

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David E. Wesson, M.D.
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Epidemiology of Pediatric Trauma

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INTRODUCTION

Epidemiology is the study of the distribution of diseases in groups or populations. One of its aims is to define the occurrence of disease by place and time in the general population and in specific subpopulations. The overarching goal is to reduce the incidence and severity of specific diseases. Injury epidemiology involves the collection of data on the time, place, mechanism, and victim of injury. Over the past 25 years, injury epidemiology has had a major impact on our understanding of pediatric trauma. It has allowed us to identify and quantify specific injury risks, develop prevention and treatment strategies, and monitor their effectiveness. The study of injury epidemiology has produced one fundamental fact: Injuries are the leading threat to the health and well-being of young people in our society today (1). This is of major importance to public health officials and health care providers alike.

Epidemiology can help clinicians by identifying common causes, mechanisms, and patterns of injury. It tells us that motor vehicle crashes and falls from a great height cause more life-threatening injuries than sports and recreational activities. We know that blunt injuries far outnumber penetrating injuries and that children are prone to develop intracranial hypertension from cerebral edema after a closed head injury. The astute trauma surgeon will learn to suspect and recognize these patterns based on the age of the child and the mechanism of injury. As in most areas of surgical practice, the history of events before presentation aids significantly in diagnosis and treatment.

HISTORICAL PERSPECTIVE

One hundred years ago, infections were the great scourge of children in our society. Today the problem is injury or trauma. Changing social conditions, better housing and nutrition, immunization, and quarantine of infectious cases all helped reduce the threat from infectious diseases. Over the same time period, new environmental factors, notably the introduction of the automobile, increased the risk of injury.
Our present understanding of the epidemiology of trauma in our society began in the 1960s with the publication of a monograph entitled “Accidental Death and Disability: The Neglected Disease of Modern Society” by the Committees on Trauma and Shock of the National Academy of Sciences (2). This report pointed out that accidental injuries were the nation’s most important environmental health problem. This was followed by another important publication “Injury in America,” which documented in much greater detail the impact of injuries on American society and suggested a broad approach to the problem encompassing epidemiology, prevention, biomechanics, acute treatment, and rehabilitation (3).

Since these two important publications appeared, much progress has been made both in prevention and treatment of injuries. During the 1980s and 1990s, the mortality rate from pediatric trauma in the United States fell by about 50%. No doubt this resulted from improvements in both prevention and treatment. But, there are many reasons why we will have to increase our prevention efforts if we hope to see another 50% reduction in the next 20 years.

- The cost of treating trauma victims and the pain and suffering they endure are very high, even when the final outcome is excellent. Prevention would eliminate these effects.
- About 50% of pediatric trauma deaths occur in the field before the victim even reaches a trauma center. Here, too, prevention is the answer.
- Most trauma systems now have very low preventable death rates. There is always room for improvement, but the curve is flattening out. It is unlikely that substantial reductions in the overall trauma mortality rate in the United States can be achieved by better trauma care.
- We lack effective treatments for primary brain injuries, the most common cause of death in pediatric trauma. Here, too, prevention is the solution. A report from the National Pediatric Trauma Registry showed that about 70% of the deaths were caused by central nervous system (CNS) injury (4). Only prevention can significantly reduce these deaths.

**INJURY FACTS**

More than half of all childhood deaths in the United States result from preventable injuries. For children 1 to 19 years old, unintentional injuries (accidents) and homicide (assault) were the first and second leading causes of death, respectively (1). Together they account for >50% of all childhood deaths among children 1 to 19 years of age. Unintentional injuries are the number one childhood killer in all age brackets, 1 to 4, 5 to 9, 10 to 14, and 15 to 19 years of age accounting for 34%, 42%, 39%, and 49% of all deaths in each of these age groups, respectively (1). In 2001, unintentional injuries of all types, including suffocation, drowning, burns, and scalds, as well as blunt and penetrating trauma, caused more than 11,196 deaths among children 1 to 19 years of age in the United States. This represents 44% of all pediatric deaths. Homicide, the second leading cause, resulted in 2640 more deaths or 10% overall.

In Harris County, Texas, which includes the City of Houston, injuries are the leading cause of death among children, even when neonates with birth weights >500 g and infants less than one year old are included (5). In 2000, injuries were the leading cause of death in all pediatric age groups in Houston and Harris County except infants <1 year of age. The mortality rate for injuries among children, from
birth to 17 years of age, in Houston and Harris County actually rose from 14.9 to 16.8 per 100,000 from 2000 to 2001. In 2000, injuries caused 147 deaths from birth to 17 years of age, compared to 93 for congenital anomalies and 86 for perinatal conditions. About 50% of the fatal injuries were sustained in motor vehicle crashes. Most were passengers, followed by pedestrians struck by a motor vehicle and drivers. The external causes of injury death were unintentional in 59%, homicide in 24%, suicide in 8%, and undetermined in 9%. In Houston, almost half of pediatric homicides are committed with a firearm, usually a handgun. Gunshot wounds are also the most common mechanism of child suicide.

RISK FACTORS

The risk of most types of injury varies with age. Homicide is the leading cause of injury death for infants from one month to one year of age in the United States. Plotted by age, homicide rates produce a U-shaped curve. In Harris County, Texas, in 2001, the homicide rates were 12.5/100,000 infants, 5.3/100,000 1 to 4 year olds, 1.1/100,000 5 to 9 year olds, 1.3/100,000 10 to 14 year olds, and 9.0/100,000 15 to 19 year olds (5).

The homicide rate for boys is almost three times that for girls. It is also much higher among African Americans than Caucasians. Child abuse causes the majority of homicides in the first year of life; gunshot wounds predominate among teenagers. A person known to the victim, most commonly a parent, perpetrates the vast majority of homicides.

Suffocation is the number one cause of unintentional injury death in infants, but is rare in other groups. Drowning and submersion are the leading cause of death for children one to four years of age. Toddlers have a much higher death rate for burns and scalds than older children do. The risk of injury for school-aged boys is far greater than for girls. Motor vehicle occupant injuries predominate among teenagers 15 to 19 years old.

The likelihood of a child being fatally injured is associated with single parentage, low maternal education, young maternal age at birth, poor housing, large family size, and parental abuse of alcohol and other drugs. A study from Newcastle, England, of fatal head injuries revealed that children from poorer neighborhoods were at greater risk than were those from more affluent areas (6). The authors concluded that the lack of proper playgrounds, which forced poor children to play in the streets, accounted for the difference. Children living in trailer homes in the United States have twice the risk of dying in house fires than children living in other types of housing.

Children who live in rural counties have a higher incidence of motor vehicle-related injury and a higher risk of dying compared to urban children. There is also a strong correlation between per capita income and mortality from motor vehicle crashes among all the counties in the lower 48 states.

Racial and ethnic factors correlate with other socioeconomic determinants, but even when these are controlled for, American Indians have the highest rates of injury mortality in the country.

COSTS

It is difficult to accurately determine all of the costs of pediatric trauma. But most estimates suggest that the costs are enormous. Hospital costs represent only one slice
of the pie. Other costs include medical services, lost productivity, indirect costs to families for lost income, etc. Rice and Mackenzie estimate that the cost of injury to children from birth to 14 years of age in the United States in 1985 was $13.8 billion (7).

A recent report entitled “Unintentional Injuries in Childhood” in the Future of Children series published this year by the David and Lucille Packard Foundation provides a lot of data on this subject (8).

- In 1996, 13,000 children and adolescents died of unintentional injuries in the United States.
- For school-aged children and teenagers, injuries are almost as frequent as the common cold.
- In 1996, injuries—mostly to the brain, spinal cord, and limbs—and burns left an estimated 150,000 children permanently disabled.
- Injuries to children resulted in the loss of 2.7 million quality adjusted life years (QALYs).

This publication also attempted to express the impact of childhood injuries in financial terms. It estimated the total financial burden of childhood injury in America for 1996 at $81 billion.

- Direct spending for medical services over the lifetime of the victim amounted to $14 billion.
- Other resource costs including emergency medical services totaled $1 billion.
- Lifetime productivity losses amounted to $66 billion.

**TRENDS**

We have made substantial progress in the fight against childhood injury. The death rate has declined significantly in one generation. Unintentional injury mortality fell by 50% from 1970 to 1995 in the Organization for Economic Co-operation and Development (OECD) nations (the 26 richest nations in the world) (9). During the same period, the proportion of all childhood deaths caused by injuries rose from 25% to 37%.

Improved highway and vehicle design, smoke detectors and alarms, car seats, and seat belts have all played a part in reducing childhood injury mortality. Even the homicide rate has declined. This trend continues: The injury death rate in the United States decreased by 3.3% in 2001 (1).

In the province of Ontario, the number of children seriously injured while bicycling has fallen sharply over the past five years (10). This is due to legislation making helmets mandatory for children riding on public roads. Across Canada, there is a clear association between bike helmet legislation and the risk of head injury. Provinces with helmet laws had 25% lower head injury risk.

**COMPARISONS WITH OTHER COUNTRIES**

Injuries are the principal cause of death for children 1 to 14 years of age in all nations in the OECD (9). Injuries account for 40% of all deaths in children 1 to 14 years of age. Together they take the lives of more than 20,000 children each year in the OECD nations. Traffic accidents account for 41% of the deaths. For every death,
there are 160 hospital admissions and 2000 emergency department visits. Injuries account for almost 30% of the total burden of childhood disease measured by disability adjusted life years (DALYs).

The Swedish, British, Italian, and Dutch child injury death rates are among the lowest; the United States rate is among the highest along with Poland, New Zealand, Portugal, and Mexico. The United States accounts for almost one-third of all child injury deaths in the developed nations. More than 12,000 child injury deaths a year could be prevented if all countries had the same child injury death rate as Sweden. Bringing the United States rate down to that of Sweden would save 4700 American children each year.

COMMON CLINICAL SCENARIOS AND PATTERNS OF INJURY

Astute clinicians learn to recognize common clinical scenarios and patterns of injury. Thus, knowledge of the circumstances can help identify patients with certain types of injury. For example, restrained children in side impact crashes are much more likely to sustain injuries from compartment intrusion than children in frontal crashes. Side impact crashes also cause more severe injuries (ISS > 15; GCS < 9) and more injuries to the head, cervical spine, and chest to restrained children (11). In contrast to this, restrained children in frontal crashes are more likely to suffer injuries to the abdomen and lumbar spine.

The following is a partial list of common pediatric trauma clinical scenarios:

- The infant brought in with a vague history (e.g., a fall at home), altered mental status, and severe neuro-trauma from child abuse
- The properly restrained toddler involved in a high-speed motor vehicle crash brought in by ambulance who proves to have no significant injury
- The school-aged child struck by a motor vehicle who presents with a lower limb fracture, intra-abdominal or thoracic visceral trauma, and a closed head injury
- The pre-teen who suffers a high-grade hepatic or splenic injury from an off-road all-terrain vehicle (ATV) crash
- The child with an acute epidural hematoma following a seemingly minor direct blow to the head
- The rear seat passenger with a transverse abdominal bruise and occult small bowel and lumbar spine and/or spinal cord injuries from a lap belt
- The child with a duodenal hematoma or pancreatic laceration from a direct blow to the abdomen from a hockey stick or bike handle bar

Emergency physicians and trauma surgeons should be on the alert for children with these typical clinical presentations.

ROLE OF THE TRAUMA CENTER

The primary role of the trauma center is, of course, to care for patients with life- and limb-threatening injuries. Trauma centers can also make important contributions to injury control through education and prevention.

Education efforts can target health care providers and the greater community. Education is a necessary component of all injury prevention programs and is usually
a necessary first step before new legislation mandating injury prevention measures such as seat belts, child restraints, bike helmets, etc.

Trauma centers can also help to identify specific causes of injury and associations or patterns of injury. Data from the trauma registry showing a significant number of fatal bicycling injuries motivated the trauma program staff at the Hospital for Sick Children, Toronto, to start a bike helmet campaign. The first phase of the campaign was intended to educate the public, health care workers, government officials, and politicians of the risk of bike-related head trauma and of the benefits of bike helmets. This eventually lead to a bike helmet law in the province of Ontario, which contributed significantly to a 26% reduction in bicycling-related head injuries among children 1 to 19 years of age. A national population-based study across Canada confirmed that parts of the country with helmet laws had lower head injury rates (12).

SUMMARY

Injuries are the leading risk to the lives and limbs of children from infancy through adolescence in our modern world. The mechanisms and the numbers vary with age, gender, race, parental education, social class, and economic status. Awareness of these variations can assist clinicians in the management of pediatric trauma victims. Analysis of these variations can also help us to develop ways of preventing childhood injuries from occurring in the first place.

REFERENCES


Organizing the Community for Pediatric Trauma

Arthur Cooper

Department of Clinical Surgery, Columbia University College of Physicians and Surgeons, New York, New York, U.S.A.

INTRODUCTION

Modern pediatric trauma care, like adult trauma care, has undergone constant evolution during the past generation, since the care of injured children first emerged as a distinct discipline. In part, this was driven by the growing recognition among pediatric surgeons—led by Dr. Jacob Alexander Haller, Junior, of the Johns Hopkins University in Baltimore, Maryland—that pediatric trauma care constituted a key component of the subspecialty of pediatric surgery, and in part by the growing recognition of the federal government that emergency medical services (EMS) for children had been neglected during the development of EMS systems nationwide (1,2). Since their inception, pediatric trauma programs have stressed the need for full integration with their affiliated adult trauma programs and their regional EMS systems, to ensure seamless care, and cost-effective use of scarce human and financial resources (3). They have also recognized the need for all who care for pediatric patients to ensure that the special needs of injured children are met at every level of trauma and EMS system organization (4).

To this end, this chapter will describe the current state of the art with respect to pediatric trauma system design. Consistent with this purpose, the public health approach to trauma and EMS systems will be emphasized. Additionally, the literature supporting the need for and components of pediatric-capable trauma and EMS systems will be reviewed. Finally, critical elements of pre-hospital care for the pediatric trauma patient will be delineated. The objective is to arm the adult trauma surgeon—the physician who provides most pediatric trauma care nationwide—with a working knowledge of pediatric trauma system design and function to ensure, insofar as is possible, that every child in every community has the benefit of state-of-the-art pediatric trauma care and, accordingly, the greatest possible chance for recovery and rehabilitation.
TRAUMA AND EMERGENCY MEDICAL SERVICES FOR CHILDREN

Modern EMS systems evolved because of the recognition that trauma and sudden cardiac emergencies were the leading causes of death in the United States, and that the largely volunteer, fire company–based rescue squads that historically comprised most EMS were not optimally prepared to meet this challenge. The physicians who first created the EMS systems were trained chiefly in the adult-oriented specialties of surgery, internal medicine, cardiology, and anesthesiology (5). Infants and children were cared for in these EMS systems, but their needs were not specifically addressed, and deficiencies in their care were not recognized, based on the false notion that children could be treated as little adults. Hence, none of the key legislative initiatives that resulted in the creation of modern EMS—the Highway Safety Act of 1966, the Emergency Medical Service Systems Act of 1973, and the Preventive Health and Health Services Block Grant Program of 1982, which ultimately replaced the EMS Systems Act—made special mention of the unique needs of infants and children in the emergency care system, even though neonatal care was regionalized under the EMS Systems Act.

The development of pediatric surgery and pediatric emergency medicine as distinct disciplines, each with approved residency and fellowship training programs and recognized board certification, fostered the development of EMS for children (EMSC) in many parts of this country. It was recognized that pediatric patients comprised some 5% to 10% of pre-hospital transports, 30% of emergency department visits, 21% of all pre-hospital trauma care, and 12% of all in-hospital trauma care (6,7). Seminal reports described the unique epidemiology of pediatric pre-hospital care documented deficiencies in the way trauma systems provided access for children and in the way they educated, equipped, and provided medical control of pre-hospital personnel (6,8–10). These led, in turn, to major federal initiatives in EMSC, including legislation and funding, systematic analysis of the nation’s strengths and weaknesses in EMSC by the Institute of Medicine (IOM), and development of specific plans to remedy the weaknesses it identified, which have continued to be updated on a regular basis (11,12).

The current federal EMSC program is administered by the Maternal and Child Health Bureau (MCHB) of the Health Resources and Services Administration (HRSA) in collaboration with its Division of Trauma and EMS (DTEMS) and the EMS Division of the National Highway Traffic Safety Administration (NHTSA), with the assistance of the EMSC National Resource Center (NRC) at the Children’s National Medical Center in Washington, DC, and the National EMSC Data Analysis and Research Center (NEDARC) at the Primary Children’s Hospital in Salt Lake City, Utah. EMSC consists of six phases of care and contains several of the elements addressed in the EMS Systems Act of 1973. It encompasses the entire spectrum of care for the child requiring emergency services and exists within the established EMS system. These phases of care may reside in one or more of the multiple independent agencies that comprise the EMS system. The program has long enjoyed generous congressional support and has been progressively expanded over the years to embrace a wide variety of projects designed and selected through competition to enhance the efficacy of each of these six phases of emergency care, as delineated in Tables 1 and 2.

Numerous professional organizations have also contributed to the development of EMSC. These efforts have led to the promulgation of national guidelines defining minimum standards of pediatric equipment and protocols for ambulances,
pediatric equipment and care for hospital emergency departments and trauma centers, and postgraduate training and continuing education requirements in pediatric emergency and trauma care (13–20). Experiments with voluntary consensus standards for pediatric emergency and trauma care have also been successful in many locales, particularly southern California’s Emergency Departments Approved for Pediatrics (EDAP) program and New York City’s 911 Receiving Hospital System (21,22). The depth and breadth of resources now provided by regional and national EMSC programs are truly expansive—an EMSC program now exists in virtually every state and territory. They provide both the foundation and the framework on which and within which to build a pediatric trauma system for every region with the United States.

THE PUBLIC HEALTH APPROACH TO PEDIATRIC TRAUMA

Trauma is the leading cause of death and disability for Americans between 1 and 44 years of age (23). It kills and maims more children between 1 and 14 years of age than all other diseases combined (23). Yet despite these grim statistics, and the fact that the estimated cost to society of a single childhood injury death exceeds $300,000, trauma remains in 2005 “the neglected disease of modern society” as it was in 1966 when the National Academy of Sciences published its now famous white paper, *Accidental Death and Disability: The Neglected Disease of Modern Society* (24,25).

Table 1  EMS System Components and EMSC System Phases

<table>
<thead>
<tr>
<th>EMS component</th>
<th>EMSC phase</th>
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<tbody>
<tr>
<td>Manpower</td>
<td>Prevention</td>
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<tr>
<td>Training</td>
<td>System access</td>
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<tr>
<td>Communications</td>
<td>Field treatment</td>
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<tr>
<td>Transportation</td>
<td>Emergency department treatment</td>
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<tr>
<td>Facilities</td>
<td>Inpatient treatment</td>
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<tr>
<td>Critical care units</td>
<td>Rehabilitation</td>
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<tr>
<td>Public safety agencies</td>
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<tr>
<td>Consumer participation</td>
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<tr>
<td>Access to care</td>
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<tr>
<td>Patient transfer</td>
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<tr>
<td>Coordinated patient record-keeping</td>
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<tr>
<td>Public information and education</td>
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<tr>
<td>Review and evaluation</td>
<td></td>
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<tr>
<td>Disaster plan</td>
<td></td>
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<tr>
<td>Mutual aid</td>
<td></td>
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</table>

Table 2  Projects Supported by Federal EMSC Program

EMSC National Resource Center (NRC)
National EMSC Data Analysis and Resource Center (NEDARC)
Partnership grants with all interested states and territories
Partnership grants with stakeholder organizations in EMSC
Targeted issues grants addressing specific issues in EMSC
Research network grants supporting multicenter trials in EMSC
Afflicting as they do the youngest and ablest members of our society, it is self-evident that injury and trauma are the leading public health problem of our age.

No doubt, much has changed over the last 30 to 40 years. In 1966, there were few trauma hospitals in America, trauma education of surgical residents was inconsistent at best, emergency medicine had yet to emerge as a distinct specialty in all but a few centers, pre-hospital care was rudimentary in most localities throughout the nation, few—if any—states had organized systems for trauma care, and injury fatalities were considered accidental events and accepted as inevitable occurrences of everyday life. In 2005, most regions have designated trauma facilities, all graduates of surgical residencies have specific education and experience in trauma care, emergency medicine is an established discipline in all but a few centers, pre-hospital care is both readily accessible and relatively sophisticated, most states have organized trauma care systems, and injuries are no longer considered accidents, but are viewed as predictable events that can be modified through the application of harm reduction strategies directed at the host, agent, and environment before, during, and after the traumatic event. Yet, despite these impressive advances in the structure and process of trauma care trauma remains the leading killer of our most productive citizens, and those who will soon become our most productive citizens—our children.

These facts have led the leadership of American trauma surgery—in partnership with the NHTSA EMS Division as well as the HRSA DTEMS, Injury Prevention Program, and EMS for Children Program—to ask why, despite the obvious investment in trauma and EMS throughout the past generation, there remains such a gap between expectations and reality. The conclusion these experts have reached, neatly outlined in two recent documents produced by these two agencies, Trauma System Agenda for the Future, published in 2002, and Trauma Systems Planning and Evaluation: A Model Approach to a Major Public Health Problem, published in 2004, is startling in its simplicity, but imposing in its implications; it is this—we have had the tools we need to solve this problem for nearly as long as it has been recognized, but we have failed to make use of them in a coherent and consistent manner (26,27). Specifically, through lack of public education and the necessary appropriation of funds, we have failed to harness the resources required to mount a comprehensive injury control strategy—one that links the expertise of our public health system in disease prevention and control with the expertise of our health care system in diagnosis and treatment. This problem is illustrated vividly in Figure 1, which depicts the disconnect between the primary and secondary prevention emphasis of the public health system and the tertiary prevention capabilities of the health care system—but in so doing, also suggests the obvious solution, namely, the formation of effective public-private partnerships in injury control between these two entities for the benefit of the public.

The fundamental concepts of public health are not new to trauma professionals. Indeed, the core elements of trauma system design enumerated in the Trauma System Agenda for the Future are fundamentally congruent with the 10 essential services provided by the public health system, as defined by the Public Health Functions Steering Committee of the United States Public Health Service in its 1994 report, Public Health in America, and reiterated in Trauma Systems Planning and Evaluation: A Model Approach to a Major Public Health Problem, and delineated in Table 3 (28). The three core functions of the public health system described by the IOM of the National Academy of Sciences in its 1988 and 2002 reports, The Future of Public Health and The Future of the Public's Health in the 21st Century, namely assessment, policy development, and assurance, which are the framework though which each of the 10 essential public health services are managed, are
strikingly reminiscent of the performance improvement processes well known to most health care professionals, as demonstrated in Table 4 (29,30a). Thus, there exists a natural affinity between public health professionals and trauma care professionals in their approach to problem solving. What remains is for regional leaders in public health and trauma care to form collaboratives that set goals and objectives for the public health system and the trauma care system within a given region with respect to injury control, which allow each component of these public–private partnerships to focus upon that which each does best—the public health system
on regional data collection, processing, and analysis, as well as primary and secondary prevention efforts; the trauma care system on trauma patient care, including tertiary prevention efforts such as pre-hospital emergency care, in-hospital acute care, and posthospital and rehabilitative care—while each keeps an eye on what the other is doing to ensure full coordination in regional injury control efforts, to the benefit of both the public at large and patients as individuals.

The benefits of such collaboration are most obvious in primary and secondary injury prevention, but they can also accrue through tertiary prevention by improvements in EMS. For example, through a population-based study of the epidemiology of pediatric trauma care in 1992 that compared vital statistics and hospital discharge data abstracts from a single state for a single year, Cooper et al. reported that while total pediatric trauma and burn deaths occurred at a rate of 11.8/100,000 population, in-hospital pediatric trauma and burn deaths occurred at a rate of only 2.6/100,000 population (7). Since only 22% of trauma and burn deaths occurred after hospital admission, these authors concluded that only through effective injury prevention programs and improved EMS were pediatric injury deaths likely to decrease. Thus, to be effective, the children’s trauma surgeon must be prepared not only to operate upon the patient, but also to “operate” within the community, bringing the resources of the pediatric-capable trauma center to adjoining neighborhoods to keep them safe for children at play, and to neighboring EMS to ensure they

<table>
<thead>
<tr>
<th>Table 3</th>
<th>The 10 Essential Services of the Public Health System Are Fully Congruent with the Fundamental Components and Key Infrastructure Elements of the Trauma System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essential public health services</td>
<td>Trauma system components and elements</td>
</tr>
<tr>
<td>Monitor health</td>
<td>Information management</td>
</tr>
<tr>
<td>Diagnose and investigate</td>
<td>Information management</td>
</tr>
<tr>
<td>Inform, educate, and empower</td>
<td>Education and advocacy</td>
</tr>
<tr>
<td>Mobilize community partnerships</td>
<td>Education and advocacy</td>
</tr>
<tr>
<td>Develop policies</td>
<td>Education and advocacy</td>
</tr>
<tr>
<td>Enforce laws</td>
<td>Injury prevention</td>
</tr>
<tr>
<td>Links to/provides care</td>
<td>Pre-hospital care, acute care facilities, and posthospital care</td>
</tr>
<tr>
<td>Assure competent workforce</td>
<td>Professional resources</td>
</tr>
<tr>
<td>Evaluate</td>
<td>Information management</td>
</tr>
<tr>
<td>Research</td>
<td>Research</td>
</tr>
<tr>
<td>System infrastructure</td>
<td>Leadership, information management, finances, and technology</td>
</tr>
</tbody>
</table>

*Source: From Ref. 28.

*Source: From “Joint Commission on Accreditation of Healthcare Organizations.”

Table 4  The Three Core Functions of the Public Health System Are Fully Compatible with the Five Steps of Performance Improvement

<table>
<thead>
<tr>
<th>Core public health functions</th>
<th>Steps in performance improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment</td>
<td>Plan, design, measure, and analyze</td>
</tr>
<tr>
<td>Policy development</td>
<td>Improve</td>
</tr>
<tr>
<td>Assurance</td>
<td>Cycle continues</td>
</tr>
</tbody>
</table>

*Source: From Ref. 29.

*Source: From “Joint Commission on Accreditation of Healthcare Organizations.”
have the knowledge, skills, and attitudes necessary, not only to treat pediatric injuries, but to prevent them.

Effective injury prevention programs are community based and require extensive collaboration with civic leaders, governmental agencies, and neighborhood coalitions. Programs such as the Injury Free Coalition for Kids® have been highly successful in creating substantial reductions in the burden of childhood injury in more than 40 communities throughout the nation (30b–36). Such programs require ongoing collaboration between regional and area trauma centers and local public health entities, so the incidence of injury can be tracked by locality using population-based databases, and specific plans made can be to target injuries endemic to the community. They require major institutional commitment on the part of trauma systems and centers in prevention of injuries, including commitment of the necessary staff, equipment, and resources.

EVIDENCE IN SUPPORT OF SPECIALIZED HOSPITAL CARE FOR PEDIATRIC TRAUMA

Improved outcomes from tertiary centers of pediatric intensive care were first noted by Pollack et al. in 1991 in a statewide comparison of tertiary and non-tertiary facilities (37). To conduct this analysis, these authors compared illness-adjusted mortality rates in pediatric intensive care units in a single state using PRISM scores to calibrate risk. They found that illness-adjusted mortality rates were significantly higher (odds ratios 1.1, 2.3, and 8 for mortality risk groups <5%, 5–30%, and >30%, respectively) among patients in non-tertiary facilities, mostly for patients with severe traumatic brain injury. Thus, they concluded that critically ill children were best cared for in tertiary care pediatric intensive care units.

Differences in pediatric trauma care between pediatric and non-pediatric trauma centers were reviewed by Nakayama et al. in 1992 in a comparison of outcomes between pediatric and non-pediatric trauma centers from a single state using a statewide trauma registry (38). They found that the mortality was highest in rural non-pediatric trauma centers. (Using TRISS analysis), they also found that mortality was similar in urban pediatric and non-pediatric trauma centers, although the probability of survival was slightly, but not significantly, higher for patients with moderately severe injuries in pediatric trauma centers. They concluded that children fared better in hospitals that made special provisions for the care of injured patients, especially for the care of injured children.

The question of whether pediatric trauma center designation impacts favorably upon the care of injured children was addressed by Hall et al. in 1993 (39). They reviewed medical examiner records from a large urban metropolis for a five year period. They documented clear improvement in outcome following designation of adult trauma centers, and further improvement upon designation of pediatric trauma centers. They concluded that pediatric trauma center designation saved many lives.

The efficacy of pediatric trauma care was reaffirmed in a population-based study by Cooper et al. in 1993 (40). They compared the frequency and mortality of pediatric trauma hospitalizations, based upon hospital discharge data abstracts from a single state in a single year, versus those reported to the National Pediatric Trauma Registry during a similar epoch. They found evidence both of triage of more seriously injured patients to pediatric trauma hospitals and an overall tenfold increase in survival in pediatric trauma centers for patients with moderately severe
(ISS 15–19) brain, visceral, and musculoskeletal injuries. They concluded that pediatric trauma center care was efficacious for those patients who need it the most, namely, those with injuries serious enough to carry a significant mortality risk, yet not so serious as to pose a potentially insurmountable threat.

The outcome of pediatric patients with blunt injuries was also found to be best at a pediatric trauma center by Hall et al. in 1996 (41). They reviewed the fatality rates of 1797 children admitted to pediatric trauma centers using TRISS analysis to stratify risk. While the Z-scores did not differ statistically between pediatric and adult trauma centers for penetrating injuries, the Z-score was significantly better in pediatric trauma centers for blunt injuries. They also found a lower incidence of surgical intervention for liver and spleen injuries in pediatric trauma centers compared to adult trauma centers (4% vs. 37–58% and 21% vs. 43–53%, respectively).

The influence of a statewide trauma system on pediatric hospitalization and outcome was studied by Hulka et al. in 1997 (42). They compared the frequency and mortality of pediatric trauma hospitalizations, based upon hospital discharge data abstracts, from two adjacent states with similar geography and demographics, one with and one without a statewide trauma system. They found the risk-adjusted mortality rate to be significantly lower in the state with the trauma system six months after its implementation. They concluded that triage to trauma centers saved many young lives.

An evidence-based review of all pediatric trauma system research reported to date was also prepared by Hulka for the Academic Symposium to Evaluate Evidence Regarding the Efficacy of Trauma Systems held in Stevenson, Washington, in 1998, also known as the Skamania Conference, and published the following year (43). Hulka found that of the studies reviewed, only two population-based studies evaluated the impact of trauma centers or trauma systems on children. One found that a trauma center did not improve the injured child’s risk of death, while the other found that a statewide trauma system improved the risk of death in seriously injured children, although a third population-based study found a lower risk of death if the child was treated in an urban trauma center. It was concluded that since only two published studies had evaluated the care of injured children treated at trauma centers versus non-trauma centers, and only one had examined the impact of a trauma system on pediatric outcome, further analysis was necessary to demonstrate that trauma systems make a difference in pediatric outcome, although all three studies had found that injured children had a reduced risk of death if treated at an urban trauma center (40–42).

The impact of pediatric trauma centers on mortality in a statewide system was extensively studied by Potoka et al. in 2000 (44). They performed a retrospective analysis of 13,351 children reported to a statewide trauma registry over a five year period, stratifying patients by mechanism of injury, injury severity score, specific organ injury, and type of trauma center. They found that most injured children were being treated at pediatric trauma centers or adult trauma centers with added pediatric qualifications, and that this improved survival rates. Moreover, the outcome for head, liver, and spleen injuries was better, while laparotomy and splenectomy rates were lower at pediatric trauma centers versus other types of centers.

Improved functional outcome for severely injured children treated at pediatric trauma centers was also documented by Potoka et al. in 2001 (45). They performed a retrospective analysis of 14,284 children reported to the same statewide trauma registry over the same five year period, stratifying patients both by type of trauma center and functional outcome. They found an overall trend toward better functional outcome at
pediatric trauma centers versus adult trauma centers with added pediatric qualifications and large adult trauma centers, but not versus small adult trauma centers to which pediatric patients were rarely triaged.

Moreover, significantly improved functional outcome was documented at discharge for head injured patients treated at pediatric trauma centers versus adult trauma centers with added pediatric qualifications and large adult trauma centers, but, once again, not versus small adult trauma centers to which pediatric patients were rarely triaged.

The question of whether pediatric trauma centers have better survival rates than adult trauma centers was also studied by Osler et al. in 2001 (46). They performed a retrospective analysis of the experience of trauma centers participating in the National Pediatric Trauma Registry over a 10-year period from 1985 to 1996, during which 53,113 cases were enrolled. While the overall mortality was lower at pediatric trauma centers versus adult trauma centers (1.8% vs. 3.9%), there was no difference in risk-adjusted mortality rate. Overall mortality was also lower at trauma centers verified by the American College of Surgeons Committee on Trauma as appropriate for pediatric trauma care.

The severity and mortality associated with pediatric blunt injuries in hospitals with pediatric intensive care units versus other hospitals was also reviewed by Farrell et al. in 2004 (47). They compared these outcomes in 8180 seriously injured (ISS ≥ 8) pediatric patients (age ≤ 12) enrolled in a population-based statewide trauma registry. They found that injury severity of patients treated in hospitals with pediatric intensive care units and regional trauma centers without pediatric intensive care units was significantly higher than at other hospitals, and that the risk-adjusted mortality rates were lower at hospitals with pediatric intensive care units than at other hospitals, except for non-trauma hospitals without pediatric intensive care units whose patients were considerably less severely injured. They concluded that there is significant triaging of the most seriously injured pediatric blunt trauma patients to hospitals with pediatric intensive care units, and found evidence that this policy is effective.

In summary, there now exists a substantial body of scientific evidence in support of the need for specialized pediatric trauma care. As with adult trauma care, such evidence has been difficult to obtain and substantiate, and has been limited by a number of confounding variables unique to pediatric patients—the relative infrequency of major pediatric trauma (despite the fact that it remains the leading public health problem of childhood), the sharply lower mortality rate of major pediatric trauma (about one-third the rate of major adult trauma fatalities), and the lack of statistically valid, reliable, risk-adjusted, population-based models to predict outcome after major pediatric trauma. While we may infer that trauma systems and trauma centers that make special provisions for the needs of injured children are likely to achieve better outcomes than those that do not, we do not know who or what is specifically responsible for this survival advantage. Although studies to date have lacked the statistical power to address these questions, the development and maintenance of a national trauma registry for children that is representative of the pediatric population as a whole will promote and permit the performance of such studies, and will allow further refinement of existing systems of pediatric trauma care to better suit the needs of the United States’ injured children.

The specific question of whether pediatric trauma patients can be optimally treated by adult trauma surgeons has been investigated by a number of authors. Knudson et al. and Fortune et al. in 1992, Rhodes et al. in 1993, Bensard et al. in 1994, and D’Amelio et al. in 1995, in comparing, respectively, 353, 303, 1, 115,
410, and 427 pediatric patients with the Multiple Trauma Outcome Study database regarding their demographics, mechanism of injury, Revised Trauma Score, surgical procedures, intensive care, Injury Severity Score (ISS), and outcome, found that their overall fatality rates, respectively, of 6%, 8.9% (mean ISS 15.6), 2.5% (mean ISS 11.1), 2%, and 4.2% (mean ISS 11.5) compared favorably with national standards—while Partrick et al. in 2000 and Sherman et al. in 2001 found similar results with respect not only to mortality outcomes, but also to the management and outcomes of injuries to two specific body regions, the head and abdomen (48–54). Taken together, these studies appear to demonstrate unequivocally that adult trauma surgeons can provide appropriate care for pediatric trauma patients. However, what is not mentioned in any of these reports is that all institutions involved in these studies had the benefit of comprehensive pediatric inpatient facilities, including pediatric emergency care, pediatric intensive care, pediatric acute care, and perhaps most important, yet most frequently overlooked, pediatric nursing care—indirectly supporting the notion that what is most critical in pediatric trauma care is proper emphasis on the special needs of pediatric patients throughout all phases of care, and validating the observation that when such provision is made, pediatric trauma patients can be expected to have optimal outcomes.

In conclusion, the implications of these research findings are clear. Trauma systems must assure that the special needs of pediatric patients are met throughout the entire continuum of trauma care—from prevention, through access, ambulance care, emergency care, operative and intensive care, acute care, recovery, and rehabilitation. To ensure that these goals are met at the system level, regional trauma advisory committees should invite representatives from the pediatric trauma care community to participate in all their activities on a permanent basis, while to ensure they are met at the hospital level, all trauma center medical directors should assume personal responsibility to invite the participation of pediatric-capable trauma professionals to the care of the pediatric trauma patient. To this end, reliance on the latest editions of the American College of Surgeons’ *Consultation for Trauma Systems and Resources for Optimal Care of the Injured Patient* will ensure that the needs of injured children are met in the system and the hospital alike, the principles of which are described below with respect to the care of the pediatric trauma patient (17,55).

**ELEMENTS OF CONTEMPORARY PEDIATRIC TRAUMA SYSTEM DESIGN**

**Pediatric Trauma System**

The pediatric trauma system is part of the fully inclusive regional trauma system, each component of which is pediatric capable. The regional trauma center and, ideally, the regional pediatric trauma center are at the hub of the system. Area trauma centers may be needed in localities distant from the regional trauma center and must be capable of surgical management of pediatric trauma. All other hospitals in the region should participate as they are able but must at least be capable of initial resuscitation, stabilization, and transfer of pediatric trauma patients. Finally, there must be a regional trauma advisory committee that includes pediatric representation with the authority to develop and implement guidelines for triage of pediatric trauma patients within the system. The regional trauma system should also collaborate with the public health system in injury prevention and with local public health, public safety, and emergency management agencies in disaster planning.
Pediatric Trauma Center

The pediatric trauma center should be located in a trauma hospital with comprehensive pediatric services, such as a full-service general, university, or children’s hospital. This hospital must demonstrate an institutional commitment to pediatric trauma care, as evidenced by the provision of appropriate staff, equipment, and resources necessary to care for the most seriously injured pediatric trauma patients. Pediatric medical and surgical subspecialty services and units must be present and should include pediatric trauma surgery, pediatric emergency medicine, pediatric critical care, pediatric neurosurgery, pediatric orthopedics, and pediatric anesthesiology. Pediatric nursing and allied health professionals must also be present, and advanced life support training in trauma and pediatrics must be current for all staff who care for pediatric trauma patients. Finally, there must be an organized pediatric trauma service within the regional pediatric trauma center with separate medical leadership, nursing coordination, social services, and performance improvement. Regional pediatric trauma centers must also support education and research in pediatric trauma and provide leadership in pediatric trauma system coordination, including pediatric disaster management.

EVIDENCE IN SUPPORT OF SPECIALIZED PRE-HOSPITAL CARE FOR PEDIATRIC TRAUMA

Resuscitation

There is scant literature on pre-hospital pediatric trauma resuscitation. Those studies that exist focus chiefly on airway management, volume resuscitation, and cervical spine stabilization, and, collectively, suggest that less is more, that a “scoop and run” philosophy remains preferable to a “stay and play” approach for pediatric trauma patients, as is also true for adult trauma patients—especially since pediatric resuscitation skills are infrequently used in pediatric trauma patients (56,57). Specifically, it appears that none of the endotracheal intubation or medical antishock trousers or intravenous fluid methods improves the survival of pediatric trauma patients, and that even under circumstances where volume resuscitation is utilized, the small volumes infused would be unlikely to have significant physiologic benefit. Furthermore, it appears that while cervical spine stabilization is critical for seriously head- and brain-injured patients, current methods are neither risk-free nor optimally designed to achieve proper neutral positioning in the majority of pediatric trauma patients.

The effect of out-of-hospital pediatric endotracheal intubation on survival and neurological outcome was studied by Gausche et al. in 2000 (58). They conducted a prospective randomized trial of pre-hospital airway management (endotracheal intubation in 51% vs. bag and mask in 49%) in 830 consecutive pediatric patients less than 13 years of age. Mortality rates were similar between the two groups (26% vs. 31%, respectively), as was good neurological outcome (20% vs. 23%, respectively), including multiply injured and head-injured patients. However, while procedural complications were identical between the two groups (51% vs. 53%, respectively), scene times were longer for patients who were ventilated via tube rather than bag and mask (11 minutes vs. 9 minutes).

In view of the relatively small numbers of head-injured patients in the above study—the very patients who might be expected to benefit most from definitive airway control—pre-hospital endotracheal intubation for severe head injury in children was reviewed by Cooper et al. in 2001 (59). They performed a retrospective analysis
of all 578 severe [Abbreviated Injury Scale (AIS) score ≥ 4] head injury patients reported to the National Pediatric Trauma Registry during its last five years of operation who required pre-hospital airway management (endotracheal intubation in 83% vs. bag and mask in 17%). Once again, mortality rates were identical between the two groups (48% vs. 48%, respectively), intubated patients being older, more often transported by helicopter, and more often resuscitated with fluid. As before, procedure or equipment failure or complications were identical between the two groups—as were functional outcomes—but injury complications occurred less often in intubated patients than in masked patients (58% vs. 71%, respectively), for reasons that could not be readily explained.

The efficacy of medical antishock trouser (MAST) use in injured children who present in hypotensive shock was examined by the same group in 1992 (60). They reviewed the experience of the National Pediatric Trauma Registry over a four year period in 179 hypotensive (systolic blood pressure ≤ 80 mmHg) children (age ≥ 5 years), of whom 48 (27%) were treated with MAST. The MAST patients were somewhat older (12.6 years vs. 10.3 years) and more severely injured [Pediatric Trauma Score (PTS) 1.9 vs. 3.8, ISS 35.3 vs. 25.8] but were otherwise similar to controls. However, survival was dramatically lower in patients treated with MAST (25% vs. 48%), except among those with severe injuries (PTS ≥ 4, ISS ≥ 20) or who were severely hypotensive (systolic blood pressure ≤ 50 mmHg), who were neither helped nor hurt by their use, but whose injuries were of such great severity that survival was uncommon.

The efficacy of pre-hospital volume resuscitation in injured children who present in hypotensive shock was also examined by this group in 1993 (61). They reviewed the experience of the National Pediatric Trauma Registry over a five year period in 1727 hypotensive children (systolic blood pressure < 80 mmHg < 5 years of age), of whom 386 (22%) were treated with intravenous fluid in the field. The fluid patients were significantly older (8.9 years vs. 3.7 years) and more severely injured (PTS 4.1 vs. 7.3, ISS 25.5 vs. 10.0), more severely head injured [Glasgow Coma Scale (GCS) 8 vs. 10], more hypotensive (systolic blood pressure 62 vs. 79), and more often victims of motor vehicle crashes and gunshot wounds but less often victims of falls. Once again, survival was significantly lower in patients treated with fluid (52% vs. 89%), a finding that was independent of age, injury severity, and systolic blood pressure, except among patients with severe injuries (ISS ≥ 20) or profound hypotension (systolic blood pressure ≤ 50 mmHg), most of whom died.

The efficacy of intraosseous fluid infusion either in the field or in the emergency department in injured children who present in hypotensive shock was also examined by the group in 1993 (62). They reviewed the experience of the National Pediatric Trauma Registry over a five year period in 405 hypotensive (systolic blood pressure ≤ 80 mmHg) children (age < 5 years), of whom 33 (8%) were treated with intraosseous fluid. The intraosseous patients were far more severely injured (PTS ~0.1 vs. 5.6, ISS 33.0 vs. 15.5), far more severely head injured (GCS 4 vs. 11), far more hypotensive (systolic blood pressure 29.0 vs. 67.0), but were similar in age and sex. As expected, survival was dramatically lower in patients treated with fluid versus unmatched controls (12% vs. 80%), but was also significantly lower in patients treated with fluid versus controls matched by severity of injury (PTS 10% vs. 38%, ISS 7% vs. 29%) and degree of hypotension (systolic blood pressure < 50 mmHg 0% vs. 18%, systolic blood pressure ≥ 50 mmHg 33% vs. 87%).

The effectiveness of pre-hospital fluid therapy in pediatric trauma patients was also reviewed by Teach et al. in 1995 (63). They reviewed the ambulance trip and
emergency department records of 50 pediatric patients less than 18 years of age
(average age 9.6 years) who received intravenous fluid in the pre-hospital setting. They
found that the combined total pre-hospital time (scene time plus transport time) did not
differ whether the intravenous catheter was placed at the scene or in the ambulance (25.6 minutes vs. 25.5 minutes, respectively), while the average pre-hospital infusion volume was only 4.4 mL/kg (range 0–17 mL/kg), or less than 25% of the dose prescribed in regional advanced life support protocols. They also determined that of the 50 patients reviewed, the intervention was possibly beneficial in two, possibly detrimental and one, and inconsequential in the remainder.

Emergency transport and positioning of young children who have an injury of the cervical spine was investigated by Herzenberg et al. in 1989 (66). They found that in ten children less than seven years old, an unstable injury of the cervical spine had anterior angulation or translation, or both, on initial lateral radiographs that were made with the child supine on a standard backboard. Supine and lateral radiographs of 72 children who did not have a fracture also demonstrated more relative cervical kyphosis in younger children when they were in the supine position. They concluded that to prevent undesirable cervical flexion in young children during emergency transport and radiography, a standard backboard should be modified to provide safer alignment of the cervical spine, either through use of a recess for the occiput or of a double mattress pad to raise the head.

The respiratory effects of spinal immobilization in children were studied by Schafermeyer et al. in 1991 (67). They performed a prospective study of the restrictive effects of two spinal immobilization strapping techniques on the respiratory capacity of 51 normal, healthy children (age 6–15 years) by measuring forced vital capacity in the standing, supine, and fully immobilized positions. They found a 20% (range 4–59%) reduction in forced vital capacity, regardless of strapping technique. They concluded that spinal immobilization significantly reduced respiratory capacity in children.

Neutral cervical spine positioning was further researched by Nypaver et al. in 1994 (68). They measured the height of back elevation required to place the cervical spine in a neutral position in a convenience sample of children less than eight years old. They found that all children required elevation of the back for correct neutral position (mean height 25.5 mm, range 5–41 mm). They further concluded that children less than four years old required more elevation than older children (27 mm vs. 22 mm).

Achieving neutral position with pediatric cervical spine immobilization was also examined by Curran et al. in 1995 (69). They conducted a prospective evaluation of current spine immobilization devices in achieving radiographic neutral positioning of the cervical spine in 118 pediatric trauma patients by obtaining lateral cervical spine radiographs while these patients remained fully immobilized. They found that 60% of patients had excessive kyphosis or lordosis, 50% were in excessive flexion, and that no single device or technique (collar, backboard, towels and collar, and backboard and blocks were most frequently used) appeared to provide superior protection from angulation. Unfortunately, no single method or combination of methods consistently achieved a neutral position.

The question of whether pre-hospital cervical spine immobilization can be safely avoided in pediatric patients with minor injuries has not been answered. Attempts were made by Jaffe et al. and Rachesky et al. in 1987 to develop clinical prediction rules that would reliably determine which of these patients had sufficiently low risk of cervical spine injury to justify omission of cervical spine stabilization in the pre-hospital setting, but neither was sufficiently accurate (68,69). However, the
National Emergency X-Radiography Utilization Study (NEXUS) criteria for clinical prediction of cervical spine injury established by Hoffman et al. in 2000 were applied to pediatric trauma patients by Viccellio et al. in 2001 and appeared to perform well, with 100% sensitivity and negative predictive value (95% confidence intervals of 87.8–100% and 99.4–100.0%, respectively) (70,71). However, the authors urged caution in applying the results due to the small size of the study—likely a wise recommendation in view of the known risks of spinal cord injury without radiographic abnormality (SCIWORA) and atlantoaxial instability, especially in patients with Down’s syndrome (72,73).

Triage

Pediatric pre-hospital trauma triage criteria are based upon the American College of Surgeons Field Trauma Triage Decision Scheme, which includes anatomic, physiologic, mechanistic, and comorbid criteria, including age less than five. The Pediatric Trauma Score was also developed as a field triage tool and correlates closely with the Injury Severity Score as a predictor of mortality (74). However, the Revised Trauma Score performs nearly as well as the Pediatric Trauma Score—despite the fact that it is based upon adult vital signs—presumably because abnormalities in respiratory rate and Glasgow Coma Scale Score tend to correlate in seriously injured pediatric patients, most of whom have serious traumatic brain injury, thereby giving “double weight” to those components of the score most likely to be abnormal following head injury (75). Yet, both scores require calculation in the busy pre-hospital setting, calling for simpler tools requiring no added calculations that would minimize both undesirable over-triage and unacceptable under-triage.

To assess patterns of pediatric trauma triage and patient transfer to regional pediatric trauma centers and proximate adult trauma centers based upon use of the anatomic, physiologic, and mechanistic criteria delineated in the American College of Surgeons Field Triage Decision Scheme, a review of 1307 pediatric trauma cases was conducted by Jubelirer et al. in 1990 (78). The study was performed in eight level-II trauma centers surrounding a major metropolitan statistical area that contained two regional pediatric trauma centers. They found that while 43 patients were transferred to the regional pediatric trauma centers based on local criteria, the remaining 1264 patients were treated in the level-II trauma centers, with outcomes that compared favorably to those in other published reports. They concluded that patients with moderate but not severe injuries (PTS > 8) could be successfully managed by level-II trauma centers—although the observed mortality rate of 1.8% suggests that at least some patients who died, all of who clearly had serious injuries (PTS ≤ 8), might have fared better if pediatric trauma triage criteria had led them to a pediatric trauma center.

The need for pediatric-specific triage criteria was reinforced following publication of the results of a statewide trauma triage study by Phillips et al. in 1996 (79). They performed a retrospective analysis of state trauma registry data and state hospital discharge data in a nine county region to determine if use of the state trauma triage “scorecard” based upon the American College of Surgeons Field Triage Decision Scheme resulted in appropriate categorization as “major” or “minor” trauma, according to standardized protocols developed by an expert medical panel. They found that of the 1505 pediatric cases available for analysis, which accounted for 9.2% of the total study population, 6.0% of all hospitalized cases, and 6.8% of all trauma deaths, there was a 15.2% over-triage rate and a 33.3% under-triage rate, well above the 5% target.
rates for acceptable over-triage and under-triage. They concluded that new pediatric triage instruments were needed to avoid unacceptable under-triage.

To this end, a better alternative for predicting inpatient mortality for pediatric trauma patients with blunt injuries was reported by Hannan et al. in 2000 (78). They performed a retrospective review of 2923 seriously injured (ISS ≥ 8) pediatric patients (age ≤ 12 years) reported to a single state’s trauma registry over a two year period. They tested all variables from the Pediatric Trauma Score and the Revised Trauma Score, as well as the individual components of the GCS score, the AVPU Score, ISS, ICISS, and age specific systolic blood pressure, finding that the only significant independent predictors of mortality were ICISS, a Best Motor Response of one from the Glasgow Coma Scale Score, and the Unresponsive category from the AVPU Score—the latter two being readily available to pre-hospital personnel. Moreover, the sensitivity and specificity of both measures exceeded 90%.

Pre-hospital triage in the injured pediatric patient was also studied by Engum et al. in 2000 (81). They performed a prospective analysis of 1295 pediatric trauma patients versus 1326 adult trauma patients who died in the emergency department, underwent operation, or were admitted to the intensive care unit, as indicators of the need for specialized trauma care. They found that the most accurate criteria for prediction of major injury were systolic blood pressure ≤ 90 mmHg, burn ≥ 15% of total body surface area, Glasgow Coma Scale Score ≤ 12, respiratory rate ≤ 29 breaths per minute, and paralysis, while less accurate criteria for major injury were fall > 20 feet, penetrating trauma, vehicle ejection, paramedic judgment, vehicle rollover, and need for vehicle extrication. Using these criteria, they found an over-triage rate of 71% but an under-triage rate of 0%, with the Revised Trauma Score and Pediatric Trauma Score missing 30% and 45% of major trauma patients, respectively.

The specific question of whether specialized tools for pediatric trauma team activation and for pediatric helicopter triage could improve pediatric trauma staff utilization and pediatric trauma survival rates, without excessive over-triage rates, has also been investigated. Sola et al. in 1994, in a study of 952 children treated at a regional pediatric trauma center over a one-year period, found that pediatric trauma triage criteria had a sensitivity of 86% in predicting which trauma patients would require either an operation or pediatric intensive care, while maintaining a specificity of 98% (82). Moront et al. in 1996, in a study of 3861 injured children treated at a regional pediatric trauma center over a four-year period, found that helicopter transport was associated with better survival rates than ground transport, and that pediatric helicopter triage criteria based on Glasgow Coma Scale Score and heart rate improved helicopter resource utilization without compromising care, although substantial over-triage rates were observed (83). However, Kotch and Burgess in 2002, in a study of 969 patients transported to a regional trauma center by helicopter over a five-year period, of whom 143 patients were children, found no differences in triage scores, injury severities, or survival probabilities in children versus adults, although pediatric lengths of stay were slightly shorter (84).

**ELEMENTS OF CONTEMPORARY PEDIATRIC PRE-HOSPITAL TRAUMA CARE**

Pediatric trauma resuscitation should begin as soon as possible after the injury occurs, ideally through pediatric-capable emergency medical dispatchers who provide pre-arrival instructions to lay rescuers at the scene. It continues upon the arrival
of pre-hospital professionals, including first responders, emergency medical technicians, and paramedics. Pre-hospital treatment protocols utilized by these emergency medical personnel should be conservative yet permissive, emphasizing basic life support modalities such as supplemental oxygen and assisted ventilation via bag and mask, only providing advanced life support interventions such as endotracheal intubation and volume resuscitation when appropriate (83). The emphasis in pediatric pre-hospital trauma care is on aggressive support of vital functions during what has been called the “platinum half hour” of early pediatric trauma care (J. A. Haller, personal communication, December 1, 2003).

Pediatric trauma protocols utilized by emergency medical personnel begin with an analysis of scene safety—including a survey for hazardous materials—and, if the scene is safe, continue with formation of a general impression of the urgency of the patient’s condition, utilizing the Pediatric Assessment Triangle to obtain a rapid evaluation of the patients appearance, work of breathing, and circulation to skin. Pre-hospital trauma professionals next proceed to the primary survey, or initial assessment, of the airway, breathing, circulation, and disabilities, with an emphasis on detection and management of neuroventilatory rather than hemodynamic abnormalities, the former being some five times more common in pediatric trauma patients than the latter. The secondary survey, or focused history and detailed physical examination, is performed next—but is omitted entirely, or performed en route, if the patient is less than fully stable. Because of the need for specialized pediatric trauma care, injured children should be transported to the nearest pediatric-capable trauma center, keeping the child warm.

Pre-hospital professionals are our “pre-hospital pediatric trauma surgeons” and must be fully trained in all aspects of pre-hospital pediatric trauma resuscitation if they are to be effective in this role. First responders currently receive 40 to 50 hours of training in oxygen administration, use of airway adjuncts, assisted ventilation via bag and mask, bleeding control, splinting, and immobilization, only six of which hours are in pediatric care (84). Emergency medical technicians currently receive 110 to 120 hours of training, including all of the above plus additional training in lifts, carries, and ambulance transport, only 10 of which hours are in pediatric care (85). Paramedics currently receive 1000 to 1200 hours of training, including all of the above plus additional training in endotracheal intubation, needle cricothyroidotomy, needle decompression of probable tension pneumothorax, and intravenous and intraosseous access for volume resuscitation, only 20 of which hours are in pediatrics (86).

Pre-hospital professionals are taught utilizing National Standard Curricula developed for each level of practice, which in the future will be periodically revised on a five- to seven-years cycle, based upon National EMS Education Standards, consistent with the EMS Education Agenda for the Future (87). An “andragogical” versus a “pedagogical” approach is taken to teaching, based upon modern principles of adult education, and the “need to know” versus what might be “nice to know.” The curricula are, for the most part, “assessment-based” rather than “diagnosis-based,” and thereby focus on presenting problems rather than underlying illnesses and injuries. Pediatric educational modules follow upon adult educational modules, to allow the limited pediatric curricular hours to be used most efficiently, and should be regularly and generously supplemented by up-to-date continuing trauma education programs such as the Pre-hospital Trauma Life Support (PHTLS) course of the National Association of Emergency Medical Technicians and the American College of Surgeons, as well as up-to-date continuing pediatric education programs.
such as the Pediatric Emergencies for Pre-hospital Professionals (PEPP) course of the American Academy of Pediatrics, and the Pediatric Pre-hospital Care (PPC) course of the National Association of Emergency Medical Technicians (88–90).

Pediatric equipment is mandatory for the successful resuscitation of critically injured children in the pre-hospital setting. Minimum standards for pediatric equipment in ambulances at both the basic life support and advanced life support levels have been published by the National EMS for Children Resource Alliance Committee on Ambulance Equipment and Supplies, which were recently updated, and are summarized in Table 5 (13). Although medications required by children differ little from those needed by adults, drug dosages, for the most part, are determined on the basis of size. The use of color-coded tapes that key drug doses and equipment selection to body length has proved effective in the field and is now standard equipment in most agencies (91).

Pediatric interfacility transport is a key component of pediatric trauma care, and many pediatric comprehensive care centers have established specialized teams for interfacility transport of critically ill and injured patients for this purpose. However, pediatric interfacility transport is not risk-free, as adverse events such as plugged endotracheal tubes and loss of vascular access occur at nearly twice the rate during interfacility transport as in the pediatric intensive care unit, and 10 times

**Table 5  Minimum Standards for Pediatric Equipment in Ambulances**

<table>
<thead>
<tr>
<th>Elementary Standards for Pediatric Equipment in Basic Life Support Ambulances</th>
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<tbody>
<tr>
<td>Pediatric stethoscope, infant/child attachments</td>
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<tr>
<td>Pediatric blood pressure cuffs, infant/child sizes</td>
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<tr>
<td>Disposable humidifier(s)</td>
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<tr>
<td>Pediatric simple/non-rebreathing oxygen masks, all sizes</td>
</tr>
<tr>
<td>Pediatric face masks, all sizes</td>
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<tr>
<td>Pediatric bag-valve devices, infant/child sizes</td>
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<tr>
<td>Pediatric airway adjuncts, all sizes</td>
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<tr>
<td>Pediatric suction catheters, all sizes</td>
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<tr>
<td>Pediatric Yankauer device</td>
</tr>
<tr>
<td>Pediatric extrication collars, all sizes</td>
</tr>
<tr>
<td>Pediatric extrication equipment (including infant car seat)</td>
</tr>
<tr>
<td>Pediatric limb splints, all sizes</td>
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<tr>
<th>Advanced Life Support Ambulance Equipment</th>
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<tbody>
<tr>
<td>All of the above, plus . . .</td>
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<tr>
<td>Pediatric endotracheal tubes, all sizes</td>
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<tr>
<td>Pediatric stylets, all sizes</td>
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<tr>
<td>Pediatric laryngoscope blades, all sizes</td>
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<tr>
<td>Pediatric Magill (Rovenstein) forceps</td>
</tr>
<tr>
<td>Pediatric intravenous catheters, all sizes</td>
</tr>
<tr>
<td>Pediatric intraosseous needles, all sizes</td>
</tr>
<tr>
<td>Pediatric nasogastric tubes, all sizes</td>
</tr>
<tr>
<td>Pediatric electrocardiogram electrode Electridats, all sizes</td>
</tr>
<tr>
<td>Pediatric defibrillator paddles, infant/child sizes</td>
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<tr>
<td>Pediatric dosage-packed medications/fluids</td>
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<tr>
<td>Pediatric dosage/volume wall chart</td>
</tr>
<tr>
<td>Mini-drip intravenous infusion sets</td>
</tr>
</tbody>
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more frequently with non-specialized teams than with specialized teams (92,93). At a minimum, transport providers must be capable of critical pediatric assessment and monitoring, and must be highly skilled in the techniques of pediatric endotracheal intubation and vascular access, as well as fluid and drug administration in critically ill and injured children (94,95). Whenever possible, interfacility transport of such patients should be conducted by specialized pediatric transport teams staffed by physicians and nurses with special training in pediatric critical care treatment and transport (96,97).

Pediatric ambulance patient transport involves both a different purpose and a different environment than pediatric automobile passenger transport. The ambulance patient compartment is open and large, contains numerous heavy pieces of equipment, and carries restrained patients and passengers and unrestrained providers in a wide variety of places and positions. However, in contrast to automobile passenger safety, formal standards are not yet developed regarding ambulance occupant protection. This unfortunate situation persists despite the documented lethal hazards of ambulance crashes, which are 10 times more common per passenger mile than automobile crashes (98).

Pediatric ambulance patient transport, though inherently unsafe, can be made less hazardous through the use of safe driving practices and effective restraint of patients, passengers, providers, and equipment. Unfortunately, many commercially available restraint devices are ineffective but are not known to be so because they have been subjected only to static testing at the laboratory bench rather than dynamic testing in a moving ambulance (99). Fortunately, recent evidence suggests that safe restraint of a child occupant can be achieved through the use of a child safety seat when secured to the ambulance stretcher using two standard ambulance gurney belts (100). Yet, the most important step in ensuring safe transport of ill or injured pediatric patients is to ensure that all personnel, most especially ambulance drivers, regularly follow the Do’s and Don’ts recently issued by the NHTSA and the EMS for Children Program, as shown in Table 6 (101).

<table>
<thead>
<tr>
<th>Do’s</th>
<th>Don’ts</th>
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<tbody>
<tr>
<td>Do drive cautiously at safe speeds observing traffic laws</td>
<td>Do not drive at unsafe high speeds with rapid acceleration, decelerations, and turns</td>
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<tr>
<td>Do tightly secure all monitoring devices and other equipment</td>
<td>Do not leave monitoring devices and other equipment unsecured in moving EMS vehicles</td>
</tr>
<tr>
<td>Do ensure available restraint systems are used by EMTs and other occupants, including the patient</td>
<td>Do not allow parents, caregivers, EMTs or other passengers to be unrestrained during transport</td>
</tr>
<tr>
<td>Do transport children who are not patients, properly restrained, in an alternate passenger vehicle, whenever possible</td>
<td>Do not have the child/infant held in the parent’s, caregiver’s, or EMT’s arms or lap during transport</td>
</tr>
<tr>
<td>Do encourage utilization of the DOT NHTSA emergency vehicle operator course (EVOC), national standard curriculum</td>
<td>Do not allow emergency vehicles to be operated by persons who have not completed the DOT EVOC or equivalent</td>
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</table>
Organizing the community for pediatric trauma requires not only specialized knowledge of the evaluation and management of childhood injury, including pediatric injury prevention and EMS for children, but also unwavering commitment to ensure that the specialized needs of injured children are met at every level of system organization. Mature understanding of the trauma system as a public good, and practiced application of the interpersonal and organizational skills necessary to lead and manage complex undertakings, are also mandatory for the trauma professional who seeks to influence the provision of care in a given region. While the principles of pediatric trauma and EMS system design may be simple, they are not always easy to implement without a clear understanding that pediatric trauma care is a truly collaborative venture that requires the coordination of numerous professionals and services from many different disciplines and agencies, all of which have a stake in the care of the injured child.

Yet, the benefit to the community that chooses to organize itself for pediatric trauma care is self-evident, even—perhaps especially—to those with whom the system itself may not interact or interface on a regular basis. For example, civic and business leaders have a major stake in the development and support of the community pediatric trauma system. Childhood injuries cost time and money, not only from the involved families, but from their employers and their insurance companies as well. There is ample ground to make common cause with such community partners, for whom the well-being of children is clearly no less important than to public health and trauma care professionals. Indeed, it is the one health care benefit on which all agree—the need for systems and services that keep children healthy.

REFERENCES


Organizing the Community for Pediatric Trauma


Organizing the Hospital for Pediatric Trauma Care

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HISTORY OF TRAUMA CENTERS

The development of trauma centers in the United States has a varied background, which takes its origins from many of the wars this country has fought. Many aspects, which are now considered to be integral parts of any trauma center, originated on the battlefield. Aspects such as immediate availability of surgeons who can provide immediate surgical care to trauma victims, facilities capable of providing any indicated treatment (Mobile Army Surgical Hospital units), pre-hospital personnel to identify and stabilize the victim in the field and transport the patient to an emergency room capable of providing the indicated therapy, transport systems such as ground ambulances and helicopters to transport the victims, just to mention a few. All of these components originated in the U.S. military.

The civilian trauma system originated in the State of Illinois in 1967 with the inception of the first “adult” trauma center at Cook County Hospital under the leadership of Drs. Robert Freeark and Robert Baker. Shortly after this, Dr. R. Adams Cowley initiated the “Shock Trauma” Unit (Maryland Institute for Emergency Medical Services System) at the University of Maryland in Baltimore.

Following closely on the heels of the first two “adult” trauma centers, the U.S. Congress passed a number of “emergency medical services systems acts,” which defined many aspects of the things needed by a trauma system in the prehospital arena. These included the makeup of ambulances (equipment), the necessity for communications systems, which would allow pre-hospital personnel to speak with either an individual distant from or in a trauma receiving facility, and the training necessary for personnel in an ambulance unit, i.e., emergency medical technicians (EMTs), paramedics, etc. It is an interesting sidelight to note that prior to the passage of the various emergency medical services systems acts, many ambulance drivers were, in fact, funeral home directors.
PEDIATRIC TRAUMA CENTERS

It is of interest to note that in 1962 the first Pediatric Trauma Center was established by Dr. Peter Kottmeier at the Kings County Hospital, in Brooklyn, New York, five years before the first adult trauma center opened its doors.

Trauma care was further advanced in the United States by the American College of Surgeons (ACS), which in the early 1920s started the Committee on Trauma (COT). The purpose of the COT was to improve the care of the trauma victim by education. In February of 1984, the COT developed the first resources or standards manual, which defined the standards of care necessary to treat trauma patients (1). These standards were primarily focused on the hospital resources necessary for this task. Not including the 1984 pamphlet, there have been four editions of this manual, the most current being entitled, Resources for the Optimum Care of the Injured Patient (2–5). The next edition is tentatively scheduled for publication in 2005.

The ACS COT established the Verification Subcommittee in February of 1987. This subcommittee’s purpose was to verify compliance by hospitals wishing to become ACS-verified trauma centers, with the standards of care promulgated by the resources manual.

The first document describing the resources necessary to treat the injured child was published in the Journal of Trauma in 1982 (6). The COT first included an appendix on Pediatric Trauma Care in their original 1984 pamphlet, Appendix J (1). The first pediatric chapter in the ACS resource manual appeared in the 1987 edition (3).

The COT has defined what is meant by the term “pediatric trauma center” by dividing trauma centers into levels. The highest level is a Level-I Pediatric Trauma Center located in a children’s hospital. A similar designation and quality of care may be present in a Level-I Adult Trauma Center with pediatric expertise. Children’s hospitals can also apply to become a Level-II Pediatric Trauma Center. By ACS standards, all trauma centers, regardless of their designation level, must have the ability to stabilize and transfer injured children when received in their institution.

PREPLANNING

Before the first patient is seen and treated in any institution that desires to become a trauma center or have a trauma unit, there is a great deal of organization that must be accomplished. The decision to apply for such a designation is the first priority. This decision is not one that can be made by a single individual or department. The decision is one that must be embraced by the entire institution for the simple reason that trauma, by its very nature, is extremely disruptive to any hospital’s schedule. Trauma is a disease that can and does occur at any and all times. The orderly carrying out of a busy operating room schedule can be disrupted because of the necessity of bringing an injured patient to the operating room at any time. Other resources such as laboratory and radiology are similarly disrupted due to the need for immediate results from the laboratory as well as immediate access to a computerized tomography scanner, magnetic resonance imaging, and/or interventional radiological procedures. The requirement for a designated and immediately available trauma team is similarly disruptive. Thus, it should be apparent that the decision to seek designation as a trauma center is one that requires agreement of many, if not all, departments within a busy hospital. The hospital’s administration must agree and support this decision.
Commitment

The single most important component for any institution seeking a trauma designation is commitment. Commitment to provide the personnel, equipment, space, and all other resources necessary for treatment of the injured patient, 24 hours a day, seven days a week.

Facilities

The injured patient generally enters an institution through its emergency department (ED). Often the ED is very busy and crowded. An injured patient should not be expected to wait until a room opens before being seen. Thus a “trauma room” or resuscitation bay must always be available. This is an expense for the institution, but assessment and resuscitation must be available without delay.

The makeup of such a room should include appropriate IV fluids, catheters, surgical instrument sets, warming equipment, including a method to rapidly warm the entire room, medications and enough space for an entire team of physicians, nurses, and technicians to have easy access to the patient. Often a hospital that constructs a new trauma room will include a ceiling-mounted X-ray unit in the room. If not, there must be sufficient space for a portable X-ray machine to be wheeled into the space.

For any institution that treats injured children, the Broselow System is a reasonable method of organizing the trauma room. This system provides color-coded equipment such as airways, laryngoscopes, endotracheal tubes, suction catheters, vascular access devices, nasogastric (NG) tubes, urinary catheters, and chest tubes. The color-coding is based on the child’s weight. In addition, the Broselow tape is a clever method of rapidly determining the child’s weight based on height and can be used in the trauma room for quick determination of weight, IV-fluid bolus infusion amounts, and emergency medications. The Broselow tape can be mounted in a Lucite holder and kept permanently in the room. When so mounted it measures roughly five feet in length and does not have a tendency to be lost.

The facilities necessary for an institution to become a trauma center are not limited to the emergency room. The institution must have immediate availability to CT scanning, angiography, interventional radiology, operating rooms, intensive care units, and patient floors. Another requirement is the availability of rehabilitation medicine.

Radiology

In addition to routine radiographic procedures such as chest, abdominal, extremity, and spine X rays, the institution must provide immediate access to CT scanning for the injured child. The CT scan is the major diagnostic modality utilized in both children and adults, and must always be available to the trauma patient.

Operating Room

An operating room must always be available for the trauma patient. In a busy hospital this is difficult because this requirement decreases by one the number of rooms available for routine elective surgery. In addition to having an OR immediately available, personnel, including nurses, technicians, and anesthesiologists, must be immediately available 24/7.
Pediatric Intensive Care

Intensive care must be available for the injured child, preferably in a pediatric intensive care unit (PICU) with appropriately trained and trauma credentialed nurses. Should a PICU not be present, an intensive care unit may meet this requirement with appropriately trained and credentialed pediatric nurses. The equipment necessary for PICU care is well documented in the ACS resources manual.

Patient Floors

There must be beds available on a pediatric floor for patients being admitted to the hospital with injuries. Nursing care must be adequate in this area as well.

Personnel

The hospital personnel required for an institution to become a pediatric trauma center includes various physician specialties, pediatric-trained nurses working in certain specialized areas of the hospital, laboratory technicians, radiological technicians, and social workers. This is not a comprehensive list but is the basic catalogue of players.

Physicians

The group of physicians immediately responsible for the care of an injured child is made up of the surgical specialties. Pediatric general surgery includes within its training the care of the injured child. The pediatric surgical team must include a leader of that team whose responsibility it is to organize the team. In the ED, this trauma team is expected to meet the patient on arrival. Once the patient has been placed in the resuscitation room, the team begins its work. Hopefully, the ED has been notified by the pre-hospital personnel of the cause of the injury, e.g., motor vehicle crash, gunshot wound, stab wound, fall, and is prepared to start the resuscitation phase. Occurring simultaneously with the resuscitation phase is the diagnostic phase. However, the team should be trained to the important fact that the diagnosis is less important than saving the life of the injured child. Thus, the team should be aware that the lack of a diagnosis should never impede the application of an indicated treatment. For example, if the patient cannot maintain their airway, the airway should be secured before the diagnosis of the cause of the unstable airway is determined. To reverse the process, and first determine the cause of the unstable airway before treating, may result in the death of the patient.

The composition of the team, in addition to the leader, is generally two other surgeons, an anesthesiologist or emergency medicine physician, and at least two nurses, one of who acts as the scribe.

Absolute responsibility for the patient rests with the team leader. The team leader will have assigned specific duties to other members of the team. For example, the leader may assign the physician at the head of the patient and either the anesthesiologist or emergency medicine physician to manage the airway. The surgeon on the patient's right side may be assigned the responsibility of evaluating the neck, chest, right-sided extremities, and the patient's back. The surgeon on the left side may be assigned the duties of evaluating the abdomen and perineum,
left-sided extremities, and neurological status. Such a setup provides for rapid and accurate initial assessment of the injured patient.

Other physicians will be part of the trauma team but not necessarily part of the physician group who initially responds upon the patient’s arrival. Clearly, Orthopedic Surgery and Neurosurgery must be included in this group. Also, Plastic Surgery, Ear Nose Throat, Urology, and Ophthalmology will be required in specific cases. These individuals must be available on short notice at the behest of the trauma team leader.

Nonsurgical physicians are also included in the requirements. Pediatric emergency medicine and pediatric intensive care physicians are included in this group, as are radiologists. Others whose expertise may be required include gastroenterologists, cardiologists, neurologists, infectious disease specialists, and general pediatricians.

Nurses

The nurses in the resuscitation room have established duties. One will serve the function of the scribe and will record everything that occurs with the patient. The second nurse prepares the room before the patient arrives, and makes sure that appropriate fluids, chest tubes and chest evacuation apparatus, IV fluids, urinary catheters, suture material, surgical trays, etc., are available and in the room. It is also this nurse’s responsibility to make sure that the room temperature is adequate so that hypothermia does not supervene.

Intensive care nurses with education, training and/or experience, and expertise in pediatrics are required in the PICU setting. Methods of training are discussed later in this chapter.

Laboratory and Radiological Technicians

These technicians are an integral part of the trauma team meeting the patient in the ED. Most trauma centers have a routine laboratory panel that is ordered on every patient. Technicians being present at the time the patient arrives shortens the length of time the team must wait for various laboratory results. As with laboratory studies, most injured patients require, at a minimum, a specific group of X rays, including lateral cervical spine, chest, and abdominal films. The presence of the X-ray technician with the X-ray machine shortens waiting time. When more sophisticated studies are warranted, such as CT scans or angiography, the technicians are helpful in organizing them.

Social Work

The stress on a family resulting from a serious injury or death of a child is significant. The presence of social services in the ED, should either occur, is comforting for the family and can function as a bridge for information when the trauma surgeons are busy providing the necessary care.

EDUCATION

Physician education in trauma care is quite obvious for surgeons. Nearly all surgical specialties have, as part of their educational curriculum, a section devoted to care of
the injured. Clearly, pediatric surgical training has a trauma component as mandated by the Residency Review Committee for Surgery. Most other surgical specialties have a similar requirement.

The ACS Advanced Trauma Life Support® (ATLS) Course for Physicians is, in many states, a requirement to participate in the care of injured children or injured patients in general (7). This course is a scaffold by which an injured child, or any injured patient, can be thoroughly evaluated and life-threatening injuries identified and treated. This requirement for ATLS has never been mandated by the ACS but has been mandated by many government agencies responsible for the individual states’ emergency medical services (EMS) or trauma laws.

Nurses caring for the trauma patient are often required to have experience and/or training in trauma nursing. There are a number of courses offered by various organizations for trauma nursing. Advanced Trauma Care Nursing (ATCN) is the course provided by the Society of Trauma Nurses, and Trauma Nurse Care Course (TNCC) is provided by the Emergency Nursing Association. As with physicians, nurses are required to have one of these courses in order to care for injured patients.

EMTs and paramedics often provide pre-hospital trauma care. The Pre-hospital Trauma Life Support (PHTLS) course is a pre-hospital course provided by the National Association of EMTs. This particular course parallels the ATLS course and provides physicians and pre-hospital personnel a common language by which care of the trauma patient can be expedited.

The trauma center must take on the responsibility of educating its own personnel, surrounding institutions’ personnel, the pre-hospital system, and the general populace. General education for the public can take the form of trauma or injury prevention lectures, posters, and public service announcements.

SEVERITY PREDICTORS AND THE TIERED RESPONSE

An essential element in organizing the hospital is to plan for what will actually happen when a trauma patient arrives. How is the commitment of the hospital and its staff put into action? There are two key components to this. The first is to define the patient at risk and to determine what resources are required in individual cases. The second is to define the relative roles and responsibilities of the members of the hospital staff in the care of trauma patients.

For these purposes most trauma centers divide their patients into three main groups (Table 1):

- Category 1—Patients with isolated, single-system injuries caused by low-energy mechanisms. This group is by far the largest. They have simple fractures, soft tissue injuries, etc. They usually arrive by private conveyance. Rarely, these patients have significant occult injuries such as a splenic laceration or an epidural hematoma. The ED staff can assess them and seek consultation when appropriate. They do not require a trauma team response.
- Category 2: Mechanism—Patients at increased risk for multisystem or life-threatening injuries without significant anatomic or physiologic derangement. This group is defined mainly by mechanism of injury such as a fall from a great height or involvement in a high-energy motor vehicle collision with ejection, serious injuries or death of another occupant, rollover, or
significant intrusion into the passenger compartment. These patients typically arrive by ambulance. Although most do not have life- or limb-threatening injuries, many do. These patients demand careful assessment by trained and experienced trauma staff.

- Category 3: Physiologic derangement—Patients with obvious anatomic or physiologic derangement such as an amputation; penetrating injury to the head, neck, or trunk; coma; or shock. These patients also typically arrive by ambulance. These patients demand immediate careful assessment by the most highly trained and experienced trauma staff.

The exact details of the field triage criteria should be worked out locally. Engum et al. have shown that a system of field triage based on anatomic and physiologic variables plus mechanism of injury provides a “sensitive and safe system of triage” (8). In Engum’s study, standard scoring systems such as the Revised Trauma Score and the Pediatric Trauma Score had unacceptably low sensitivities, missing approximately one-third and one-half of “major” trauma cases, respectively.

A system for activating the receiving hospital staff is also necessary. Trauma responses should be tailored to the expected needs of the individual patient and based on objective information, either from the field or referring hospital, which places the patient into one of the three categories described above. The first category of patients with low-energy, single-system injuries can be handled by the ED staff on duty with referral to appropriate surgical services as required. The second and third groups with high-risk mechanisms or overt evidence of life-threatening injury both require trauma team activation and full assessment according to protocol. A trained and experienced trauma surgeon should direct the team, but the team should include other physicians, nurses, a respiratory therapist, a radiology technologist, a laboratory technician, a pharmacist, a social worker, and a chaplain. The roles of each member of the team vary depending on local circumstances, but they must be clearly defined.

### Table 1 Criteria for Triaging Pediatric Trauma Patients

<table>
<thead>
<tr>
<th>Category 1</th>
<th>Category 2: Mechanism</th>
<th>Category 3: Physiologic derangement</th>
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</thead>
<tbody>
<tr>
<td>No significant mechanism of injury</td>
<td>Blunt trauma with abdominal pain</td>
<td>Altered mental status—GCS ≤13</td>
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<tr>
<td>GCS 15</td>
<td>Suspected chest or abdominal injury</td>
<td>Airway or breathing compromise</td>
</tr>
<tr>
<td>Normal pulse, BP, and respiratory rate</td>
<td>Falls &gt;20 feet</td>
<td>Hypotension</td>
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<tr>
<td>Hemodynamically stable patient with an isolated extremity injury</td>
<td>Motor vehicle accident with ejection</td>
<td>Trauma arrest/CPR</td>
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<tr>
<td></td>
<td>Motor vehicle accident with death in same compartment</td>
<td>Multiple injuries (≥3 systems)</td>
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<tr>
<td></td>
<td>Rollover</td>
<td>Penetrating injury to head, neck, chest, or abdomen</td>
</tr>
<tr>
<td></td>
<td>Prolonged extrication</td>
<td>Paralysis post injury—spinal cord injury</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Major extremity amputation</td>
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</tbody>
</table>
Many hospitals have revised or modified their team response for the second category of patients that meet mechanism-only criteria to avoid inefficient use of staff time and resources, what might be called “false alarms.” Dowd et al. have shown that patients who meet mechanism-only criteria are less likely to require a resuscitative intervention than those who meet anatomic and physiologic criteria, and therefore do not require full trauma team activation (9). They concluded that use of anatomic and physiologic criteria only for the highest level of trauma team activation results in increased specificity without sacrificing sensitivity.

EMERGENCY MEDICAL SERVICES

No trauma center or institution can exist without emergency medical services (EMS). By and large EMS is responsible for all pre-hospital care, including transportation to the trauma center. Pre-hospital personnel generally work under the medical license of a physician who is charged with providing pre-hospital care guidelines. The physician is often online with the in-field ambulance personnel, receiving data and providing instructions to the emergency medical technicians in the field. Other systems work by off-line medical control where there are specific protocols developed beforehand. EMS will generally transport a patient to a specific hospital or, in the case of injured child, to a pediatric trauma center. There must be telephone or radio communication with the receiving institution so that the trauma team can meet the patient in the ED on arrival.

There must also be a method for the ED to communicate with the trauma team to alert them as to the mechanism of injury and types of injuries suffered by the victim. This can be accomplished in a variety of ways. Walkie-talkies are used in some systems, as are beepers. Most commonly today, cellular telephone communication is the method of choice. The various communication devices are, of course, an expense for the hospital.

For any trauma center to succeed in its mission of providing appropriate and rapid care to an injured patient, the institution must be on good terms with the EMS system. The trauma center must always be aware of the fact that pre-hospital personnel work in the most difficult and primitive emergency room of all, the field. The institution must provide appropriate feedback to these pre-hospital personnel so that the education of these individuals is steadily increased. This is often accomplished by run reviews, case studies, and lectures on specific topics.

When “errors” are identified, alternatives should be suggested to help the pre-hospital personnel improve their performance. One common error is spending too much time in the field trying to stabilize a patient who would be better served by rapid and temporary stabilization and rapid transport to the trauma center. Ambulances carry a limited amount of supplies. The hospital should provide needed supplies to a pre-hospital unit when requested. All of these courtesies will be rewarded by loyalty to the trauma center.

SUMMARY

The decision to become a trauma center is one that takes significant commitment from the entire institution. Commitment is the single most important aspect in becoming a trauma center. The institution must determine the specific type of
trauma center it wishes to become based on the standards that apply to that particular state or region. The ACS “resources” document is generally a good place to start to put together all of the in-hospital systems that need to be in place prior to a site survey to verify that the institution meets all of the applicable standards. In most states, there is an entity in either the board of health or fire department that has responsibility for verification. There are necessary equipment, space, personnel, and educational requirements that the institution must meet in order to function as a trauma center. It is neither cheap nor easy for an institution to meet the requirements, but if the hospital has the commitment to become a trauma center, it can be accomplished.

REFERENCES

1. The American College of Surgeons, Committee on Trauma. Hospital and Pre-Hospital Resources for Optimum Care of the Injured Patient and Appendices A–J. 1984.
INTRODUCTION

Pediatric multiple trauma victims present a unique set of problems to the emergency physician, pediatrician, or surgeon. Children rarely sustain lethal injury; however, delayed recognition and inappropriate management of the common problems encountered in the pediatric trauma patient can lead to a poor outcome. The ultimate common pathway leading to death in the injured child is profound shock: the inadequate delivery of oxygen to the tissues. It is therefore the goal of the initial phase of resuscitation to rapidly evaluate and treat any immediate life-threatening injuries that compromise tissue oxygenation. This is known in Advanced Trauma Life Support\textsuperscript{\textregistered} (ATLS) courses as the primary survey or the ABCs of trauma: airway, breathing, and circulation (1). Appropriate management of the ABCs is necessary for optimal outcome in pediatric trauma, regardless of whether it is managed in an adult or pediatric trauma center (2). In fact, with a relatively limited number of pediatric trauma centers, most improvements in pediatric trauma care are likely to come from improvements at combined trauma centers (3).

When performing the primary survey of an injured child, one must keep in mind that frequent reassessment is mandatory. Children have tremendous physiologic reserve and may rapidly decompensate when their threshold level is crossed. Only by frequent evaluation and assessment can the physician detect and treat the child appropriately prior to decompensation. Before a child leaves the trauma room for a diagnostic procedure, they must have their ABCs assessed and stabilized. The computed tomography (CT) scanner is no place to lose an airway or require chest tube placement. As the trauma workup proceeds into the secondary survey, any deterioration in an otherwise stable trauma patient, whether adult or child, should prompt a reassessment of the ABCs.

Performance of the primary survey is divided into the three separate stages of airway, breathing, and circulation only for discussion. In practice, it is a dynamic process in which the clinician must be aware that all three aspects occur together in real time. The proficient physician managing pediatric or adult trauma must be able to evaluate all three simultaneously, not in sequence, and recognize that problems with the airway influence breathing and circulation, and vice versa. It is
the goal of this chapter to provide a framework upon which to base the initial management of the “Golden Hour” in pediatric trauma. A MEDLINE search was performed with a restriction to articles dealing with children (ages 1 to 12) published since 1990. Using the Eastern Association for the Surgery of Trauma guidelines, no class-I articles could be found. Mostly class-III articles and a few class-II articles were used as a basis for this review. Recommendations are based on current ATLS® guidelines, with an attempt to include current evidence-based data as they relate to the primary survey in children.

ANATOMIC AND PHYSIOLOGIC CONSIDERATIONS

Children differ from adults in several specific areas relevant to trauma care. Infants and young children, in particular, have a relatively large body-surface-area-to-body-cell-mass ratio and are thus prone to developing hypothermia. This is particularly true when exposed for resuscitation or operation or when given large volumes of intravenous fluids or blood products. To prevent hypothermia, it is important to keep injured children covered as much as possible and to have available warm blankets, heat lamps, room temperature controls, and fluid warmers in resuscitation areas and operating rooms (OR).

The child’s vital signs and circulating blood volume also vary with age. This obviously affects the recognition and treatment of physiologic derangement.

Young children have relatively large heads and are more likely to suffer head injuries, especially with deceleration mechanisms such as falls and motor vehicle trauma. Their cranium is also thinner and their brains are less completely myelinated, both of which tend to increase the severity of injury. Infants with open cranial sutures, larger subarachnoid space and cisterns, and greater extracellular space in the brain may tolerate expanding intracranial hematomas and cerebral edema better.

The glottis lies in a more superior and anterior position relative to the pharynx. This makes orotracheal intubation much easier than nasotracheal intubation, especially in an emergency. In children up to about eight years of age, the airway is narrowest at the level of the cricoid cartilage. This is why uncuffed endotracheal tubes are generally used. Because it is narrower foreign material, fluid or blood more easily occludes the child’s airway. The fact that the trachea is relatively short increases the risk of malposition of endotracheal tubes because they are either too high or too low in the trachea. Tube position must be checked carefully at the time of intubation and monitored regularly thereafter.

In children, the thorax is much more compliant to external forces and the vital organs are closer to the surface, both of which tend to increase the risk of blunt injury to the tracheobronchial tree, the heart, and great vessels. The elasticity of pediatric arteries and the normal absence of atherosclerosis offset this risk. In children, the mediastinum is more mobile so that an increase in pressure from a pneumothorax or hemothorax on one side is more apt to compromise both lungs. In the abdomen, the liver, spleen, and kidneys are less well protected by the ribs in children because the ribs are more pliable and because these organs are less well covered by the ribs.

AIRWAY

The main reason for ensuring a stable airway is to provide effective oxygenation and ventilation while protecting the cervical spine and avoiding increases in intracranial
pressure. Airway control is intimately related to cervical spine protection, but the scope of this chapter will be limited to managing the airway only. Any child involved in a significant trauma should be assumed to have a cervical spine injury until proven otherwise. Movement of the neck, as is commonly employed to provide an airway, can convert a bony or ligamentous injury into a permanent disability. C-spine protection should be initiated at the scene and maintained in the emergency department. Any child that arrives without neck stabilization should be held with in-line traction or have an appropriate sized rigid cervical collar applied while the airway is evaluated.

**Anatomy and Assessment**

Several anatomic features predispose the child to potential airway obstruction. The child’s head is relatively large and causes flexion of the neck in the supine position. The tongue is larger in proportion to the rest of the oral cavity and predisposes the child to more rapid upper airway obstruction with posterior displacement of the tongue. Even a minimal amount of pressure on the submental soft tissue during bag-valve-mask ventilation can displace the tongue posteriorly and occlude the airway. The larynx is higher in the neck (C3-4) compared with that of the adult (C4-5); this alters the preferred angle of insertion of the laryngoscope blade and makes the cords appear to be more anterior. “Cocking” the laryngoscope, as is commonly practiced in adult intubation, will only push the cords more anterior and make intubation difficult. The infant epiglottis is short and angled away from the long axis of the trachea, increasing the difficulty of its control with the laryngoscope blade. Infant vocal cords are more cartilaginous and easily injured when passing the endotracheal tube. The narrowest portion of the airway in the child is the subglottis, not the glottis, as in the adult. A tube that readily passes the cords in an infant may be too tight in the subglottis. Uncuffed tubes are often used for this reason, and an acceptable air leak should be heard at a pressure that is neither too low to allow adequate tidal volumes nor too high. The airways are much smaller and the supporting cartilage is less well developed, making the trachea more susceptible to obstruction from mucus, blood, or edema. In addition, the pediatric trachea is much shorter than the adult trachea, and advancing the tube too far into the right main stem bronchus is common.

It can be difficult to recognize early airway obstruction in the child. Certainly the infant who is screaming or crying loudly and the older child who can converse with you have airways that are not in immediate jeopardy. The child who arrives comatose (Glasgow Coma Score less than 8) or with obvious laryngeal trauma has an airway that is in immediate danger. Often the child is obtunded. If spontaneous breathing is absent, the airway should be opened with a jaw thrust maneuver taking care to protect the C-spine. A finger sweep to rule out a foreign body should be performed. If no breathing effort is seen after this maneuver, hand ventilation with a mask should be initiated and preparation made to intubate the child. During assisted mask ventilation, the operator must take care not to place undue pressure on the base of the tongue, as this will occlude the airway. It is the metastable pediatric trauma patient that can present difficulties in determining whether an airway is adequate. The patient may appear only slightly agitated, with nasal flaring, stridor, and air hunger. The child with an innocent-appearing face and neck burn may have significant airway edema. When in doubt, the following maneuvers should be attempted to secure the airway.
Managing the Airway

Studies investigating field intubation have demonstrated complication rates as high as 25% (4). Appropriate mask ventilation can provide adequate gas exchange until one skilled in the task can intubate the child (5). Newer airway techniques, including the laryngeal mask airway (LMA), have been shown to be an effective temporary airway in children until secure endotracheal intubation can be performed in the emergency department (6). The LMA is placed in the posterior pharynx and advanced until it seals over the vocal cords and larynx. Excessive extension of the neck must be avoided in any airway technique. Oral and nasal airways do not protect the airway. In fact, their insertion can induce emesis. Nasal airways are too small to be effective in the child. An oral or nasal airway is, at best, a temporary technique to improve bag ventilation in preparation for endotracheal intubation.

Oral endotracheal intubation is the “gold standard” for airway control. It is critical to maintain neutral alignment of the cervical spine during all airway manipulation. Even though nasotracheal intubation in adults requires less spine manipulation, in children it is difficult and time-consuming, and therefore has little role in the acutely injured child. The size of the nares is often not large enough for an appropriate-sized tube. In addition, the path that the tube has to follow to the cords is at a very acute angle, requiring direct laryngoscopy and forceps to accomplish. Enlarged tonsils and adenoids can bleed if blindly injured with the endotracheal tube.

Children less than six years of age should receive an appropriately sized uncuffed endotracheal tube to minimize trauma to the cords and subglottic edema. Formulas exist for calculating endotracheal tube size (Table 1), but a quick reference is the size of the middle phalanx of the fifth digit. The Broselow tape, which bases drug doses and weight on the child’s length, also estimates endotracheal tube size (7). Stylets are helpful for pediatric intubation to give the tube a gentle “J” curve. The tip of the stylet should never be extended beyond the end of the tube, and a thin coat of lubricating jelly can aid in removing the stylet without extubating the child.

Endotracheal Intubation

The process of intubating a child can be harrowing for those not accustomed to it. Current ATLS® recommendations call for a rapid sequence induction of sedation.

<table>
<thead>
<tr>
<th>Age</th>
<th>Internal diameter (mm)</th>
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<tbody>
<tr>
<td>Term infant</td>
<td>3.0</td>
</tr>
<tr>
<td>6 months</td>
<td>3.5</td>
</tr>
<tr>
<td>1 year</td>
<td>4.0</td>
</tr>
<tr>
<td>2 years</td>
<td>4.5</td>
</tr>
<tr>
<td>4 years</td>
<td>5.0</td>
</tr>
<tr>
<td>6 years</td>
<td>5.5</td>
</tr>
<tr>
<td>8 years</td>
<td>6.0</td>
</tr>
<tr>
<td>10 years</td>
<td>6.5</td>
</tr>
<tr>
<td>12 years</td>
<td>7.0</td>
</tr>
<tr>
<td>14 years</td>
<td>7.5</td>
</tr>
<tr>
<td>Adult</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Note: May estimate tube internal diameter with formula: ID (mm) = Age/4 + 4.
and paralysis, especially in those with closed head injury and possible elevated intracranial pressure (1). Attempts to intubate a partially responsive, coughing, combative child will cause further elevation of the intracranial pressure. The use of drugs in rapid sequence induction must induce unconsciousness and paralysis, as well as blunt the intracranial pressure response (8). Our current choice of drugs for rapid sequence induction is listed in Table 2. Care should be taken if the patient is in shock not to induce hypotension with too much sedative. Paralysis should not be induced in the spontaneously breathing patient until the physician is capable of visualizing the cords.

Gentle mask ventilation with cricoid pressure should be attempted to pre-oxygenate the child. In-line cervical immobilization with the collar opened anteriorly should provide adequate exposure. Rapid sequence induction is initiated after proper equipment is obtained and the child has been pre-oxygenated. This should include a bag and mask connected to high flow oxygen, suction, a laryngoscope with functioning bulb, and an endotracheal tube with stylet of appropriate size as well as tubes that are a half size larger and smaller than the estimated correct size. A Miller (straight) blade is most often easiest to use and should be gently inserted into the oropharynx and the tongue elevated anteriorly to visualize the cords. Avoid the temptation to “cock” the laryngoscope, as this will further displace the cords anteriorly and increase the likelihood of breaking or loosening an incisor. The tube should only be inserted a few centimeters past the vocal cords. The trachea is short and intubation of the right main stem bronchus can easily occur. The tube should be placed no deeper than three times the endotracheal tube size, in centimeters, from the lips. The Broselow tape will also specify a depth of insertion (7). Endotracheal tube position should be confirmed with a disposable capnometer, as well as auscultation of both lung fields and listening over the epigastrium for esophageal intubation. Breath sounds transmit easily in young children and listening in both axillae will give the best point of auscultation to determine if the breath sounds are equal. Symmetry of chest wall excursion with ventilation should be noted; diminished sounds and movement of the left side should be treated by withdrawing the tube 0.5–1 cm. If diminished sounds persist, a left-sided pneumothorax should be considered. Since the trachea is so short, movement of 1 cm in either direction can often displace the tube into an inappropriate position. Vigilance in securing the tube and constant checking of its position is mandatory. Current ATLS recommendations call for obtaining a chest X ray, as well as lateral C-spine and pelvis films, at the end of the primary survey to confirm tube position as well as rule out injury (1).

### Table 2  Drugs and Doses Commonly Used for Rapid Sequence Induction

<table>
<thead>
<tr>
<th>Drug class</th>
<th>Drug name</th>
<th>Dose (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-acting sedatives</td>
<td>Etomidate</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td></td>
<td>Pentothal</td>
<td>2–4</td>
</tr>
<tr>
<td></td>
<td>Versed</td>
<td>0.01–0.02</td>
</tr>
<tr>
<td>Short-acting paralytics</td>
<td>Rocuronium</td>
<td>0.6–0.9</td>
</tr>
<tr>
<td></td>
<td>Vecuronium</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td></td>
<td>Succinylcholine</td>
<td>1–2</td>
</tr>
<tr>
<td>Vagolytic (infants)</td>
<td>Atropine</td>
<td>0.01–0.02</td>
</tr>
</tbody>
</table>

*Note: Avoid propofol and ketamine in children with elevated intracranial pressure. Sedatives and barbiturates can aggravate hypotension.*
Special Airway Situations

Any child with a severe burn to the face and neck should be assumed to have an airway at jeopardy. Heat injury to the upper airway results in edema of the pharynx, larynx, and tongue that can rapidly occlude the airway. As tissues become more distorted, intubation can become more difficult. Furthermore, children injured in a confined space can have a compromised airway, even without obvious face and neck burns. Inhaled toxic fumes and particles can irritate the airway and cause edema. Prophylactic intubation is appropriate whenever heat injury to the upper airway is suspected, or if transportation to another facility is expected. It is much easier to remove a tube that is not needed than to obtain an airway emergently in a swollen burn victim. In addition, carbon monoxide poisoning is difficult to detect, as the pulse oximeter will continue to read high saturation. Tracheal intubation insures efficient delivery of oxygen under these circumstances.

In the child with severe face or neck trauma, alternative maneuvers to endotracheal intubation may be necessary to secure the airway. A child with severe facial trauma that is able to maintain an airway should have a quick primary survey and all immediate life-threatening injuries addressed. The child should then be transported to the operating room where a formal tracheostomy can be performed. If the patient is unable to maintain an airway, a needle cricothyotomy is preferred to a surgical cricothyrotomy, especially if the child is less than 10 years of age. Insertion of a 14-gauge needle or angiocath requires less skill and can provide a temporary airway until the child can have a formal tracheostomy in the operating room. Needle cricothyrotomy provides good oxygenation, although normocarbia can be difficult to maintain and therefore it should be converted to a surgical airway as soon as possible. Other alternatives, including fiber optic-assisted intubation and retrograde intubation or tracheostomies, are institution- and operator-dependent.

Laryngeal trauma is rare in children but may need to be addressed with penetrating trauma or “clothesline” injuries sustained on bicycles and ATVs. Endotracheal intubation can potentially worsen the injury by causing complete separation of the trachea from the larynx and total loss of the airway. Signs and symptoms of laryngeal fracture include stridor, subcutaneous emphysema of the neck, pneumothorax, and hoarseness. If the child is able to maintain an airway, oxygen should be provided until a surgical airway can be obtained in the OR. Cricotracheal separation is an airway emergency that often requires immediate tracheostomy in the emergency department.

BREATHING

Once an airway is secure, attention must next be directed toward injuries that affect ventilation and oxygenation. Most of these injuries comprise the immediate life-threatening injuries of the chest. Although these will be discussed in detail elsewhere in this textbook, they must be mentioned now, as an adequate primary survey can’t be performed without including these injuries in the differential diagnosis. Ventilation and oxygenation must occur in an effective manner, and if they are not, correctable causes should immediately be sought. The intubated child with stable blood pressure and good saturation likely does not have an immediately life-threatening chest injury, but can still have a potentially life-threatening chest injury. The intubated child that decompensates after intubation most likely has a life-threatening
chest injury and must be managed appropriately to preserve a good outcome. The major life-threatening thoracic injuries include tension pneumothorax, open pneumothorax, massive hemothorax, flail chest, and cardiac tamponade. Other potentially life-threatening injuries to consider are simple pneumothorax, hemothorax, pulmonary contusion, tracheobronchial tree injuries, cardiac contusion, traumatic aortic disruption, aerophagia, and traumatic diaphragmatic injury (Table 3).

**Assessment and Monitoring**

Assessing adequacy of ventilation and oxygenation in a busy trauma bay can be problematic. The child’s breathing should be observed, looking for symmetry of excursion or flail chest segments (rare in children). Auscultation can be difficult in a noisy emergency department, but the best point of auscultation to check for equality of breath sounds is in the axilla. Pneumothorax will initially result in loss of expiratory breath sounds, followed by the loss of inspiratory breath sounds. To distinguish the loss of breath sounds associated with a hemothorax versus a pneumothorax, percussion can be attempted; however, dullness and resonance to percussion can be difficult to appreciate in a noisy emergency department. Fortunately, both are initially treated with placement of a chest tube and are easy to distinguish afterwards. If the child is stable, a chest X ray can be obtained prior to initiating therapy. A decompressing child with decreased breath sounds should not wait for an X ray prior to decompression of the hemo/pneumothorax.

Any child that has been intubated will require mechanical ventilation. In infants less than one year of age, pressure regulated ventilation is our preferred mode of ventilation in order to minimize iatrogenic barotrauma. A peak pressure is chosen such that the resulting tidal volume is 7–10 cm$^3$/kg, and a rate of 20 to 40 is chosen and adjusted based on the pCO$_2$ on an arterial blood gas. If the child has a closed head injury, the pCO$_2$ should be maintained at approximately 30–35 mmHg, otherwise a pCO$_2$ of 40 mmHg is acceptable. In children over one year of age, volume control ventilation is our preferred method of ventilation. However, pulmonary compliance should be monitored closely, and if it acutely changes secondary to fluid resuscitation, pulmonary contusion, or other causes, pressure control ventilation must be considered to minimize barotrauma as much as possible. Initial settings in volume control are similar in that a tidal volume of 7–10 cm$^3$/kg is desired, but the older the child, the lower the rate necessary to maintain adequate ventilation.

Most emergency departments are equipped with pulse oximeters, and many have capnometers to monitor end tidal CO$_2$. Arterial blood gases are useful but can be difficult to obtain. If perfusion is adequate, arterial oxygen saturation can

<table>
<thead>
<tr>
<th>Immediate life-threatening injuries</th>
<th>Potential life-threatening injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airway obstruction</td>
<td>Simple pneumothorax</td>
</tr>
<tr>
<td>Tension pneumothorax</td>
<td>Hemothorax</td>
</tr>
<tr>
<td>Open pneumothorax</td>
<td>Pulmonary contusion</td>
</tr>
<tr>
<td>Massive hemothorax</td>
<td>Tracheobronchial injury</td>
</tr>
<tr>
<td>Cardiac tamponade</td>
<td>Cardiac contusion</td>
</tr>
<tr>
<td>Flail chest</td>
<td>Aortic disruption</td>
</tr>
<tr>
<td></td>
<td>Diaphragmatic rupture</td>
</tr>
</tbody>
</table>
be monitored with pulse oximeters. The pulse oximeter is also useful for assessing poor circulation in that if the extremities are cool and the pulse oximeters will not register, hypovolemic shock is undoubtedly present and must be addressed. If the child is intubated, an end tidal CO₂ monitor can be placed on the endotracheal tube. The absolute value on end tidal CO₂ should be correlated to the pCO₂ on blood gas initially, and changes in end tidal CO₂ then are monitored and useful in guiding changes in ventilation. Disposable capnometers are available to confirm position of the endotracheal tube. However, continuous monitoring can be performed, which is especially useful for monitoring ventilation in the child with a closed head injury until an arterial line can be obtained in the intensive care unit.

Tension Pneumothorax

Trauma to the rib cage may result in rib fracture and parenchymal injury. A small parenchymal injury with air leak as well as a major tracheobronchial tear may result in pneumothorax. The child with a pneumothorax may have an asymptomatic simple pneumothorax or have severe respiratory distress secondary to an open or tension pneumothorax. Physical findings of pneumothorax include an absence of breath sounds on one side of the chest, hyperresonance to percussion, subcutaneous emphysema, and tracheal deviation away from the affected side. Physical findings may be very subtle.

A tension pneumothorax occurs with progressive entry of air that is unable to escape from the pleural space. This compresses the ipsilateral lung and results in a shift of the mediastinum to the contralateral side. Since the mediastinum is so compliant, it shifts earlier in the course, resulting in decreased venous return and more rapid cardiovascular collapse in the child. An open pneumothorax allows communication between the environment and pleural space. Equilibration of atmospheric and pleural pressure occurs with collapse of the lung and less shift of the mediastinum. Because of the loss of negative inspiratory pressure, respiratory distress can occur due to decreased ventilation on the ipsilateral side. Massive hemothorax occurs secondary to parenchymal injury with severe vascular injury, or secondary to intercostal bleeding from rib fractures. This condition is more common with penetrating chest trauma than blunt chest trauma.

Treatment of a tension pneumothorax is accomplished by insertion of a chest tube. Temporary relief can often be obtained with needle decompression. Any child that has had needle decompression of the chest needs an appropriate-sized chest tube placed as soon as possible. Children are more susceptible to the associated mediastinal shift than adults. Therefore, any child with acute cardiovascular collapse, especially if it occurs shortly after the initiation of positive pressure ventilation, should have needle decompression or tube thoracostomy performed bilaterally if it is unclear which side is the symptomatic side. If acute cardiovascular collapse occurs, this decompression should be performed prior to obtaining a confirmatory chest radiograph. Needle decompression of the second intercostal space anteriorly may alleviate the condition long enough to allow for completion of the primary survey prior to placing a chest tube. However, if needle decompression fails to reverse the collapse, a chest tube should immediately be placed. Clinically, a hemothorax may be difficult to distinguish from a tension pneumothorax; however, treatment is the same for both conditions and an X ray is not necessary prior to treatment. Massive hemothorax will not usually respond to needle decompression unless there is an associated tension pneumothorax component. A three-sided occlusive dressing that allows air to
exit the pleural space on expiration and prevents its return on inspiration can treat open pneumothorax. With massive open pneumothorax, intubation and positive pressure ventilation may be necessary to overcome the defect.

**Tube Thoracostomy**

Even in emergency situations, chest tube placement should be performed aseptically. The skin should be prepared with an antiseptic and sterile towels draped to expose the appropriate chest. The most important landmark is the nipple, which should be visible after draping. Usually the fifth or sixth interspace is located at the level of the nipple, and a skin incision is made one or two fingerbreadths below the nipple in the anterior axillary line after anesthetizing with 1% lidocaine. A hemostat is then used to tunnel the chest tube for 1–2 cm in the subcutaneous space. The hemostat is then inserted on top of the rib and pushed firmly until the pleural space is entered. If tension is present, this maneuver alone will alleviate the tension and restore hemodynamic stability. An appropriate-size chest tube is then inserted into the pleural space (Table 4). Many pediatric chest tubes come with a sharp trochar, which should never be used to blindly place the chest tube. The trochar can be safely used as a stylet to help guide the tube into the previous dissected tunnel and entrance into the pleural space. It should always be pulled back 1–2 cm from the end of the chest tube, but can then help stiffen the tube for easier placement. The other method of inserting the tube would be to remove the trochar completely, grasp the tube in the end of a hemostat, and direct it through the tract and into the pleural space. The tube should be gently inserted until it is felt contacting the apex, then withdrawn 2 cm and secured with a suture. Fogging of the tube should be noted on insertion, and tidal movement of the water seal chamber should be noted with ventilation. A chest X ray is always obtained to check tube position.

**Other Chest Injuries**

One must keep in mind that pneumothorax may be associated with more severe injuries of the tracheobronchial tree. A large continuous air leak after chest tube placement or continued respiratory distress may signal a larger tracheobronchial injury. Bronchoscopy in the operating room should be performed soon after the primary survey to diagnose the injury in those who fail to resolve their air leak, or who remain difficult to ventilate and oxygenate. If the air leak is on the left side, passing the endotracheal tube into the right main stem may temporarily allow adequate ventilation and oxygenation until it can be addressed operatively. Tidal volumes must be decreased and rate increased to avoid a pneumothorax on the right side as well. Blood loss from a massive hemothorax should continuously be

<table>
<thead>
<tr>
<th>Size of patient (kg)</th>
<th>Pneumothorax</th>
<th>Hemothorax</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3</td>
<td>8–10</td>
<td>10–12</td>
</tr>
<tr>
<td>3–8</td>
<td>10–12</td>
<td>12–16</td>
</tr>
<tr>
<td>8–15</td>
<td>12–16</td>
<td>16–20</td>
</tr>
<tr>
<td>16–40</td>
<td>16–20</td>
<td>20–28</td>
</tr>
<tr>
<td>&gt;40</td>
<td>20–24</td>
<td>28–36</td>
</tr>
</tbody>
</table>
monitored to avoid hypotension and determine the need for thoracotomy. In general, loss of more than 207 mL/kg of blood from the chest with continued bleeding should be addressed surgically.

Although a true flail chest is rare in children, the compliance of the chest wall frequently allows impact to cause an occult pulmonary contusion without obvious rib fracture. This underlying pulmonary contusion and/or injury to the lung parenchyma can result in respiratory distress. A large pulmonary contusion can result in hypoxia from severe ventilation-perfusion mismatch. Management of severe pulmonary contusion should aim to maintain the child in a state of euvoeemia (9). Attempts to avoid pulmonary edema by keeping the child hypovolemic are likely to result in hemodynamic instability and worsen the ventilation-perfusion mismatch. If the child is able to maintain saturation with spontaneous ventilation and supplemental oxygen, the contusion is best treated with aggressive pain management, including epidural catheter or rib blocks to provide adequate pain control for aggressive chest physiotherapy. If paradoxical motion is severe and the child is hypercarbic or hypoxic, a contusion or flail segment is best managed with intubation and positive pressure ventilation. Aggressive pulmonary toilet while intubated, sufficient tidal volume to prevent atelectasis, and maintaining a normovolemic state are ideal management. Positive end expiratory pressure is beneficial, and positive pressure ventilation is often needed for two to three days before the patient’s chest wall is stable enough to allow for spontaneous ventilation.

Potential life-threatening injuries, which usually do not manifest symptoms early in evaluation, include traumatic aortic rupture and diaphragmatic rupture. The mobile mediastinum that makes the child more susceptible to tracheobronchial injuries makes them less likely than the adult to sustain a torn aorta (10). Although rare, an aortic injury should be suspected especially in chest trauma with a significant deceleration mechanism. Signs suggesting a torn aorta include the chest X ray findings of a widened mediastinum, apical cap, left hemothorax, deviated left main stem bronchus, deviated nasogastric (NG) tube, or first and second rib fractures. In a severely injured patient with multiple potential sources of hypotension, the presence of a widened mediastinum should not interfere with completion of the primary survey. There is the temptation to rush into repair of the aorta, due to its devastating consequences should it rupture. However, the unstable pelvis, bleeding liver and spleen, or open femur fracture must be addressed prior to placing the patient in a thoracotomy position for repair of the torn aorta (11). Hypotension induced by a torn aorta is acute in onset, extremely short in duration, and the patient expires rapidly.

Diaphragmatic rupture can result from a fall from excessive height or crush injury to the chest and abdomen. Loss of diaphragmatic function as well as herniation of abdominal contents into the thorax can result in respiratory distress. It can present subtly on chest X ray with loss of left diaphragm border, or obvious loops of bowel can be seen in the chest. Axial cuts on CT scan can miss a small defect as well. A plain film with NG tube in stomach noted above the diaphragm and/or UGI with bowel in the chest is diagnostic. Initial treatment in the primary survey should be placement of an NG tube to decompress the abdominal contents in the chest. The diaphragmatic defect is most often repaired from an abdominal approach.

A non-life-threatening condition common in pediatric trauma victims that can cause significant respiratory distress is massive aerophagia. Small children that present to the emergency department crying and screaming can swallow a significant quantity of air and induce massive gastric distension. This aerophagia can result in
increased girth, respiratory compromise, and emesis with potential for aspiration. This can be rapidly cured by early insertion of an NG tube.

Cardiac Injury/ER Thoracotomy

Blunt injury to the heart is rare in the child; however, it must be assumed with any penetrating trauma to the chest, especially if the wound is potentially transmediastinal. If a child’s cardiopulmonary status acutely deteriorates, bilateral chest tubes should be placed for the likely tension pneumothorax; if these fail to alleviate the condition, a pericardiocentesis should be performed. A positive pericardiocentesis for blood is an indication for urgent thoracotomy or sternotomy to identify and repair a cardiac injury. Myocardial contusion is rare in children, but can occur in adolescent drivers who may sustain a significant chest impact from the steering wheel. Rarely is contusion severe enough that acute decompensation occurs.

Emergency room thoracotomy is a topic of debate in the literature and in many trauma centers. Even though children have much greater physiologic reserve than adults, loss of vital signs that do not return with adequate Cardio Pulmonary Resuscitation prior to arrival in the emergency department (ED) is almost universally fatal. This is especially true when the injury is secondary to blunt trauma and does not warrant an emergency room (ER) thoracotomy. Over the years, a number of institutions have reviewed their success rate with ER thoracotomy in blunt trauma, and few if any survivors have been noted (12,13). Even those children whose vital signs return with CPR prior to arrival in the ED have a 25% survival rate, at best, and two-thirds of those that did survive had a significant impairment in one or more activities of daily living (14). In contrast, an ER thoracotomy can be life saving with penetrating chest trauma when vital signs are not lost until the child arrives in the ED.

CIRCULATION

After a patent airway is established and adequate ventilation has been insured, the diagnosis and management of shock takes precedence. Evaluation of circulation is a process that must be performed simultaneously with the assessment of the airway and breathing. Successful treatment of shock requires rapid recognition that the child is in shock and simultaneous treatment maneuvers. Direct pressure may be required to control external bleeding, especially from scalp, neck, and groin wounds. Long bone and pelvic fractures should be stabilized with traction and splinting.

Pediatric Physiology

In general, the physiologic concepts of hemorrhagic shock apply to both children and adults. However, children are unique in several aspects of anatomy and physiology that make recognition of shock more difficult, but at the same time provide them tremendous reserve to survive many injuries that adults would be unable to. Most notably, the variability in size and weight that one encounters in dealing with pediatric trauma poses a problem in insuring that appropriate equipment and medications will be available for the resuscitation of the child.

Normal circulating blood volume in a child is 7% to 8% of total body weight, 70–80 mL/kg. Although in relative terms the circulating volume is 20% greater than in adults, what may appear to be a small amount of blood loss can be very significant
in a young child. A 200-mL estimated blood loss in a 10-kg child is equal to 25% of their blood volume. Children also have a higher body-surface-area-to-mass ratio. This leads to an increase in insensible water loss that makes them susceptible to hypovolemia and increased heat loss, which can lead to hypothermia. In extremely young children, hypothermia is a major problem associated with trauma resuscitation. Hypothermia aggravates pulmonary hypertension, hypoxia, and acidosis and results in a significant increase in oxygen consumption. The extremely compliant mediastinum makes infants and children more susceptible to wide swings induced by tension pneumothorax or hemothorax. Shifting of the mediastinum not only decreases venous return and cardiac output, but can also interfere with ventilatory capacity of the contralateral lung.

The clinician evaluating pediatric trauma must be familiar with the wide variability in normal vital signs based on age. A pulse rate and blood pressure that are acceptable in an infant may indicate significant hypovolemia in an adolescent (Table 5). The goal of management is to recognize that shock exists before the vital signs change. The signs of late hypovolemic shock are easy to recognize, but the clinical presentation of early shock requires a high index of suspicion. The clinician must rely on subtle findings during the physical examination as well as the vital signs (Table 6).

<table>
<thead>
<tr>
<th>Age</th>
<th>Weight (kg)</th>
<th>Heart rate (beats/min)</th>
<th>Pressurea (mmHg)</th>
<th>Respiration (breaths/min)</th>
<th>Urine output (mL/kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–6 months</td>
<td>3–6</td>
<td>160–180</td>
<td>60–80</td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td>Infant</td>
<td>12</td>
<td>160</td>
<td>80</td>
<td>40</td>
<td>1.5</td>
</tr>
<tr>
<td>Preschool</td>
<td>16</td>
<td>120</td>
<td>90</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Adolescent</td>
<td>35</td>
<td>100</td>
<td>100</td>
<td>20</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*Systolic blood pressure should be 80 + 2 age (yrs).

Source: Taken from Advanced Trauma Life Support for Doctors Instructor Manual.

### Table 6 Systemic Response to Blood Loss in Pediatric Trauma Patients

<table>
<thead>
<tr>
<th>System</th>
<th>&lt;25% blood loss</th>
<th>25–45% blood loss</th>
<th>&gt;45% blood loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac</td>
<td>Tachycardia</td>
<td>Weak, thready pulse and tachycardia</td>
<td>Hypotension, tachycardia to bradycardia</td>
</tr>
<tr>
<td>CNS</td>
<td>Lethargic, irritable, and confused</td>
<td>Changing level of consciousness and dulled response to pain</td>
<td>Comatose</td>
</tr>
<tr>
<td>Skin</td>
<td>Cool and clammy</td>
<td>Cyanotic, decreased capillary refill, and cold extremities</td>
<td>Pale and cold</td>
</tr>
<tr>
<td>Renal</td>
<td>No decrease in output and increased specific gravity</td>
<td>Decreased urine output</td>
<td>No urine output</td>
</tr>
</tbody>
</table>

*Source: From Chapter 10: Pediatric Trauma in Advanced Trauma Life Support for Doctors, Instructor Course Manual, American College of Surgeons Committee on Trauma, 6th Edition, Chicago, IL, 1997.*
Assessment

Shock is a state in which there is inadequate delivery of oxygen to meet the demands of the child. Absolute values of blood pressure have little to do with defining the shock state. A child with normal blood pressure can be in shock, just as a child with low blood pressure can be well perfused and not in shock. The earliest warning signs that a child is in shock include signs of decreased skin perfusion (capillary refill, temperature, and color), central nervous system perfusion (lethargy, inappropriate response to painful procedures, and lack of recognition of parents), pulses (tachycardia and presence or absence of pulses), and falling blood pressure. With a quick physical exam, the physician should be able to readily estimate the degree of shock and estimate blood loss (Table 6). After the airway and breathing are secured, most astute trauma physicians palpate the child’s feet or hands. A child that has warm feet with bounding pedal pulses is not in acute shock. A child with cool feet, weak and thready pedal pulses, depressed capillary refill, and mottled cool extremities is already in significant shock. The child with hypotension and a markedly depressed mental status is in late shock with blood loss up to 40% of blood volume. Waiting until hypotension is present to begin treating shock is too late.

There are no laboratory tests or X rays that can rapidly estimate the degree of blood loss and shock. In acute hemorrhage, the hemoglobin level does not change immediately, only after compensatory fluid shifts have occurred and resuscitation has begun. The best laboratory predictor of shock and volume loss is the arterial base deficit. Adult trauma surgeons have identified base deficit as a predictor of survival, and recently this test has been demonstrated to be predictive of morbidity and mortality in pediatric trauma victims (15–17). As anaerobic metabolism is increased in response to inadequate tissue perfusion, lactic acid is produced. Most anxious children hyperventilate, which helps compensate for the developing metabolic acidosis. If shock persists, the metabolic acidosis worsens. Sodium bicarbonate can improve the laboratory values obtained, but until the cause of shock is addressed and resuscitation is initiated, the overall clinical picture will not improve. Sodium bicarbonate has not been shown to improve survival and may aggravate any existing respiratory acidosis with increased CO₂ production (18,19).

Intravenous Access

In order to resuscitate the child from shock, intravenous access is a must. In the very young, this can pose more of a problem than obtaining the airway. At the same time that access is being established, blood should be drawn for a standard trauma laboratory panel. A specimen for typed and crossed blood must be sent early in the resuscitation. Establishing two large-bore peripheral intravenous catheters is clearly the first choice for resuscitation (1). A short catheter should be chosen to minimize resistance to flow. This can be a daunting task in a small, hypovolemic child. Preferably, lines should be placed above and below the diaphragm. The most desirable sites for peripheral IV access include percutaneous IVs in the antecubital fossa, distal saphenous vein, or other peripheral vein. The veins are usually more superficial than initially anticipated. Another tip is to rotate the needle and angiocath 180° so that the bevel hooks under the venotomy and insures that the angiocath will thread into the vein. The most common cause of failure is not getting a flash of blood in the angiocath, but successfully threading it into the vein.
Most authors and texts recommend a distal saphenous vein cutdown in the event that peripheral lines cannot be obtained. In the child less than one year of age, performance of a cutdown quickly may be a difficult task to those unaccustomed to doing this. When attempting a cutdown, a transverse incision is made over the vessel with a scalpel just anterior to the medial malleolus. The remainder of the dissection should be done bluntly with a small hemostat. The vessel is isolated with a suture, and often an angiocath can be inserted under direct vision using the stylet without making a venotomy. If the angiocath can be placed through the skin just below the incision and then directed into the vessel, it can be maintained more easily.

Other options include a percutaneously placed central venous catheter. In elective circumstances, the jugular or subclavian approach would be preferred. However, in the emergency department environment, and with the possibility of cervical spine trauma, the risk of pneumothorax or spine injury may be prohibitory. Temporary cannulation of the femoral vein with a large-bore IV catheter or venous introducer can provide access as quickly as a cutdown in many instances. These catheters should be removed as soon as possible as long-term use of femoral catheters may be associated with an increased risk of venous thrombosis (20). The line must be placed as aseptically as possible, and many trauma surgeons demand that all lines placed in the field or emergency department be removed once they are stable in the hospital. The groin is steriley prepped and draped and the femoral pulse is palpated. With a finger over the palpable arterial pulse, the femoral vein is aspirated with a needle and syringe just medial to the palpable pulse. A wire is threaded by the Seldinger technique, and the line placed over the wire. Long multiple lumen catheters should be avoided due to the resistance to flow. A single lumen six French catheter introducer, if available, or even a large-bore angiocath should be sufficient for large volume resuscitation.

In children less than six years old, intraosseous infusion provides a rapid and safe route of success. Blood products, fluids, and medications can be given through this type of catheter (21,22). Although not a good long-term route of IV access, it allows the initiation of fluid resuscitation, and with improved circulatory status, a peripheral route of venous access may become feasible. Complications with intraosseous needles are rare if placed appropriately. A 16- or 18-gauge bone marrow aspiration needle is placed in the tibia, 2–3 cm below the tibial tuberosity, angled slightly away from the growth plate. If the tibia is fractured, it can be placed in the femur 3 cm above the femoral condyle.

In all pediatric trauma victims, percutaneous peripheral intravenous access should be attempted first. If this fails in a child less than one, if a pediatric surgeon or intensivist is not available, an intraosseous line should be obtained and the child transferred as soon as possible. In the child one to six years of age, a percutaneous femoral line and/or saphenous vein cutdown may be feasible prior to resorting to an intraosseous line. Most children over six years of age have veins of sufficient size for percutaneous peripheral placement. If in extremis and access is difficult, a femoral central line or saphenous vein cutdown would be the best choices for access.

Resuscitation

Once shock has been identified and intravenous access has been obtained, resuscitation should be initiated. Many algorithms for resuscitation exist, and most are based on
ATLS® recommendations (Fig. 1). Any injured child that shows clinical signs of hypovolemic shock should have prompt surgical consultation. A 20-mL/kg bolus of lactated ringers or normal saline is given as soon as shock is suspected. Response to this bolus is monitored. It may be repeated once or twice if perfusion is not improved. If after a second bolus of crystalloid the child is still clinically in shock, a 10-cm³/kg bolus of crossmatched packed red blood cells (or type specific or O-negative cells) should be given. At this point in the resuscitation, if the child is not in an institution capable of handling a hemodynamically unstable child, preparation for transfer should be initiated. Furthermore, if the surgeon responsible for the child’s care has not been notified yet, surgical consultation is needed immediately.

Children with stable spleen and liver lacerations, as well as stable fractures, will usually stabilize after a 10-cm³/kg bolus of packed cells. Those that do not and continue to exhibit signs of hypovolemic shock are likely to need their primary survey completed in the operating room. The primary survey is not complete until the child is hemodynamically stable and does not have an ongoing fluid requirement. Until that time, if an adequate airway and ventilation are confirmed, hypovolemic shock must be assumed and a source sought and treated.

CONCLUSION

Initial management of the pediatric trauma victim is similar to that of the adult trauma victim. However, it requires sufficient knowledge of the physiologic and anatomic differences between children and adults. Successful management requires adequate assessment and control of the airway, breathing, and circulation. Evaluation of the ABCs is a dynamic process that requires simultaneous assessment and resuscitation, as well as persistent reassessment until the child is hemodynamically stable.

Figure 1 Resuscitation flow diagram for the pediatric trauma patient. Source: From Advanced Trauma Life Support® for Doctors Instructor Manual. Source: From Chapter 10: Pediatric Trauma in Advanced Trauma Life Support for Doctors, Instructor Course Manual, American College of Surgeons Committee on Trauma, 6th Edition, Chicago, IL, 1997.
stable. Although class-I and -II data are rare in the current literature, guidelines such as those developed through the ATLS® program can be used to successfully manage most pediatric trauma victims.

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Clearance of the Cervical Spine in Children

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Immobilization of the cervical spine at the scene of the injury is an important part of the early care of pediatric trauma patients. Exclusion of injury and discontinuation of immobilization (cervical spine clearance), while relatively routine in the awake, asymptomatic patient, can be very challenging in small children or in patients with a decreased level of consciousness. Expeditious clearance of the cervical spine is important to avoid the possible complications of spinal immobilization, including decubiti and aspiration. While a pediatric neurosurgeon or orthopedist is involved early for a patient with closed head injury or obvious neurological deficit, a pediatric surgeon, general trauma surgeon, or emergency room physician performs the majority of cervical spine assessments on trauma patients. Clinical assessment is the most important aspect of cervical spine evaluation, but a variety of imaging modalities, including plain radiography, computed tomography (CT), and magnetic resonance imaging (MRI) can assist the clinician with decisions about discontinuation of immobilization. The judicious use of these modalities attempts to discover all injuries while avoiding the overuse of radiologic procedures and prolonged immobilization.

Spinal cord injury should be considered in any victim of major blunt trauma, especially with a history of head and neck trauma or significant flexion or extension injury of the neck. The incidence of cervical spine injuries among trauma victims is relatively low (1.6–2.2%) with a mean age around 10 years. Motor vehicle crashes are the leading cause of cervical spinal injury (52%) followed by sports (27%) and falls (15%) (1). Nearly 70% of pediatric injuries involve the upper cervical spine (C1–C4); approximately one-half are fractures and one-quarter are dislocations (2).

Compared to adults, pediatric trauma victims have fewer cervical spine fractures but a higher proportion of spinal cord injury without radiographic abnormality (SCIWORA). The greater elasticity and ligamentous laxity of the pediatric cervical spine provide some protection against bony injury, but may increase the risk of SCIWORA. The incidence of SCIWORA in children ranges from 19% to 38% with the highest incidence in younger children (1,2).

Protection of the cervical spine should be part of the initial evaluation of patients with significant trauma. Early cervical spine immobilization allows for attention to resuscitation (airway, breathing, and circulation). Soft collars do not provide immobilization and should not be used after acute injuries. A variety of hard
collars are in use, but those most commonly used are the Philadelphia collar and the Miami Junior. No direct comparative study of the differences between hard collar manufacturers is available.

A detailed physical examination is conducted during the secondary survey to look for superficial injury over the spine, hematoma, malalignment, tenderness, and sensory or motor deficit (3). Most alert children with spinal cord injury complain of neck pain or have tenderness along the bony cervical spine, while numbness, paresthesias, or evidence of a peripheral neurological deficit are rare (4). Neurologic deficits can manifest as paraplegia (lower extremity paralysis) or quadriplegia (paralysis of all four extremities) along with corresponding sensory deficit. Rarely, patients may present with central cord syndrome in which upper extremity symptoms are evident with normal neurologic function of lower extremities. High spinal cord injury may lead to diaphragmatic paralysis, shock, or cardiopulmonary arrest (5). After stabilization and clinical evaluation, the physician must decide if radiological studies are needed.

Several professional groups, including the Eastern Association for the Surgery of Trauma (EAST) and the American College of Radiology, have promulgated guidelines for the evaluation of the cervical spine in trauma patients (6,7). The guidelines are perhaps best documented by EAST, which performed a computerized search of the National Library of Medicine’s Medline database, looking at 20 years of citations with “cervical spine” in the title and subject words “radiography,” “cervical vertebra,” and/or “trauma.” The articles were classified according to study design. No randomized controlled trials (class I) and few prospective, nonrandomized (class II) studies were found. Recommendations were mainly based on retrospective studies (class III) that can be weakened by bias in patient selection, symptom detection, choice of diagnostic studies, or options for treatment. In addition, retrospective studies may be hampered by lack of complete patient follow-up.

The published guidelines do not specifically discuss pediatric trauma patients. Therefore, for this review, the Medline search was repeated using the same parameters with restriction to children (aged 1–18 years) and articles published since 1990. Recommendations concerning the evaluation of the cervical spine in children are based on the EAST guidelines as well as the more recent references with findings related to children.

The published guidelines are consistent with respect to patients who are completely asymptomatic with no physical findings, normal mentation, and no distracting injuries, proposing that these patients do not require radiological evaluation. Recent studies support the conclusion that asymptomatic patients do not need screening radiography (8–10), but include few pediatric patients. One study of pediatric patients supported the view that fractures will usually manifest symptoms but the study included only eight injured patients and was restricted to falls of less than five feet (11). All of these studies were retrospective, making comparison of clinical and radiologic findings subject to significant bias.

For a valid comparison of clinical and radiologic evaluation, clinical findings must be recorded prospectively, prior to radiographs. One such study was recently done primarily in adult patients (aged 14–93 years) (12). Consecutive blunt trauma patients who were alert on admission (GCS 14 or 15) were evaluated for cervical spine injury. Symptoms and physical findings were documented on study forms that were then placed in sealed envelopes prior to radiographic studies. Of the 2176 patients, 33 (1.6%) were found to have cervical spine injuries. Three missed injuries were seen in 1768 asymptomatic patients with normal clinical examination (sensitiv-
ity > 99%). In one of these, the fracture was also missed on screening lateral C-spine radiography, but was found with further radiography due to the onset of pain one day after admission. The sensitivity of radiography when blinded to clinical data was 61% as 13 of 33 injuries were missed. Radiography is clearly deficient without clinical examination, but even when used together they are not perfect in immediately finding all injuries.

A recent multicenter study prospectively tested cervical spine evaluation guidelines in a population of 34,069 adults and children who underwent radiography of the cervical spine after blunt trauma (13). The five criteria in the decision rule that defined a low probability of injury (screening X rays unnecessary) were: no midline cervical tenderness, no focal neurological deficits, normal alertness, no intoxication, and no painful distracting injuries. The study identified 12% of patients who could have avoided radiographic evaluation according to the decision rule. The screening tool was predictive in 810 of 818 patients who had radiographically documented cervical spine injury. Of the eight patients identified as low probability of injury who had a radiographically documented cervical injury, only two were felt to have a clinically significant injury, according to predefined criteria in the study. Unfortunately, the study did not extensively evaluate pediatric patients: only 2.5% of patients were eight years old or younger, and 1.3% of patients with cervical spine injuries were eight years old or younger.

Patients who are asymptomatic with respect to the cervical spine (no cervical pain or tenderness; no neurologic deficit), but have injuries that may distract their attention, should have cervical spine films to screen for injury. One recent retrospective study questioned these recommendations, but the study population was small and did not include children (9).

Most pediatric trauma patients do not meet all of the criteria for a low probability of injury and, therefore, should undergo screening radiological examination. Plain radiography may show bony deformity/fracture, malalignment (especially of the posterior aspect of vertebral bodies), asymmetry of distance between spinous processes, vertebral canal narrowing, or increased prevertebral soft tissue. A lateral C-spine radiograph is the minimal study for screening and must include the base of the occiput down to the upper portion of the first thoracic vertebra (Fig. 1). The addition of odontoid and anterior/posterior views does increase sensitivity and specificity (14). Some have questioned the value of the anterior/posterior view when odontoid and lateral views are normal (15). Some authors would also include oblique views for screening. Many trauma patients (10–15%) require more than the initial screening radiography to completely visualize the cervical spine (16,17). Supplemental swimmer’s views are sometimes required to visualize the lower cervical spine and its junction with thoracic vertebra.

Axial CT scans with sagittal reconstruction can help to evaluate the extremes of the upper or lower cervical spine when they are difficult to see on plain films or to elucidate abnormalities seen on plain radiography (Figs. 2–4). CT can also help with spurious abnormalities that are often seen in pediatric patients, including pseudosubluxation of C3 on C4 or skeletal growth centers (apical odontoid epiphyses and basilar odontoid synchondrosis) (18).

Patients with symptoms of pain or tenderness whose initial screening radiographs are normal often undergo flexion and extension films in the erect position to evaluate for ligamentous injuries. EAST recommends these films be obtained with the patient actively positioning the neck in extreme flexion and extension (6). The value of these additional films has been questioned in children (19). A careful
retrospective comparison of static cervical films followed by flexion/extension films concluded that the additional films were not helpful when plain films were normal (no acute abnormality and no loss of normal lordosis) (20). Other authors recommend MRI because of excellent detail of soft tissue injuries, including vessel injuries, ligament disruption, disc herniation, and spinal cord injury or hematoma (Fig. 5) (21,22). Fractures are not always seen on MRI, thus plain radiographs should precede MRI studies. No consensus exists for symptomatic patients in whom all studies are negative. Some authors recommend, in addition to neurosurgical consult, the use of a stiff collar for two weeks, followed by repeat clinical exam and plain radiography (16).

Patients with neurological deficits but no obvious abnormalities on plain X ray (SCIWORA) should undergo MRI of the cervical spine. In the evaluation of soft tissue or spinal cord injury, magnetic resonance is superior to plain radiography or CT scan (21,23). Early neurosurgical evaluation is needed for consideration of therapies that may improve outcome, such as systemic steroids or surgical decompression.

Patients with closed head injury or obtundation are a special challenge for evaluation. Most of these patients undergo three-view screening X rays, but the

Figure 1  Compression fracture, anterior, superior portion of C7 sustained by a 15-year-old who fell 8 feet from a swing.
The adequacy and quality of these films is frequently compromised by lack of cooperation. Blacksin and Lee suggest that inclusion of the upper cervical spine during cranial CT scan for the head injury (thin cut axial CT images through C1 and C2) can simplify this problem (24). Because not all patients had complete plain radiography, no direct comparison was made between the sensitivity of plain radiography versus CT. When C-spine abnormalities are seen on a limited upper cervical CT scan, the remainder of the C-spine must be evaluated to look for other injuries, either with plain C-spine films or with CT scanning. Some have advocated routine complete cervical CT scanning in closed head injured or obtunded patients rather than or in addition to the lateral C-spine radiograph (25,26). In a prospective, blinded study of adult patients (≥17 years) who had both plain radiography and CT of the cervical spine, specificity was 100% for both studies, but sensitivity for CT was 90% versus only 60% for plain radiography (25). Of two injuries seen by plain radiography but not CT, both were considered stable. The fact that all of the injuries were seen by CT or plain radiography and that no patient suffered a delayed diagnosis suggests
Figure 3  (A) Motor vehicle injury in a 17-year-old patient resulting in fractures through the posterior neural arch of C1 and pedicles of C2 with anterior displacement. (B) Further definition of fractures was aided by computed tomography.
inadequate description of patient follow-up or retrospective inclusion of suspicious results as positive when later confirmed by other studies. Despite these limitations, CT is probably the most sensitive study for bony cervical injury in obtunded patients.

Even after normal C-spine evaluation with plain radiographs or CT scan, physicians are reluctant to discontinue immobilization in patients who do not allow reliable clinical examination. Patients can be immobilized for 24 to 48 hours to allow time for improved wakefulness and repeat assessment. For patients who remain unreliable, one study suggests cervical flexion and extension under fluoroscopy with concomitant monitoring of somatosensory evoked potentials (SSEP): patients with normal studies were cleared; malalignment leads to a neurosurgical consultation; and abnormal SSEP leads to an MRI (27). Normal MRI allowed for clearance of the C-spine. The algorithm was complicated and included too few patients, but further studies are ongoing.

The published guidelines promote thorough evaluations but also attempt to diminish the number of unnecessary radiographic examinations. Emergency centers vary greatly in the use of radiography to evaluate trauma patients. A recent survey showed a low of 15.6% of trauma patients evaluated with radiography at one center to a high of 91.5% (28). Differences in missed injuries were not observed but the study follow-up was poor.

The validity of guidelines depends on the ability of clinicians to understand and properly apply criteria. In trying to implement clinical guidelines, the reliability of individual criteria was evaluated in a prospective study (29). Physicians showed substantial inter-rater reliability (high $\kappa$ scores) for evaluation of altered neurologic
function (83.6%, $\kappa_s = 0.58$), intoxication (96.7%, $\kappa_s = 0.86$), posterior midline tenderness (89.3%, $\kappa_s = 0.77$), distracting injury (91.8%, $\kappa_s = 0.77$), and all criteria combined (87.7%, $\kappa_s = 0.73$). In another prospective study, emergency medical technicians (EMTs) were not able to reliably eliminate the possibility of spinal cord injury by use of a similar decision rule. Over half of patients who were cleared clinically by EMTs were immobilized by physicians and required radiography on arrival to the hospital. Low $\kappa$ scores between emergency physicians and EMTs were noted for several of the clinical criteria on which the decision rule was based, including: mechanism consistent with injury, reliable mental status, presence of distracting injury, neck pain or tenderness, neurologic deficit, and neck pain with motion (30). The $\kappa$ scores were < 0.5 for all criteria except reliable mental status. Considered together these studies suggest that the implementation of guidelines for cervical spine evaluation requires clinical examination and sophisticated judgment by experienced physicians.

Figure 5  A 12-year-old with a trampoline injury and neck pain. (A) Computed tomography showed fracture of superior aspect of odontoid. (B) The 1-cm fragment was displaced anterior and inferior. (C) Magnetic resonance imaging revealed severe central canal stenosis at the cervical-medullary junction and edema within the cervical cord at the C2 and C3 levels. In addition, distension of the cerebrospinal fluid spaces within the posterior fossa was evident, likely due to the degree of stenosis.
Many different algorithms for clearance of the cervical spine have been published (16,27,30). The algorithms differ in a variety of ways: presenting symptoms, physical findings, complexity of radiologic assessment, and final disposition of patients. Considering the current interpretation of the published studies, an algorithm was developed that attempts to triage patients into separate categories to provide efficient care (Fig. 6). Expert interpretation is required at each decision point.

The physician caring for trauma victims has many choices to aid in the evaluation of the cervical spine. Proper understanding of the epidemiology of the cervical spine injury, careful attention to the history of the traumatic incident, elucidation of current symptoms, a careful neurological examination, and judicious radiographic

**Figure 6** Algorithm for clearance of the cervical spine in children.
testing should allow appropriate care of these patients. The evaluation must be
carried out in the context of a cervical spine that is immobilized to avoid the
possibility of secondary injury.

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Trauma from Child Abuse

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INTRODUCTION

Caffey and Kempe first focused the medical community’s attention on the problem of child abuse by identifying an association between long bone fractures and subdural hematomas in children. Further work led to Kempe’s symposium and article “The Battered Child Syndrome” (1–3). As awareness increased, it became clear that a constellation of injuries is associated with child abuse and that these injuries occur in patterns. Because the history is often unreliable or deliberately deceptive, the recognition of known patterns of injury and the judicious use of diagnostic imaging are important in the evaluation of these patients. Unfortunately, prospective, randomized, controlled trial data on child abuse are unavailable. Since the treatment of most of the injuries associated with child abuse is well described elsewhere in this and other texts, this chapter will not review the treatment of specific injuries. Instead, it will attempt to assist the practitioner in deciding whether identified injuries could be caused by the reported mechanism and in recognizing the unique associations that have been previously identified.

LITERATURE-BASED GUIDELINES

The author examined the literature obtained from MEDLINE from 1990 to 2000 and classic articles from earlier time periods. There were no class-I papers. Thus, standards of care cannot be developed according to the definitions of evidence-based medicine. A few papers fit into class II (prospectively collected data submitted to retrospective analysis). Most were class III. There is a vast amount of empirically derived information that is supported by class-III data.

EPIDEMIOLOGY

Child abuse accounts for 3% to 4% of all traumatic injuries evaluated in pediatric trauma centers. However, abuse and assault result in the highest injury severity
and mortality of all mechanisms of injury (National Pediatric Trauma Registry, 1998). Estimates of fatal child abuse and neglect have been tabulated using death certificate data and statistical modeling. Serious abuse occurs most often in children under five years of age (Table 1) (4). The National Incidence Study of Child Abuse and Neglect studied the relative impact of demographic characteristics of the child, family structure, and economic variables on types of child abuse and neglect (5). Physically abused children were more likely to live in poverty with mothers who were unemployed. Race had little influence on the likelihood of neglect or abuse.

### INITIAL EVALUATION AND TREATMENT

#### History

The history of the presenting illness or injury is a critical component of the initial evaluation of inflicted injury in children. The typical finding is a discrepant history that is modified over time as the caretaker adapts the history to developing medical information. Therefore, documentation of each interaction is important to catalog the evolution of the history during the hospitalization. Because the history is often unreliable, most injuries are discovered by physical exam and imaging studies.

#### Clinical Presentation

**Unexplained Loss of Consciousness or Shock**

Seriously abused children are often evaluated for an unexplained loss of consciousness or shock. As with any life-threatening injury or clinical situation with hemodynamic instability, standard resuscitative interventions are employed. When the history is not consistent with the clinical scenario, or there are external signs of abuse, the evaluation should focus on imaging studies to define the injury. Typically, computed tomography (CT) scanning of the head and of the abdomen and pelvis during the same radiographic session are useful for demonstrating intra- and extra-cranial pathology as well as visceral injury. The imaging studies help classify the mechanism and timing of injury. The evaluation of these children also includes retinal examination using indirect ophthalmoscopy by an ophthalmologist, soft tissue examination to evaluate for patterned bruising or burns, as well as careful palpation for point tenderness suggesting acute fractures. Children less than five years old should also undergo a skeletal survey to evaluate for occult bony injuries.

**External and Soft Tissue Trauma**

Injuries to the skin and soft tissue include burns (contact and immersion), bruises, and patterned marks and scars. Patterns and locations of burns and bruises are often

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### Table 1  Deaths Due to Child Abuse or Neglect

<table>
<thead>
<tr>
<th>Age</th>
<th>Percent of all deaths</th>
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<tr>
<td>&lt; 1</td>
<td>41%</td>
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<tr>
<td>1–4</td>
<td>49%</td>
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<tr>
<td>5–9</td>
<td>4%</td>
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<td>10–14</td>
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self-explanatory, e.g., clothing iron imprint directly on the back or thigh, or hand-shaped bruise on the cheek. All of these physical findings can be correlated with the history. Pathologic bruising can be a source of confusion. This can usually be eliminated by routine coagulation studies. Bruises of the buttocks, perineum, or abdomen, or multiple bruises of varying ages, are suspicious for inflicted injury. Inflicted burns are usually either immersion or pattern-type injuries due to a hot object. Immersion burns often occur in a stocking/glove distribution or on the buttocks and posterior surfaces of the thighs, legs, and feet. Pattern burns such as those caused by an iron are rarely unintentional.

Fractures
Fractures are brought to the attention of the physician in three ways: (1) acute evaluation for fracture-related signs and symptoms, (2) incidental discovery of old fractures on another radiographic study, and (3) by skeletal survey. The most critical step in determining the etiology of the fracture is the correlation of the injury with the age and development of the child. Fracture patterns and their associations with intentional injury are discussed below.

Imaging Studies
Skeletal Survey
All infants and children under five years of age with suspected abuse should undergo a skeletal survey. Postmortem skeletal surveys should be performed on all children who die when abuse is suspected. High-detail systems with specific images should be performed, avoiding the ‘‘baby-gram’’ technique. Repeat imaging in one to two weeks may show injuries not readily apparent on the initial survey due to the development of fracture calluses.

Nuclear Medicine
Bone scintigraphy has been suggested as an alternative or complementary imaging method to plain radiographs for occult fractures associated with child abuse (6–8). There have been no definitive studies demonstrating the superiority of one over the other. The major value of radionuclide scintigraphy is its increased sensitivity for periosteal trauma of the extremities and trauma of complex anatomic structures such as the spine, ribs, and scapula. Thus, scintigraphy can further characterize or rule out multiple injuries in the child with a suspected mechanism of abuse.

Neuroradiology
CT of the brain is critical in the management of traumatic brain injury (TBI). Magnetic resonance (MR) imaging is less readily available in the acute setting. Thus CT is the primary imaging modality for central nervous system (CNS) trauma in most institutions. MR imaging can be useful in the less acute setting to more precisely define chronic abnormalities. A class-II study compared two groups of patients with similar Glasgow Coma Scores and perinatal histories, categorizing the TBI as either accidental or inflicted (9). Patients with inflicted TBI had higher rates of subdural, interhemispheric, and convexity hemorrhages and signs of pre-existing abnormalities such as cerebral atrophy, subdural hygroma, and ex vacuo ventriculomegaly. Subdural hygroma occurred exclusively in patients with inflicted TBI with atrophy, suggesting
a previously undetected TBI. Intraparenchymal hemorrhage, shear injury, and skull fractures were more frequent after accidental TBI.

**CNS INJURY**

**Shaken-Infant Syndrome**

Caffey first postulated a link between shaking infants and intracranial and intraocular hemorrhage without evidence of external trauma (1,2). This has become known as the shaken-infant syndrome or shaken-baby syndrome. Many infants with this syndrome also show signs of impact injury to the head, ranging from skull fractures to soft tissue injury. Thus, it is often referred to as the “shaken-impact syndrome” (10). Often these infants present with “sudden death” (SIDS), seizures, coma, or apnea. The risk of any child suffering non-accidental head injury by this mechanism in their first year has been estimated to be one in 4000 (11). Intracranial hemorrhage and retinal hemorrhage are key elements of this syndrome. Associated findings may include long bone fractures or rib fractures.

In shaken-infant syndrome, the subdural hematoma is usually not associated with signs of external trauma. The cause of the subdural hematoma is avulsion of the venous bridges between the brain and dura due to the rapid acceleration and deceleration that occurs with violent shaking (2). External head trauma technically changes the classification of the injury to shaken-impact syndrome. There may also be associated skull fractures. Accidental subdural hematoma is rare in infants, and is not typically related to low-level (<4 feet) falls. In the absence of a high-energy mechanism of injury, such as a motor vehicle crash or fall from a significant height, child abuse must be considered in every case of subdural hematoma in children. In the clinical scenario of reported minimal trauma in infants, the presence of a skull fracture without intracranial injury suggests accidental trauma, whereas skull fractures and intracranial bleeding or intracranial bleeding alone are highly suggestive of child abuse (12).

A critical, although not mandatory, component of the diagnosis of shaken-infant syndrome is the presence of retinal hemorrhage. This finding must be evaluated and rigorously documented by an ophthalmologist. The validity of clinical information and diagnostic studies in shaken-infant cases is dependent on the completeness of the retinal examination. A full assessment includes indirect ophthalmoscopy to examine the peripheral retina. One study demonstrated that 29% of patients with retinal hemorrhages were not detected by non-ophthalmologists (13). Complete postmortem ocular evaluation (including the optic nerve) is the gold standard for the diagnosis of retinal hemorrhage (14). The mechanism that produces retinal hemorrhage is the subject of debate in the literature. One theory postulates that an abrupt increase in intracranial pressure results in venous obstruction and retinal hemorrhage. This may be augmented by abrupt increases in intrathoracic pressure due to thoracic compression. A second theory holds that acceleration/deceleration forces result in tractions of the vitreous on the retina with hemorrhagic retinoschisis cavities. Numerous class-II and -III studies show that retinal hemorrhages occur only rarely (<5%) with severe head trauma and not at all with moderate or mild head trauma (15,16). Other causes of retinal hemorrhage in infants include birth trauma, cardiopulmonary resuscitation (CPR), hematological diseases, and ruptured vascular malformations. With rare exceptions, CPR does not cause retinal hemorrhage (14,17–19). Bacon et al. and Kirschner and Stein each reported a case of retinal hemorrhage in an
infant after vigorous resuscitation (20,21). Purtscher retinopathy, a lesion of diverse pathophysiological origin, is a rare cause of retinal hemorrhage. However, this is rarely the cause of retinal hemorrhage and should be interpreted in the context of the clinical presentation.

ABDOMINAL INJURY

Although the true incidence of abdominal trauma as a result of child abuse is unknown, it is less common than burns, head injuries, and musculoskeletal injuries (22). The most common mechanism is a direct blow to the mid-epigastrum. This compresses the abdominal viscera against the thoracolumbar spine, which can in turn produce a burst injury to the intestine, pancreatic contusion or transection, duodenal hematoma or perforation, or mesenteric laceration (Figs. 1 and 2) (23,24). As with any blunt abdominal trauma, bleeding from a solid organ injury can also occur.

Children with abdominal injuries tend to be older than those with shaken-infant/shaken-impact syndrome. The mean age of children with severe intra-abdominal injuries is two years old. The mortality rate is 45% (23). Patients with abdominal injuries secondary to abuse often present in shock late after their injuries. The cornerstones of the diagnosis of these injuries are the physical exam and CT scan of the abdomen and pelvis. Ultrasound is less helpful. The focused abdominal sonography for trauma

![Image](image-url)

**Figure 1** Flat abdominal radiograph demonstrating massive free intraperitoneal air. This was due to a jejunal perforation from a direct blow to the mid-abdomen.
Figure 2  Intra-operative photograph of the child whose radiographs are depicted in Figures 1 and 3. Note the avulsed proximal jejunum with perforation. The forceps are within the lumen of the avulsed segment, demonstrating the perforation. The child was struck in the mid-abdomen approximately 12 to 18 hours prior to presentation in hemorrhagic shock.

Figure 3  Skeletal survey demonstrating rib fractures with fracture calluses noted. These findings were detected on the skeletal survey of the child whose injuries are shown in Figures 1 and 2. These old fractures and new injuries are pathognomonic of abuse.
FAST (FAST) exam may play a role in the prioritization of injury management in the multisystem injured child, but CT scanning provides more complete, organ specific information. Patients with other injuries from non-accidental mechanisms should undergo CT scanning of the abdomen and pelvis to evaluate for occult intra-abdominal injuries. While minor solid organ injuries in hemodynamically stable patients may be managed nonoperatively, patients with hemoperitoneum often present late after their injuries and in hypovolemic shock. The principles of management of abdominal injury due to blunt abdominal trauma have been applied successfully to these injuries.

FRACTURES AND FRACTURE PATTERNS

Caffey recognized the pattern of fractures and head injury that are indicative of non-accidental injury (1). Eighty percent of non-accidental fractures occur in children less than 18 months of age (25). In evaluating a child with one or more fractures, a careful history and physical exam, with particular focus on age and developmental milestones, are important. A critical comparison of the history with the physical findings helps to determine the likelihood of fractures being intentionally inflicted. The discovery of multiple fractures in different stages of healing or fractures inconsistent with the developmental age of the child or the reported mechanism should raise suspicion of non-accidental trauma. The presence of a non-accidental fracture places the child at high risk for subsequent injuries and child protective services (CPS) notifications (26).

Long Bone Fractures

Femur

Long bone fractures, without consideration of mechanism, age of the patient, or associated injuries, have a low specificity for child abuse (27). Spiral fractures have been classically viewed as pathognomonic of abuse in non-walking children. In a class-III study, Scherl et al. noted that the majority of fractures in children were transverse, and that this was also the most common pattern in cases of confirmed abuse. Because transverse fractures are often not felt to be caused by abuse, they are less frequently the subject of investigation (28). Perhaps the most important factor in assessing the probability of abuse with femur fractures is age. In children less than 12 months old, 60% to 80% of femoral fractures are related to abuse. In contrast, femoral fractures are almost never related to abuse in children older than two years of age (29,30).

Humerus

The location of the humeral fracture is the most important distinguishing feature to delineate between accidental and non-accidental fractures. In infants and toddlers, mid-shaft and metaphysseal fractures are more likely to be related to abuse, whereas supracondylar fractures are usually due to accidental falls (25,29).

Rib Fractures

Rib fractures are uncommon in childhood, mainly because it requires a high-energy impact to break a child’s rib. Rib fractures are believed to result from anterior–posterior thoracic compression during violent shaking (Fig. 3). It has been estimated that 85% to 100% of rib fractures in infants are due to abuse (29,31). Most reports
state that fractures due to abuse occur in the posterior part of the rib near the costo-vertebral junction where the rib articulates with the transverse process (32). However, some studies claim that fractures caused by abuse can also occur in the anterior and lateral aspects of the rib (6). A postmortem radiologic–histopathologic study using high resolution radiographic techniques demonstrated that the majority of rib fractures are not detected by routine skeletal surveys (33). CPR is often implicated as a cause of rib fractures in children. This arose from reports of rib fractures in adults after CPR (34). However, as is true for retinal hemorrhages from CPR, this association is either nonexistent or extremely rare in children. Class-II and -III data report that 0% to 3% of pediatric rib fractures result from CPR (6,7). Regardless of location, rib fractures are a marker for severe thoracic injury. If rib fractures are not explainable by a high-energy impact motor vehicle crash or auto–pedestrian injury) or intrinsic bone disease, then child abuse should be considered as a possible cause.

STAIRWAY INJURIES AND LOW-LEVEL FALLS

Stairway falls are common during childhood. As opposed to falls from a height, stairway falls are discretely quantifiable without the confounding variable of hitting another object. Falls down stairways are often implicated as the mechanism of injury by caregivers after non-accidental trauma. Knowledge of the expected injury patterns and injury severity may provide a more objective basis for the diagnosis of non-accidental trauma. Two class-II studies have specifically addressed the issue of injury pattern after stairway-related injury (35,36). Both studies concluded that truncal injuries were rare (2–3%) and that head, neck, and distal extremity injuries were common (70–90%). Importantly, multiple injuries involving more than one body region were rare. While extremity injuries are common, one class-III study of 363 children found no instances of femur fractures from a stairway or low-level fall (35). Indeed, intestinal perforation as a result of stairway falls has never been reported. A 29-year review of all English language publications demonstrated no intestinal perforations due to an unobstructed stairway fall (37). Therefore, intestinal perforation after a reported stairway fall should be viewed as highly suspicious.

PHYSICIAN RESPONSIBILITIES

It is the duty of the examining physician to report all suspected cases of child abuse to CPS. It is not the duty of the physician to be absolutely certain that suspicious injuries or circumstances are related to abuse. Most large children’s facilities have child protection teams that consist of social workers, nurses, and physicians with expertise in this area. Following CPS notification, a written physician’s statement is required to document the basis for the reasonable suspicion, the probable mechanism of injury, its severity, and the actual and anticipated medical consequences. The physician who prepares this statement must be prepared to testify about their findings in court. Many physicians and CPS teams find that medical photographs of the described injuries assist in communicating and memorializing the physical findings in their report.

Diseases such as osteogenesis imperfecta, Menkes’ syndrome (sex-linked recessive copper deficiency), temporary brittle bone disease, and congenital syphilis can cause bony abnormalities that mimic the effects of child abuse (38,39). Hemophilia, purpura fulminans, or other disorders of coagulation may present with bruising and
frank bleeding, suggesting trauma. The history may appear inconsistent with the physical exam if the examiner is unfamiliar with these diseases. Hermansky–Pudlak syndrome (functional platelet disorder) has presented with both subdural hematoma and retinal hemorrhage in an infant (40). Mongolian spots may be mistaken for contusions.

Physicians accustomed to evaluating children for suspected abuse learn to recognize most of these diagnoses. In fatal cases, autopsy results can clarify the diagnosis. In nonfatal cases a pediatric specialist trained in the evaluation of child abuse should assess all children with suspected abuse to minimize the possibility of a mistaken diagnosis.

REFERENCES

Fetal Trauma

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INTRODUCTION AND BACKGROUND

Trauma is the leading non-obstetric cause of death in the pregnant patient (1). Approximately 7% of all pregnancies are complicated by trauma, and four of every 1000 pregnancies require hospital admission because of a traumatic injury (2). With an increasing number of women working outside the home during pregnancy, there has been a proportional increase in the number of pregnant patients treated for injuries resulting from motor vehicle crashes (3). The risk of injury from a violent crime during pregnancy also parallels that of the general population. In a large multicenter review, penetrating trauma was responsible for 20% of admissions of pregnant women to a trauma center (4). Blunt and penetrating trauma are associated with increased pregnancy complications, and higher severity of injury correlates with markedly higher fetal loss (5). Since the fetus and mother are intimately linked, as the fetus is dependent on the mother for survival and that the physiology of pregnancy is such that perfusion to the uterus may be severely compromised with little obvious change in maternal physiologic parameters.

Advances in the field of fetal therapy and intervention over the past two decades have led to increasing recognition of the fetus as a patient. This chapter will address some unique considerations associated with trauma during pregnancy in order to assist the surgeon, when called upon, in delivering optimal care to both mother and fetus.
ANATOMIC AND PHYSIOLOGIC CHANGES ASSOCIATED WITH PREGNANCY

General Considerations

Treatment priorities for the pregnant trauma victim remain the same as in her non-pregnant counterpart, although stabilization and resuscitation must be modified to account for the anatomical and physiological changes associated with pregnancy. The first step in resuscitation of the fetus is restoring the hemodynamics of the mother. With obvious signs of maternal hemodynamic instability, the chances of saving the fetus are less than 20% (6). The uterine vascular bed is without significant autoregulatory control, and oxygen delivery across the placenta to the fetus is directly dependent on uterine perfusion pressure (7). Maternal hemorrhage and shock result in decreased uterine and placental perfusion, which ultimately leads to fetal hypoxia, bradycardia, and death (7).

Cardiovascular and Hematopoietic Systems

During pregnancy, maternal blood volume increases by 50% (8). Plasma volume increases by 30% to 45%. However, erythropoiesis does not keep pace with the changes in plasma volume, and red cell mass expands by only 10% to 15%, creating a “physiologic anemia” (8). Due to the increase in blood volume, hemodynamic instability may not become clinically apparent until blood loss approaches 2000–3000 mL, or 30% to 40% of circulating blood volume (9). Initially, the increase in blood volume protects the fetus. However, once hemodynamic instability becomes clinically apparent it implies a significantly greater loss of blood and may require a much larger resuscitation volume than is otherwise suspected (8).

Cardiac output begins to increase in the first trimester, peaks at a level 50% greater than normal during mid-trimester, and is sustained at this level until delivery (8). An increase in the stroke volume and basal heart rate by 10–15 beats/min contribute equally to the increase in cardiac output. Maternal systolic and diastolic blood pressures decrease steadily throughout pregnancy, reaching a nadir at 28 weeks gestation (10). Progesterone-induced vasodilation is one mechanism thought to be responsible for this effect (7). This combination of a physiologic decrease in blood pressure and increase in heart rate can confound efforts to assess the patient’s hemodynamic stability during the initial assessment. Further complicating the hemodynamic profile is the patient’s position at time of evaluation. When the patient is in the supine position, the inferior vena cava is partially compressed by the gravid uterus. This translates to a decrease in venous return, resulting in the “supine hypotensive syndrome” (11). This syndrome is marked by dizziness, pallor, tachycardia, sweating, and hypotension. In the supine position, partial aortic compression by the enlarged uterus also reduces uterine perfusion, further compromising blood flow to the fetus (12). Turning the mother onto the left lateral decubitus position and flexion of the right hip partially restore the circulation and increase the cardiac output by 30% (12). A summary of the hemodynamic changes during pregnancy is provided in Table 1.

Respiratory System

Maternal oxygen consumption is increased by as much as 20% during pregnancy due to the metabolic demands of the growing breasts, uterus, placenta, and fetus.
Through an increase in tidal volume mediated partially by increased progesterone levels, minute ventilation increases by as much as 50% (7). This increase in tidal volume is offset partially by a decrease in residual volume and expiratory reserve volume owing to the upward displacement of the diaphragm (8). These two effects combine to decrease the functional residual capacity by about 18%, which renders the pregnant woman particularly intolerant to hypoventilation and apnea (8). The net result of these respiratory dynamics is an unchanged arterial partial pressure of oxygen (PaO₂), a decreased partial pressure of carbon dioxide (PaCO₂), and a compensatory decrease in plasma bicarbonate levels compared to the non-gravid state (13).

### Gastrointestinal System

Increased circulating levels of estrogen and progesterone inhibit gastrointestinal motility and nutrient absorption throughout pregnancy (14). Gastrin production is also increased during pregnancy, mainly as a result of its production by the placenta (9). This leads to elevation of maternal gastric acid and enzyme production. In the second and third trimesters, increased progesterone levels inhibit cholecystokinin-mediated smooth muscle contraction in the gallbladder (14). This leads to impaired gallbladder emptying and, along with the increased concentration of cholesterol in bile during pregnancy, contributes to a higher incidence of gallstones (9).

As the gravid uterus enlarges throughout pregnancy, it displaces other intra-abdominal organs and increases intra-abdominal pressure. As expected, the signs and symptoms of injury to abdominal viscera during pregnancy will vary significantly compared to the non-gravid state due to the shift in their position within the abdominal cavity.

In addition, with progression of the pregnancy, stretching and diastasis of the rectus abdominus muscles may lead to loss of the usual guarding and muscular rigidity associated with intra-abdominal organ injury (6). These factors may contribute to physical exam findings inconsistent with the degree of maternal injury and must be taken into account when examining the pregnant trauma victim.

### Endocrine System

Throughout pregnancy, the placenta is a constant source of hormone production and is responsible for many of the associated hormonal changes. Progesterone, estrogen, and thyroid-stimulating hormone (TSH), adrenocorticotropic hormone

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**Table 1** Hemodynamic Changes in the Third Trimester of Pregnancy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Non-gravid</th>
<th>Gravid</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean arterial pressure (mmHg)</td>
<td>86 ± 8</td>
<td>90 ± 6</td>
<td>NS</td>
</tr>
<tr>
<td>Pulmonary capillary wedge pressure (mmHg)</td>
<td>6 ± 2</td>
<td>8 ± 2</td>
<td>NS</td>
</tr>
<tr>
<td>Central venous pressure (mmHg)</td>
<td>4 ± 3</td>
<td>4 ± 3</td>
<td>NS</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>71 ± 10</td>
<td>83 ± 10</td>
<td>+17%</td>
</tr>
<tr>
<td>Cardiac output (L/min)</td>
<td>4.3 ± 0.9</td>
<td>6.2 ± 1.0</td>
<td>+43%</td>
</tr>
<tr>
<td>Systemic vascular resistance (dyne/sec/cm⁻⁵)</td>
<td>1530 ± 520</td>
<td>1210 ± 266</td>
<td>−21%</td>
</tr>
<tr>
<td>Pulmonary vascular resistance (dyne/sec/cm⁻⁵)</td>
<td>119 ± 47</td>
<td>78 ± 22</td>
<td>−34%</td>
</tr>
<tr>
<td>Serum colloid osmotic pressure (mmHg)</td>
<td>20.8 ± 1.0</td>
<td>18.0 ± 1.5</td>
<td>−14%</td>
</tr>
</tbody>
</table>

Fetal Trauma
ACTH), human chorionic gonadotropic hormone (hCG), and human placental lactogen (hPL) are all produced by the placenta throughout pregnancy (15). The hPL enhances maternal lipolysis and inhibits maternal utilization of glucose, thereby making nutrients available to the fetus. In the maternal bloodstream, hPL functions as a physiologic antagonist of insulin and contributes to increased peripheral resistance to insulin (16). This results in increased maternal protein catabolism and ensures a constant supply of amino acids to the growing fetus (17).

Renal System
Maternal renal perfusion increases by up to 50% throughout pregnancy as maternal and fetal metabolic requirements increase significantly (16). Maternal glomerular filtration rate is increased by up to 100% as a result of the increase in blood volume and cardiac output in pregnancy (18). This contributes to a steady decline in maternal blood urea nitrogen and creatinine, and hyperemia and enlargement of both kidneys, an effect mediated in part by progesterone-associated smooth muscle relaxation (18). In the third trimester, the increase in size of the uterus may contribute to compression of the ureters, resulting in hydroureters and hydronephrosis (18). Thus an intravenous pyelogram demonstrating a dilated renal collecting system may not be due to other abnormalities (6). As pregnancy progresses, the mother’s bladder is gradually elevated out of the pelvis, and is therefore more susceptible to direct injury.

INITIAL EVALUATION AND MANAGEMENT
Armed with a basic understanding of maternal and fetal anatomy and physiology, a physician faced with a pregnant trauma victim can modify the resuscitation and subsequent management to optimize outcome for both the mother and the fetus. Regardless of the estimated gestational age of the fetus, the physician’s first priority during the initial evaluation remains resuscitation and stabilization of the mother.

Primary Survey
The primary survey of the injured pregnant patient begins with assessment of the airway, breathing, and circulation. After establishing a patent airway, generous use of supplemental oxygen is advocated in order to prevent maternal and fetal hypoxia (19). Due to the differences between adult and fetal oxyhemoglobin dissociation curves, small decreases in maternal oxygen content are associated with significant fetal hypoxia (20).

If maternal circulatory compromise is suspected due to the mechanism of injury, the patient must be placed in the left lateral decubitus position with flexion of the right hip to minimize mechanical aortocaval compression by the uterus. The mother with a suspected spinal injury can be secured on the backboard prior to initiating these positional maneuvers. Manual displacement of the uterus toward the left upper quadrant may be appropriate in cases where emergency room interventions such as intubation and placement of central venous lines are not easily accomplished in the lateral decubitus position. Once on the backboard, the board may be tipped 45° to the left in order to decompress the inferior vena cava and restore central venous pressure.
Early in pregnancy, the diameter of the mother’s chest increases by approximately 2 cm, primarily under the control of hormonal effects (9). As the uterus enlarges, upward displacement of the diaphragm may exceed 6 cm (9). These changes obscure the anatomy of the thoracic cavity, and care should be taken while attempting invasive procedures such as tube thoracostomy or thoracentesis, as standard placement in the fifth and sixth intercostal spaces has been associated with both visceral organ and uterine perforation (21). As a rule, such tubes should be placed in the second or third intercostal spaces to avoid risk of injury to intra-abdominal organs.

The physiologic hypervolemia of pregnancy may mask early signs of shock. Therefore, generous resuscitation with crystalloid is advocated in patients who appear normotensive on initial presentation (22). Even minor maternal trauma may be associated with increased circulating maternal catecholamines, resulting in uteroplacental vasoconstriction (7). Treatment of maternal hypotension with vasopressors should be avoided and used only as a last resort, understanding the implications for blood flow to the uterus and placenta and the potential for fetal compromise (11).

**Secondary Survey**

The secondary survey begins with a thorough history of the mother, including the obstetrical history, and is followed by a thorough physical examination. As part of this survey, fetal evaluation and monitoring are initiated and continued while management decisions are being made. A history of preterm labor, placenta previa, or placental abruption puts the pregnant patient at increased risk for recurrence of these conditions and must be elicited during the secondary survey (11). The obstetric history must include the starting date of the last menstrual period, date of the first perception of fetal movement, expected date of delivery, and any complications associated with the current and previous pregnancies.

An estimation of the gestational age and fetal maturity can be obtained by determination of uterine size by palpating the most superior aspect of the uterine fundus and comparing its location with known anatomical landmarks. This is especially useful when the history is not readily available due to maternal incapacitation or lack of adequate prenatal care. For example, a uterine fundus palpated midway between the umbilicus and the xiphoid process is consistent with an estimated fetal age of 24 to 26 weeks (23). This information may play a critical role in the decision making regarding early delivery.

A gynecologic exam must be performed to indicate the status of the pregnancy. Vaginal bleeding, a bulging perineum, ruptured membranes, presence of contractions, and abnormalities of fetal heart rate and rhythm are all associated with increased risk to the pregnancy (23). Vaginal bleeding is abnormal prior to the onset of labor and may be associated with uterine injury, placental abruption, premature cervical dilation, or placenta previa (23). Bulging fetal membranes are caused by pressure from a presenting part of the fetus and are associated with spontaneous abortion early in pregnancy (11). The presence of cloudy green fluid around the cervical os or perineum indicates rupture of the amniotic sac and may be associated with compression of the umbilical cord vessels (23). The presence of amniotic fluid may be confirmed by the change in color of nitrazine paper from blue-green to deep blue, and may be significant in predicting potential for infection. However, differentiation of amniotic fluid from urine may be difficult, and insertion of a Foley catheter is recommended if rupture of membranes is suspected to support the diagnosis. Uterine contractions are assessed by palpation of the abdominal wall overlying
the uterine fundus and determination of the frequency, intensity, and duration of the contraction pattern. Beta agonists such as mitodrine may be used to control uterine contractions and progressing pregnancy without decreasing uterine perfusion. Strong contractions may be associated with true labor, and their presence indicates the need to prepare for delivery and resuscitation of the newborn (11).

Evaluation and Monitoring of the Fetus

Fetal assessment begins with auscultation for fetal heart tones. The baseline fetal heart rate is defined as the rate in beats per minute around which the fetal heart rate oscillates for 10 or more minutes. The normal range is 120–160 beats/min. Tachycardia is defined as a heart rate greater than 160 beats/min and is the initial fetal response to stress, hypoxia, and hypotension (24).

Once fetal heart tones are detected by auscultation, continuous electronic fetal heart rate monitoring (EFM) is initiated for constant assessment of fetal well-being. Both internal and external techniques may be used to monitor the fetal heart (25). The internal approach is reserved for the near term fetus, and involves detection of the fetal QRS pulse by placement of an electrode directly on the presenting part of the fetus. This technique may be utilized in cases where the amniotic membranes are ruptured and provides more accurate information about variations in fetal cardiac activity (10). It is also associated with a higher incidence of infection and direct fetal injury (26). External monitoring involves Doppler ultrasonography to detect fetal heart wall motion. Its advantages include noninvasiveness and wide clinical applicability. However, motion artifacts associated with the fetal tracing may impair the reliability of this technique (26).

Sudden fetal bradycardia is most commonly associated with acute fetal hypoxia and in the traumatized obstetric patient is often due to complete or partial placental abruption. Acute fetal bradycardia has also been associated with amniotic fluid embolus syndrome, acute maternal respiratory insufficiency, or eclamptic seizure (10). Late onset fetal tachycardia is commonly a result of overwhelming maternal infection and is often associated with maternal pyrexia and chorioamnionitis (7). Isolated fetal hemorrhage is not usually associated with a tachycardic response in the fetus, and persistent fetal tachycardia is not always a sign of uncontrolled bleeding from direct injury to the fetus (7). A normal fetal heart rate has a 95% correlation with adequate fetal perfusion and is the single best predictor of fetal survival after traumatic injury to the mother (27).

The ideal duration of fetal monitoring after trauma has been a subject of debate by experts in the field. Numerous studies have attempted to determine risk factors that affect pregnancy outcome and establish guidelines for fetal monitoring. Pearlman et al. in a prospective randomized trial of 85 injured pregnant patients found four hours of cardiotocographic monitoring to be a sensitive but not specific indicator of fetal survival (28). A recent study by Curet et al. identified risk factors for premature contractions, preterm labor, and fetal loss after traumatic injury during pregnancy (29). In this series, risk factors associated with fetal death included major mechanisms such as ejections, and collisions involving motorcycles or pedestrians. Maternal death, maternal tachycardia, abnormal fetal heart rate, lack of restraints, and maternal Injury Severity Score >9 were also associated with increased fetal mortality. Risk factors associated with premature contractions or labor in this study included gestational age >35 weeks, assaults, and pedestrian collisions. These
authors concluded that patients with any of these risk factors should be monitored for at least 24 hours, and that stable patients without any risk factors or other reasons for further observation and monitoring could be safely discharged after six hours of fetal monitoring. Current guidelines of the American College of Surgeons Committee on Trauma recommend 24 hours of fetal monitoring for patients with frequent uterine activity (>6 contractions/hr), abdominal tenderness, vaginal bleeding, or hypotension (23). In patients with these findings, obstetrical consultation should be obtained after the initial evaluation and resuscitation is complete.

**Fetal Viability**

The presence of a viable fetus is a central point in the subsequent management of the injured pregnant patient. A fetus is considered viable when it has achieved 24 weeks of a 40-week gestation, as fetal lungs mature and become capable of gas exchange (29). With aggressive neonatal resuscitation and vigilant intensive care monitoring, approximately 50% of these fetuses survive, although morbidity remains high and is often attributed to intracranial hemorrhage, necrotizing enterocolitis, and respiratory distress syndrome (30). Real-time ultrasonography is the optimal method for measurement of parameters such as head size (circumference and biparietal diameter), abdominal circumference, and femur length (31). Palpation of the uterine fundus halfway between the umbilicus and the xiphoid process is also consistent with fetal viability (31).

**DIAGNOSTIC STUDIES**

Keeping in mind the basic rule that preservation of fetal life is largely dependent on maternal stabilization, radiographic studies should not be foregone simply because of potential exposure of the fetus to ionizing radiation. In addition, adequate assessment of maternal injuries through imaging studies is usually possible without significant teratogenic risk to the fetus. This risk is greatest during the process of organogenesis, which takes place between weeks 3 and 16 of gestation (3). The risk declines significantly after this point, and radiation-induced injuries after the 20th week of gestation are rare. As a general rule, a direct-beam radiograph (i.e., abdomen, pelvis, and lumbar spine), delivers a dose of 0.05 Gray units (GY) (Table 2). An indirect film (skull, chest, and extremities) is associated with a 0.001 GY dose of radiation. The radiation energy absorbed during a CT scan of the abdomen ranges from 0.02 to 0.026 GY. Magnetic resonance imaging does not involve ionizing radiation, and does not entail risk at any gestational age. Other variables that affect fetal exposure include shielding, exposure time, tube to film distance, and unnecessary repetition of a study due to inadequate planning by the caregiver. Necessary radiographic examinations should be obtained according to the following guidelines:

1. Careful planning to obtain the minimum number of radiographs to obtain the maximum information.
2. Shielding the patient’s abdomen during the study with a lead apron.
3. Use of a dosimeter badge to keep track of total radiation exposure in a critically ill patient in whom a protracted intensive care unit stay is anticipated.
MANAGEMENT STRATEGIES

Blunt Trauma

Automobile accidents account for the majority of cases of blunt trauma during pregnancy (23). Three-point restraints are effective in reducing severe maternal injuries, and are associated with increased fetal survival when compared to two-point restraints (32,33). Other causes of blunt trauma during pregnancy include falls and aggravated assaults. Due to the anatomic and physiologic changes that occur during pregnancy, different patterns of injury are observed in a pregnant patient with blunt thoracoabdominal injuries compared to her nonpregnant counterpart. The incidence of splenic injury and retroperitoneal hematoma is greater due to the increased intra-abdominal venous congestion associated with pregnancy (6). Conversely, the incidence of bowel injury in the mother is decreased, presumably as a result of the anatomic displacement of the intestines away from the lap belt distribution by the enlarged uterus (33).

Severe lower abdominal trauma during pregnancy is often associated with direct injury to the fetus. This mechanism is usually associated with fetal skull fracture and resultant intracerebral hemorrhage (10). Pelvic fracture in the pregnant patient is associated with a high maternal and very high fetal mortality rate (34).

An intact uterine–placental interface is essential for oxygen and nutrient delivery to the fetus. Even in the absence of direct fetal injury, severe fetal injury may result from abruptio placentae (27). Placental abruption refers to the abnormal separation of the placenta from the uterus, and in blunt trauma occurs as a result of the sudden increase in intrauterine pressure that results from sudden deceleration in a restrained patient (33). In addition, the uterus is thought to elongate on a vertical axis during deceleration, and deformation of the relatively elastic uterine musculature in relation to the more rigid placental tissue creates a shearing effect thought to contribute to placental separation. Abruptio placentae complicates 1% to 5% of minor injuries, and 20% to 66% of major blunt traumatic injury (35). Clinical findings associated with placental abruption include: vaginal bleeding, abdominal pain, tenderness, and uterine contractions. The reduced area of the uterine–placental interface for fetal–maternal gas exchange and nutrient delivery in these instances is thought to be responsible for resultant fetal hypoxia, prematurity, and death. One of the most serious complications associated with placental abruption is disseminated intravascular coagulation (DIC), which is thought to result from entry of thromboplastins from the injured placental tissue into the maternal circulation. The DIC in the injured pregnant patient is associated with a three- to five-fold increase in fetal and maternal mortality (27). Thus, early diagnosis of placental abruption is necessary to avoid this serious complication. Although most patients suffering myometrial contusions will exhibit mild to moderate uterine contractions in the ensuing recovery period, uterine activity of greater than eight contractions per hour in the first four hours after blunt trauma is associated with a 25% risk of placental abruption (36). The vast majority of trauma-related placental separations occur within the first four hours after injury. However, delayed separations after 24 to 48 hours have been reported (35). Ultrasound can detect placental abruption with high sensitivity and specificity in the trauma setting (31). Computed tomography (CT), which may be used for maternal evaluation, can confirm the ultrasound findings.

In a study aimed at delineating factors affecting fetal outcome after blunt maternal trauma, Scorpio et al. reported that admission Injury Severity Scores (ISS) and bicarbonate levels were the best predictors of pregnancy outcome (37).
The average ISS on admission for mothers who experienced fetal demise after blunt trauma was 31 and average bicarbonate level was 16.8, compared to 11 and 20.3, respectively, in cases where the fetus survived.

After maternal resuscitation has been initiated and secondary survey begun, the management of the pregnant blunt trauma victim should proceed with three key considerations in mind:

1. The determination of gestational age in a stable patient is the key factor in determining the subsequent management of the mother and fetus.
2. The physiologic hypervolemia associated with pregnancy may mask ongoing intra-abdominal hemorrhage and hypotension.
3. The physical exam is unreliable due to the displacement of intra-abdominal organs by the enlarging uterus and related changes in peritoneal response to irritation from stretching of the abdominal wall.

Penetrating Trauma

Penetrating trauma during pregnancy is neither rare nor insignificant, accounting for up to 36% of maternal deaths (38). A review of several large series demonstrated that gunshot wounds suffered during pregnancy are associated with a maternal mortality rate of 4%, while fetal mortality in the same cases ranged between 40% and 70% (39). Undoubtedly, a portion of this mortality is due to prematurity from early delivery; however, delay in diagnosis of a potentially correctable lesion in a viable fetus contributes. Unlike blunt traumatic injury, where the cause of fetal demise is most often due to placental abruption, fetal death from penetrating injuries is most commonly associated with ongoing bleeding, hepatic injuries, and disruption of the central nervous system. A well-informed, multidisciplinary approach with participation of a fetal surgeon in the decision-making process may improve fetal survival and outcome in cases where fetal viability is threatened.

Patterns of Injury

Most cases of penetrating trauma during pregnancy result from violence against the mother (40). Other causes include attempted suicide and attempted abortion. The altered anatomy of intra-abdominal organs has important implications. Near term
a penetrating injury inferior to the xyphoid process is associated with a high likelihood of uterine perforation, while injury to the thoracoabdominal areas bilaterally is associated with a high incidence of gastrointestinal organ injury due to crowding of the organs in this portion of the abdomen. Most cases of intentional gunshot wounds to the uterus are not associated with extrauterine organ injury. However, the chance of fetal injury is 60% to 90% (40).

Management of Penetrating Injuries

The decision to operate in cases of penetrating trauma follows similar algorithms in pregnant and nonpregnant individuals: abdominal gunshot wounds require celiotomy, and stab wounds warrant exploratory laparotomy based on the assessment of the likelihood of entrance through the parietal peritoneum into the abdominal cavity (Fig. 1).

A recent controversial report advocates conservative management of gunshot wounds to the lower abdomen in the gravid patient who is stable, provided certain conditions are met (40). These conditions are:

1. The entrance wound is below the fundus.
2. The bullet can be demonstrated to be within the uterus.
3. The mother is stable.
4. The abdominal examination is benign.
5. There is no demonstrable blood in the gastrointestinal tract or urine.
6. There is no indication for uterine evacuation.

These author recommendations are supported by the fact that only 19% of women who sustain gunshot wounds to the pregnant uterus will have associated intra-abdominal injuries with surgical significance.

Although these studies deserve consideration, the current prevailing opinion is that the gravid patient with an intra-abdominal gunshot wound must undergo

![Algorithm for management of penetrating trauma in pregnancy.](figure1.png)
exploratory celiotomy. This view is supported for several reasons. The abdominal exam may be unreliable in pregnancy, and peritoneal signs resulting from hollow viscus injury may be masked. In addition, the risks associated with missing an intra-abdominal injury usually outweigh those associated with anesthesia and celiotomy.

In a stable woman with a previable fetus, abdominal exploration followed by hysterotomy by a fetal surgeon may reveal a fetal lesion, which can be repaired in utero, delaying delivery until fetal viability is achieved. Indications for fetal surgery are limited to ongoing hemorrhage in the fetus. Since the fetal abdominal cavity is sterile, a suspected hollow viscus injury in the fetus does not warrant exploration. However, uncontrollable fetal hemorrhage may result in fetal demise and may be amenable to correction in utero.

Stab wounds to the abdomen during pregnancy are managed similarly in pregnant and nonpregnant patients: exploration is mandatory for patients who demonstrate obvious signs of intra-abdominal injury, including shock, peritonitis, and evisceration. In cases where indications for exploration are not clear, adjunctive diagnostic studies such as CT scanning and diagnostic peritoneal lavage aid in supporting the decision to operate.

Once the decision to operate is made, a midline celiotomy is undertaken and usually provides adequate exposure. Careful retraction of the uterus may be necessary to improve exposure and must be performed with care to avoid aortocaval compression. Celiotomy alone does not warrant caesarean section since it prolongs the operation and increases blood loss by at least 1000 mL (41). Specific indications for emergency caesarean section are listed in Table 3. The risk of inducing labor by manipulation of the gravid uterus is very low (41). In cases where uterine injury is severe and hemorrhage uncontrollable, a caesarean section may be indicated to evacuate the uterus prior to hysterectomy or uterine repair.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Indications for Emergency Caesarean Section</th>
</tr>
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<tbody>
<tr>
<td>Uncontrollable uterine hemorrhage</td>
<td></td>
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<tr>
<td>Irreparable uterine injury</td>
<td></td>
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<tr>
<td>Access to maternal injuries is obscured by uterus</td>
<td></td>
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<tr>
<td>Maternal instability with a potentially viable fetus</td>
<td></td>
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<tr>
<td>Systemic complications of pregnancy (eclampsia, DIC)</td>
<td></td>
</tr>
<tr>
<td>Maternal death</td>
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</table>

Table 3: Indications for Emergency Caesarean Section

Once the decision to operate is made, a midline celiotomy is undertaken and usually provides adequate exposure. Careful retraction of the uterus may be necessary to improve exposure and must be performed with care to avoid aortocaval compression. Celiotomy alone does not warrant caesarean section since it prolongs the operation and increases blood loss by at least 1000 mL (41). Specific indications for emergency caesarean section are listed in Table 3. The risk of inducing labor by manipulation of the gravid uterus is very low (41). In cases where uterine injury is severe and hemorrhage uncontrollable, a caesarean section may be indicated to evacuate the uterus prior to hysterectomy or uterine repair.

<table>
<thead>
<tr>
<th>Time between maternal death and delivery</th>
<th>Influence on survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5 min</td>
<td>Excellent</td>
</tr>
<tr>
<td>5–10 min</td>
<td>Good</td>
</tr>
<tr>
<td>10–15 min</td>
<td>Fair</td>
</tr>
<tr>
<td>15–20 min</td>
<td>Poor</td>
</tr>
<tr>
<td>20–25 min</td>
<td>Unlikely</td>
</tr>
</tbody>
</table>

Table 4: Postmortem Caesarean Section: Predictors of Successful Outcome

Duration of gestation: Fetal viability is defined as ≥24 weeks of gestation. This corresponds to a fundal height of approximately 24–26 cm above the pubis or a uterus palpable midway between the umbilicus and costal margin. Under optimal conditions, the fetus has a 50–60% estimated chance of survival without a major handicap; therefore, caesarean section is indicated shortly after maternal death.
A postmortem caesarean section is indicated in cases where a dead or moribund woman is carrying a potentially viable fetus. A review of 120 successful postmortem caesarean sections found that 70% of surviving infants were delivered within five minutes of maternal death. The same findings have been confirmed by others and are listed in Table 4.

REFERENCES

8

Imaging the Injured Child

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INTRODUCTION

For many reasons, ranging from normal childhood activity to motor vehicle crashes and child abuse, fractures and soft tissue injuries are common in children almost to the point that they are part of growing up in our modern world. Radiological assessment has played an ever-increasing role in the management of these injuries since the early days of X-ray use. In our efforts to bring children back to their normal state of health, diagnostic images now play an essential part in accurately diagnosing injuries and monitoring how they respond to treatment. As technology has evolved, pediatric trauma care has led the field in some areas and lagged behind in others. Because of the differences between adults and children in anatomy, physiology, and tissue and wound healing, and in the spectrum of injuries that they suffer, the exact role of imaging studies will also differ.

LITERATURE-BASED GUIDELINES

A National Library of Medicine search of over 1000 articles revealed very few randomized prospective trials that specifically address the use of imaging modalities in pediatric trauma (1–5). The vast majority of published articles concerning imaging of the injured child are nonrandomized and uncontrolled, i.e., type-II studies. There are considerably more studies overall concerning imaging in trauma in the adult population as compared to children. These are cited where applicable.

Most clinicians caring for injured children would likely agree that computed tomography (CT) is the standard for imaging pediatric trauma patients with suspected or known intracranial injuries and/or abdominal solid organ injuries (level-II recommendation) (6,7). Similarly, clinicians agree that a chest radiograph should be the most common first imaging study of the chest (level-II recommendation) (Table 1), and plain radiographs of an injured extremity are the standard of initial...
investigation for suspected fractures (level-II recommendation) (1). Arteriography is most often considered the “gold standard” for diagnosing arterial injuries (level-II recommendation). Aside from these generally accepted “standards,” other imaging modalities are typically left to the discretion of the treating surgeon.

**TYPES OF STUDIES**

**Initial Radiographs in the Emergency Department**

Plain X rays are the initial radiologic diagnostic tests in use in emergency departments today. The initial physical examination of the child determines which studies should be performed and when. While the patient is undergoing resuscitation in the emergency department, the diagnosis of injuries is begun with standard radiographs, usually performed with a portable X-ray machine or one dedicated to the trauma room, thus avoiding movement of the patient. The most frequently ordered initial imaging studies in the emergency department include plain radiographs of the chest, abdomen, pelvis, cervical spine, and extremities (Fig. 1). Thoracic and lumbar spinal X rays are commonly ordered when neurologic injuries are suspected, or when the physical examination reveals point tenderness over the spine. Detecting a pneumothorax, pneumoperitoneum, pelvic fracture, or long bone fracture is an important component of the initial care of a traumatized child.

As experience and technology have expanded, some previously common studies have been shown to be of limited use. Plain X rays of the skull may document fractures, but they have little value in directing management of the head injured child, with the excepted situations of penetrating injury and suspected child abuse (8,9). Wang and colleagues have documented the poor predictive power of plain skull

<table>
<thead>
<tr>
<th>Table 1 Pathology Potentially Noted on Chest X Ray</th>
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<tbody>
<tr>
<td>Bony thorax for fracture</td>
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<tr>
<td>Ribs</td>
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<tr>
<td>Clavicles</td>
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<tr>
<td>Vertebrae</td>
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<tr>
<td>Scapulae</td>
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<td>Sternum</td>
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<tr>
<td>Soft tissues</td>
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<td>Emphysema</td>
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<tr>
<td>Opacification</td>
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<tr>
<td>Foreign object</td>
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<tr>
<td>Lung fields</td>
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<tr>
<td>Pneumothorax</td>
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<tr>
<td>Hemothorax</td>
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<tr>
<td>Consolidation</td>
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<tr>
<td>Lung contusion</td>
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<tr>
<td>Foreign bodies</td>
</tr>
<tr>
<td>Mediastinum</td>
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<tr>
<td>Pneumomediastinum-airway rupture</td>
</tr>
<tr>
<td>Widening of the mediastinum-aortic rupture</td>
</tr>
<tr>
<td>Shift of the mediastinum-tension pneumo/hemothorax</td>
</tr>
<tr>
<td>Foreign body</td>
</tr>
<tr>
<td>Cardiac silhouette</td>
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<tr>
<td>Cardiac tamponade</td>
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radiographs in determining intracranial bleeding in children with mild head injury (Glasgow Coma Scale of 13–14) (10).

Intravenous pyelography has been used to document injuries of the urinary system, but its usefulness is also limited. It does not allow for grading of renal, ureteral, or bladder injuries, or for determining the presence of other intra-abdominal injuries. Similarly, nuclear isotope scanning has little utility in the initial workup of the severely injured child. The grading of injuries is also uncertain and not all organs are evaluated. Skull films, intravenous pyelography, and radionuclide studies have now been supplanted by CT scanning in most cases.

**Ultrasound**

Ultrasound has been used extensively since it became widely available. In the United States, radiologists traditionally perform sonographic imaging, while in Europe and Asia surgeons commonly perform it. In the past decade, surgeon-directed ultrasonography has been popularized in the United States. Several recent studies by adult and pediatric trauma surgeons have attempted to determine the role of Focused Acute Sonography for Trauma, also called Focused Abdominal Sonography for Trauma (FAST) in the evaluation of the injured child. The most common FAST evaluation examines the heart, right and left upper quadrants, and the pelvis for fluid. Some surgeons include an evaluation of the thorax for fluid in the pleural space and for pneumothorax. Review of the National Library of Medicine revealed three prospective trials of the use of FAST in children (3–5), as well as other studies providing

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**Figure 1**  Gunshot wound to the chest in a 13-year-old male. Note the pulmonary contusion and foreign object.
useful data (6,11–13). In some studies, a radiologist performed the FAST, while other publications have evaluated surgeon-directed ultrasonography.

The technique of B-mode ultrasound in the hands of an experienced ultrasonographer should be as accurate in detecting blood in the abdomen as CT scanning or diagnostic peritoneal lavage (DPL) (Fig. 2) (14–16). In a collected series of over 4900 patients, surgeons who performed ultrasound to detect hemoperitoneum and visceral injury demonstrated a sensitivity of 93.4%, a specificity of 98.7%, and an accuracy of 97.5% (14–17). This can be compared to a group of 1043 patients in whom the ultrasonographic study was performed by radiologists. This collected series showed a sensitivity of 90.8%, a specificity of 99.2%, and an accuracy of 97.8% (11,18–21). Both of these series include adults and children. Garcia et al. (5) have suggested that sonography for the sole purpose of establishing the presence of free intracavitary fluid in the child is of questionable usefulness as it does not necessarily identify the specific organ injured nor the grade of the injury. They suggest that some solid organ injuries will be missed if free fluid alone is the indication for abdominal CT scan. Currently, non–radiologist-directed ultrasound is considered an extension of the physical examination and not a conclusive diagnostic study. Although its sensitivity, specificity, and accuracy are high, it is used mostly as a screening tool to determine the need for more in-depth imaging studies or invasive evaluation.

The typical FAST examination takes three to five minutes when performed by a physician experienced in its use. A 3.5 MHz probe is used for children over 10 kg, while either a 3.5 or a 5 MHz probe can be used for children under 10 kg. The relative lack of subcutaneous tissue in most children makes this an easy study to perform on children compared to adolescents and adults. Obvious benefits of the FAST evaluation include its portability, eliminating the need to transport the child to the radiology suite, and the fact that it limits the child’s radiation exposure.

Figure 2  Positive right upper quadrant ultrasound for trauma in a 4-year-old child. White arrow denotes fluid (dark area) between the liver and kidney.
The American College of Surgeons in conjunction with emergency medicine groups is in the process of establishing training guidelines and teaching programs for FAST evaluation. The American College of Surgeons has developed a program that provides basic education in ultrasound physics and technique, as well as some advanced courses in FAST evaluation of the abdomen and other regions of the body. In the near future, it is foreseeable that surgical training programs, in which the trainee is responsible for the care of the injured child, will likely include emergency ultrasound as part of their curriculum. However, due to the current lack of availability of FAST training and uncertainty of the usefulness of the technique at present, ultrasound evaluation of the injured child is of secondary importance in the initial workup of the pediatric trauma patient at this time.

Vascular ultrasound studies, with color Doppler, are useful in detecting vascular injuries in children. These studies use 7 MHz (or higher) transducers with color capability. The use of color Doppler ultrasound may help to avoid the complications associated with arteriography in children with tiny blood vessels. As the quality of these devices has improved, the need for arteriography and the risk of vascular injury are increasingly avoided.

**Computed Tomography**

The CT scan is the accepted diagnostic imaging study of choice in the vast majority of stable injured children suspected of having a potentially life-threatening injury. The newer CT scanners have a gantry, which encircles the patient and rotates continuously in the same direction. During scanning, data acquisition is combined with continuous movement of the patient through the gantry. The path of the radiation is described as a spiral or helix, giving rise to the name spiral or helical CT. These scanners acquire data very quickly, allowing them to scan a fairly large volume or length in a short period of time. The rapidity of the scanner is advantageous for a number of reasons:

1. Motion artifact is reduced as the patient can often hold his breath for the entire study.
2. Optimal use of intravenous contrast enhancement is allowed.
3. The test is quicker than conventional CT scanning, resulting in higher resolution in the same study time.
4. The data obtained from spiral CT are best for 3D imaging because of the lack of motion artifacts.

The CT scans of the head, abdomen, and chest are considered the standard of care for the evaluation of an internal injury in a stable, traumatized child. The majority of children with suspected intra-abdominal injuries should have a CT scan performed prior to instituting operative or nonoperative treatment unless an absolute indication for surgery is present (Fig. 3). A lap belt injury, a bicycle handlebar injury, or child abuse are the mechanisms most often associated with blunt intestinal injury. Unstable children in the emergency department are either taken directly to the operating room or evaluated by other modalities such as DPL or ultrasound.

It is generally observed that a high percentage of CT scans on injured children will reveal no injuries. Ruess et al. evaluated the CT scans of 1500 consecutive children evaluated for blunt abdominal trauma (22). Abnormal CT scans were seen in only 26% of patients. A normal study was found to strongly predict a lack of deterioration in that only one delayed laparotomy was required in the 1112 children with a normal CT. In addition, a CT scan affected the decision to operate on children with a solid viscus injury in a very small subset of patients (5 of 1500 CT scans).
Despite the liberal use of head CT scans, it is possible for the child with a severe neurological injury to have a normal initial scan, or for a child to develop late manifestation of a neurologic injury or cerebral edema despite an initial normal study (23).

The optimal technique of performing an emergency CT scan on an injured child and the use of contrast material remain unclear. Most institutions perform an initial head CT scan without intravenous contrast. The use of intravenous contrast during a CT scan for intrathoracic or intra-abdominal trauma improves its diagnostic accuracy, but is not required and can be omitted during the initial scan, depending upon the experience and protocols of the particular trauma center. The benefit of using oral contrast for an abdominal CT scan in injured children is also a matter of debate. In a randomized, prospective adult clinical trial, the addition of oral contrast to an acute abdominal CT scan for trauma was found to be unnecessary and to cause delay in the time to CT scanning (24). In a review of 2162 patients with blunt trauma and an abdominal CT scan, Tsang et al. found that all seven patients with an intestinal perforation had studies that showed neither extraluminal air nor extraluminal oral contrast (25). In some centers, due to the length of time needed to fill the bowel with contrast and the resultant full stomach, which is thought to promote vomiting with aspiration, gastrointestinal (GI) contrast is avoided in the initial CT scan of the abdomen in the injured child. However, others suggest that it improves the accuracy of abdominal CT scans when intestinal or retroperitoneal injury is suspected, and that oral contrast administration is safe with minimal risk of aspiration (26,27). In summary, the use of GI contrast in emergency CT scans of the abdomen for trauma is a matter of institutional preference at the present time.

Evidence, on CT scan, of intra-abdominal injuries requiring operative correction may be subtle (Fig. 4). While the findings of free intraperitoneal or retroperitoneal air, extraluminal GI contrast medium, a bowel wall defect and active hemorrhage are often obvious and have a high correlation with intestinal injury requiring operative intervention, potentially life-threatening intestinal injuries may be manifest only by

Figure 3  The CT scan of a patient with spleen injury and blood in the abdomen, noted by arrow.
focal bowel wall thickening or peritoneal fluid accumulation without solid organ injury (28,29). Other less specific findings associated with intestinal injuries include mesenteric stranding, fluid at the mesenteric root, focal hematomas, mesenteric pseudoaneurysm, and the hypoperfusion complex (Table 2).

**Magnetic Resonance**

Magnetic resonance imaging (MRI) is most often utilized for the patient with a suspected or confirmed neurologic injury. It is also useful in the evaluation of complex findings that correlate with the need for surgery.

<table>
<thead>
<tr>
<th>High correlation</th>
<th>Potential correlation</th>
<th>Nonspecific findings</th>
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<tbody>
<tr>
<td>Free intraperitoneal or retroperitoneal air</td>
<td>Focal bowel wall thickening</td>
<td>Mesenteric stranding</td>
</tr>
<tr>
<td>Extraluminal GI contrast medium</td>
<td>Peritoneal fluid accumulation without solid organ injury</td>
<td>Fluid at the mesenteric root</td>
</tr>
<tr>
<td>Bowel wall defect</td>
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<td>Focal hematomas</td>
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<tr>
<td>Active hemorrhage</td>
<td></td>
<td>Mesenteric pseudoaneurysm</td>
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<td></td>
<td></td>
<td>Hypoperfusion complex</td>
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**Table 2** The CT Findings That Correlate with the Need for Surgery

**Figure 4** Blunt abdominal trauma in an 8-year-old male. The arrow indicates a complete transection of the tail of the pancreas, 12 hours after injury.
orthopedic injuries, especially of the spine, pelvis, and joints. The MRI is rarely indicated as a primary study in the acute setting. It is especially helpful in patients with neurologic abnormalities whose X rays and CT scans are normal and to confirm clinically suspected fractures in children with no abnormality on standard radiographs (30,31). Some investigators advocate MRI to evaluate patients with traumatic aortic rupture, suggesting that in patients who would otherwise be managed with observation and delayed surgical intervention, it is the ideal modality with which to follow the patient prior to repair (32). The use of magnetic resonance cholangiopancreatography (MRCP) has not been extensively investigated with respect to pediatric pancreatic injuries, but we have found it a valuable imaging technique.

Angiography and Interventional Radiology

Vascular imaging studies are useful when large vessel injuries, especially those of arteries, are suspected. While pediatric vascular injuries are rare, they are often subtle in presentation and can be difficult to repair. Blunt injury of the aorta is best evaluated with angiography. It is the standard to which other diagnostic tests are compared (7). Spiral or helical chest CT scans are useful screening or diagnostic studies, but if indeterminate, the surgeon should rely on arteriography for diagnosis.

A wide assortment of vascular injuries may be managed by the interventional radiologist’s use of endovascular transcatheter therapies. The intentional occlusion of a vessel using particulate matter is the current FDA-approved radiologic treatment for some vascular injuries. Using catheters as small as 2F or 3F, tiny vessels can be permanently occluded with a variety of microcoils, beads, or Gelfoam® Pharmacia and UpJohn Company, Michigan, U.S.A. Embolic therapy for vascular injuries in children should be considered when surgical control of the vessel or vessels would be difficult or impossible, and only expendable vessels would be permanently occluded. This technique should be considered “damage control angiography” (33). Vascular injuries of the head and neck, pelvis, liver, spleen, kidney, retroperitoneum, and extremities are all amenable to transcatheter embolic management (34–40).

In addition, interventional radiologic management of pancreatic injuries, intrathoracic fluid collections, and intra-abdominal infections is now widely accepted (41–43). This image-based approach to managing complex complications of trauma should be included in the armamentarium of the physician treating the injured child.

In summary, the radiologic study of the injured child is a vital component of the diagnostic evaluation that begins as the patient enters the trauma system. As imaging modalities improve with technical advancements, the ability to quickly diagnose injuries will likely keep pace.

REFERENCES


Transfusion Therapy in Injured Children

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INTRODUCTION

Historical Perspective

The beginnings of transfusion therapy may be traced to Harvey’s discovery of the systemic circulation in 1628. In 1667 Jean Baptiste Denis reported the transfusion of lamb’s blood to a 15-year-old boy. Lacking a full understanding of the implications of blood infusion, repeated deaths followed and transfusion was abandoned. The use of blood transfusion remained dormant for the next 150 years until James Blundell recognized that only human blood should be used for human transfusion. Yet, deaths continued to occur, most likely due to blood incompatibility and hemolytic transfusion reaction. In 1900, Karl Landsteiner determined the heterogeneity of blood and the importance of blood groups, a discovery for which he would later win the Nobel Prize. The integration of Landsteiner’s work in blood typing into effective therapy was limited by technical factors such as poor vascular access and frequent clotting of blood due to the lack of understanding of coagulation (1).

In the decades that followed, techniques for reliable venous access were improved and sodium citrate was discovered as an effective anticoagulant, permitting storage of blood until transfused. World War II served as a catalyst for further developments, leading to the concept of blood banking and blood service organizations to procure blood. The Viet Nam War led to integration of transfusion therapy into the acute care of injured patients. Resuscitation times decreased and operative intervention occurred earlier, relative to previous conflicts. Improvements in the treatment of wartime casualties were quickly incorporated into the management of civilian injuries.

The rapid expansion of transfusion therapy abruptly ended when it became apparent that blood components could transmit potentially fatal viral pathogens. Viral transmission associated with blood exposure prompted efforts at more effective screening of blood and highlighted the importance of the judicious use of blood products. In the 1980s red blood cell and component transfusion began to stabilize, in contrast to the exponential increase observed in the preceding decades. Approximately 10 million
red cell units were transfused in the United States in 1980, peaking at 12.2 million units in 1986, and subsequently declining to 11.4 million units in 1997 (2).

LITERATURE-BASED GUIDELINES

A computerized search of MEDLINE from 1990 to 2002 was performed and the following summarizes a review of the literature regarding the indications, results, and complications of transfusion therapy. Few randomized, controlled studies of transfusion practices have been conducted (class I) (3–7). The majority of studies represent class-II evidence (nonrandomized, controlled trials; controlled observational studies; or uncontrolled observational studies) and class-III evidence (expert opinion) developed in consensus conferences (8–13).

Approximately 22 million blood component units are currently transfused annually in the United States, with the major portion administered to surgical patients. At an average cost $150 per unit transfused, transfusion therapy is expensive. In the United States, approximately $2 billion is spent annually for blood transfusion; the cost actually may be as high as $7 billion per year if indirect costs due to inefficient transfusion practices and complications are included (12,14). The risk of a transfusion-related complication ranges from 1:100 for a minor allergic reaction to 1:30,000 for hepatitis C infection to 1:250,000 for a fatal acute hemolytic reaction (2).

The risks of transfusion therapy led to efforts to reduce and develop guidelines for its use. Like prior National Institute of Health (NIH) consensus conferences, the Blood Management Practice Guidelines Conference Group and the American Society of Anesthesiologists Task Force on Blood Component Therapy concluded that no single measure is capable of replacing clinical judgment regarding transfusion practices (8–12). With respect to red cell transfusion, there appears to be no single criterion for transfusion, such as a hemoglobin concentration of less than 10 mg/dL. Acknowledging that blood transfusion carries a documented risk for infection, adverse events, and potential immunologic effects, these groups recommend that blood transfusion should be kept to a minimum and that alternative blood substitutes be developed.

EPIDEMIOLOGY

An audit of blood component use in the United States showed that 11,107,000 red blood cell (RBC) units (42.8 units per 1000), 7,866,000 platelet units (16.5 units per 1000), and 2,621,000 fresh frozen plasma (FFP) units (10.1 units per 1000) were transfused in 1994 (15). The prevalence of transfusion therapy in injured children is less clear. In a review of children treated in the emergency department (ED) of a pediatric trauma center over a four-month period, 20 units of blood were transfused to 2 of 38 (5%) children suffering major trauma (14). Review of the National Pediatric Trauma Registry (NPTR, October 2000) demonstrates that, of the 39,681 children in the database, 3453 (0.9%) received blood component therapy. This low incidence of transfusion is likely due, in part, to the mild (ISS 1–9) to moderate (ISS 10–19) injury severity, which comprises 90% of the children within the NPTR.

Selected injured children with multiple injury or severe solid organ injury will require blood transfusion. In a population of severely injured children, ISS > 25, GCS < 7, immediate blood transfusion >20 mL/kg, and Pediatric Trauma Score < 4.
were all independent risk factors for death. The probability of death was 0.63 in those children with all threshold values (16). A review of 832 children with isolated splenic or liver injury treated in 32 pediatric surgical centers demonstrated that incidence of transfusion and laparotomy increased with the computed tomography (CT) grade of injury [transfused (%)/laparotomy(%)]: grade I – 1.8/0; grade II – 5.2/1; grade III – 10.1/2.7; and grade IV – 26.6/12.6 (17).

Nonoperative management is now the accepted treatment of solid organ injury in the hemodynamically stable child (17,18). The fear of excessive transfusion has led some to question this form of management. Using decision analysis, Feliciano concluded that the nonoperative management of splenic injuries was associated with an increased mortality from transfusion-related deaths (19). These concerns seem unfounded in children, since a number of studies demonstrate that the operative management of splenic and liver injuries is associated with a greater transfusion requirement than nonoperative management (20–22). Moreover, the tendency to transfuse children with solid organ injury appears to be declining (23). In a series of children treated over a six-year period with liver or splenic injury, Bond found that transfusion rates during the latter half of the study declined from 50% to 19% for hepatic injuries, despite increasing grade of injury, and 57% to 23% for splenic injuries with comparable injury grade (24). Similar trends have been observed in the management of injured adults (25).

Although children with multiple injuries appear to have a higher transfusion requirement, we found that the frequency of transfusion declined from 67% to 35% during the last decade in children with multiple intra-abdominal injuries (21,23). Isolated orthopedic injuries rarely require transfusion in children unless other injuries are present or they involve major disruption of the pelvic ring (26–28). In summary, while it appears that the need for transfusion in children is low, severely and multiply injured children are more likely to require blood component therapy.

PATHOPHYSIOLOGY

Hypovolemic shock due to acute blood loss is the most common form of shock observed in injured children. By definition, shock represents a state of inadequate tissue perfusion to maintain normal cellular and organ function. The maintenance or restoration of normal oxygen delivery (DO2) to tissues, not an arbitrary hemoglobin value, should be the primary therapeutic goal of red blood cell transfusion. The DO2 is defined as the product of blood flow (cardiac output) and arterial oxygen content (CaO2). At or near the critical DO2 point, two parameters that reflect tissue perfusion begin to change: (i) lactate level increases, and (ii) the oxygen extraction ratio (OER), defined as oxygen consumption/DO2, increases. Increases in the OER and lactate below the critical DO2 point represent a physiologic transfusion trigger (29).

Interventions to improve DO2 are directed to maximize carbon monoxide (CO) and O2 carrying capacity. In the setting of traumatic shock, cardiac output is optimized first by increasing preload with fluid resuscitation. Reducing afterload or supplementing cardiac contractility may become necessary if fluid resuscitation alone fails. If efforts to improve cardiac output are insufficient to improve DO2, then oxygen content may be targeted. Oxygen-carrying capacity depends on several variables [CaO2 = 1.36 × hemoglobin × saturation (%) + 0.0034 PaO2], but hemoglobin concentration is the principal determinant. An acute decrease in hemoglobin produces
a drop in DO$_2$ unless there is a compensatory increase in cardiac output (Fig. 1). A healthy individual may tolerate up to a 40% decrease in blood volume by increasing heart rate, redistributing fluid from the extravascular space to the intravascular space, reducing blood viscosity, and increasing oxygen extraction. Ensuring complete oxygen saturation with the augmentation of inspired oxygen is easily accomplished with the addition of supplemental oxygen. In general, the healthy patient can compensate as hemoglobin falls to 5 g/dL, but below this level compensatory responses begin to fail. They become inadequate at levels below 3.5 g/dL. The mortality rate exceeds 50% for hemoglobin concentration less than 3 g/dL (30). In the setting of refractory shock and maximized cardiac output, increasing the hemoglobin concentration with blood transfusion becomes necessary.

The actual utilization of oxygen by tissues is oxygen consumption. When oxygen consumption exceeds oxygen availability, anaerobic metabolism begins and lactate production increases. In hemorrhagic shock, reduced O$_2$-carrying capacity and blood volume contraction exist at the same time. Restoration of blood volume by crystalloid infusion can reestablish cardiac output. Current experience suggests that otherwise healthy patients with hemoglobin values of less than 10 g/dL rarely require transfusion. Studies in Jehovah’s Witness patients who refuse blood transfusion demonstrate that extremely low hemoglobin levels can be tolerated (31). In surgical patients who refuse blood, Carson found that no deaths occurred among patients with hemoglobin levels >6 g/dL and blood loss less than 500 mL (32).

The critical principle in the management of the trauma patient is the restoration of DO$_2$ and correction or avoidance of tissue hypoxia. The decision to augment DO$_2$ in the setting of hemorrhagic shock with the administration of blood depends upon the severity of preexisting blood loss, the degree of ongoing blood losses, and the individual’s compensatory ability to maintain the balance of DO$_2$ to consump-

**Figure 1** Changes in oxygen delivery (DO$_2$) with changes in hemoglobin (Hb) concentration and oxygen saturation (SaO$_2$). Note the effect of decreased SaO$_2$ on the need to increase cardiac output (CO) to maintain normal global DO$_2$. Correction of SaO$_2$ will measurably decrease CO. *Source: From Ref. 29.*
tion. The optimal transfusion trigger remains elusive, but healthy patients tolerate hemoglobin as low as 7 g/dL if adequately resuscitated and without ongoing blood loss. In a study of healthy volunteers, acute isovolemic reduction of hemoglobin to 5 g/dL results in increased heart rate, stroke volume, and cardiac index and a slight increase in oxygen consumption, but does not produce evidence of inadequate systemic DO$_2$ or increased lactate production (33). The same is true of euvolemic patients undergoing elective surgical procedures (32). In an elderly population undergoing surgical repair of hip fracture, a hemoglobin concentration of $>$8 g/dL had no apparent effect upon 30- or 90-day mortality (34). Together these studies demonstrate that in diverse populations of patients, low hemoglobin is well tolerated, even in patients undergoing surgery, if intravascular volume is maintained and cardiac function is satisfactory.

In the setting of trauma, the adequacy of resuscitation is guided by the restoration of normal vital signs and organ perfusion. The use of lactate measurements to detect inadequate tissue perfusion and, therefore, inadequate resuscitation is helpful in selected situations. Minimally invasive measures of tissue oxygenation, skeletal muscle oximetry, or gastric tonometry, as well as the more invasive techniques of central vascular monitoring, have been used in an attempt to identify the endpoints of resuscitation. Yet, no single parameter exists to define the optimal transfusion trigger, and the decision to transfuse must be made on a case-by-case basis.

**COMPONENT THERAPY**

At the time of collection blood is typically fractionated into its constitutive components of red blood cells, platelets, plasma, cryoprecipitate, and concentrated clotting factors. Component therapy allows the more efficient use of donated blood and avoids the undesirable effects of whole blood due to antibody–antigen reactions to platelets and white blood cells. For these reasons, whole blood is rarely transfused.

**Packed Red Blood Cells (PRBCs)**

Red blood cells are obtained by removing the supernatant plasma from 450 mL of whole blood after centrifugation and anticoagulation. The average volume of 1 unit of PRBCs is approximately 250 mL with a hematocrit of 60%. Small amounts of clotting factors and platelets are present but nonfunctional. Red blood cell infusion is indicated to increase RBC mass and therefore oxygen transport. Blood volume varies with age, ranging from 90 to 100 mL/kg in the premature infant to 70 mL/kg in children over one year of age. Therefore, blood should be administered in boluses of 10 mL/kg in infants and small children.

**Consensus Guidelines for Transfusion of Red Blood Cells**

1. The use of a single hemoglobin trigger for all patients and other approaches that fail to consider all-important physiologic and surgical factors affecting oxygenation are not recommended.
2. Transfusion is rarely indicated when hemoglobin is $>$10 g/dL but generally indicated when the hemoglobin is $<$6 g/dL when the anemia is acute.
3. The determination of whether intermediate hemoglobin concentrations (6–10 g/dL) justify or require RBC transfusion should be based on the patient’s risk for complications of inadequate oxygenation (9,12,13).
Washed Red Blood Cells

After the red blood cells have been separated they are washed with isotonic saline solution. This process removes nearly all white cells, platelets, plasma proteins, and debris. The resultant product significantly decreases antigenicity and non-hemolytic febrile reactions caused by recipient antibodies to leukocyte antigens. Washed red blood cells are reserved for patients suffering complications of previous transfusion because of the increased processing time and cost.

There appears to be a dose-dependent relationship between early blood transfusion and the later development of multiple organ failure (MOF) (35). Sauaia found that transfusion of greater than six units of PRBC within the first 12 hours post-injury is an independent risk factor for the development of MOF (36). The lipid fraction in the stored blood, which increases with storage time, has been implicated as a mechanism for this phenomenon (37). Zalen demonstrated that trauma patients were more likely to develop MOF if transfused blood is >14 or >21 days old (38).

Platelets

A unit of platelet concentrate is extracted from the platelet rich plasma of one unit of whole blood to yield $5 \times 10^{10}$ platelets in 60 mL of plasma. Platelets may be stored up to five days. The product will retain 70% of platelet viability and 80% of the original clotting factor activity. Platelet transfusion is indicated to correct clinically significant thrombocytopenia. Platelet concentrates contain white cells and may cause febrile reactions due to white cell antigens. However, since platelets are stored near room temperature, the risk of bacterial infection due to contamination should be considered. In children, transfusion of one unit of platelets per m$^2$ increases the platelet count 20,000, with an average platelet survival of six to seven days. The usual dosage is: less than 5 years = 1–3 units; 5–10 years = 4–5 units; and greater than 10 years = 6 units.

Consensus Guidelines for the Transfusion of Platelets

1. Surgical patients with microvascular bleeding usually require platelet transfusion if the platelet count is less than 50,000/mL and rarely require therapy if it is greater than 100,000/mL; with intermediate platelet counts the determination should be based on the patient’s risk for more significant bleeding.
2. Platelet transfusion may be indicated despite an apparently adequate platelet count if there is known platelet dysfunction and microvascular bleeding (10,12,13).

Fresh Frozen Plasma

When a unit of whole blood is fractionated the plasma components are frozen. Coagulation factors are present in the levels obtained from fresh whole blood. Storage at $-18^\circ$C preserves clotting factor activity. The time to prepare and thaw FFP for transfusion is 30 to 45 minutes. Unfortunately, FFP is often overused for ongoing bleeding when more specific or more effective therapy is available. The NIH Consensus Conference concluded that 90% of FFP is given for inappropriate indications (8). Microvascular bleeding in the trauma patient typically results from massive transfusion, thrombocytopenia, and/or consumption of fibrinogen, none
of which is readily corrected with FFP. The FFP transfusion should be reserved for the bleeding patient with a coagulation defect caused by liver disease, coumadin, or congenital factor deficiency. The FFP should never be used for volume expansion. The FFP carries the same risk of transfusion-transmitted disease as blood. In infants and small children FFP is administered in 10mL/kg boluses.

Consensus Guidelines for the Transfusion of Fresh Frozen Plasma

1. The urgent reversal of coumadin therapy
2. Correction of known coagulation factor deficiencies for which specific concentrates are unavailable
3. Correction of microvascular bleeding in the presence of elevated (>1.5 times normal) prothrombin time (PT) or partial thromboplastin time (PTT)
4. Correction of microvascular bleeding secondary to coagulation factor deficiency in patients transfused with more than one blood volume and when PT/PTT measurements cannot be obtained in a timely fashion
5. FFP is contraindicated for augmentation of plasma volume or albumin concentration (8,12,13).

Cryoprecipitate

Cryoprecipitate is prepared from individual donors and contains concentrated factor VIII, von Willebrand Factor (vWF), and fibrinogen. Freezing of plasma to −80°C and then rewarming to 4°C allows separation of the precipitate, which contains 200mg of fibrinogen, 150 units of factor VIII/vWF and 100 units of factor VIII. Since it is usually administered as a pooled product obtained from individual donors, cryoprecipitate carries the greatest risk of transfusion-transmitted disease. A typical adult dose (10 units) represents 10 donor exposures. Cryoprecipitate is the only concentrated form of fibrinogen and is therefore indicated for patients with dysfibrinogenemia, hypofibrinogenemia, or consumptive coagulopathy. In the past cryoprecipitate was used for patients with hemophilia A and von Willebrand disease but today specific factor replacement is available for these patients. Cryoprecipitate may also be used for fibrin glue, but commercial fibrin glue preparations are now available, which substantially reduce the risk of transfusion-transmitted disease.

Consensus Guidelines for the Transfusion of Cryoprecipitate

1. Correction of microvascular bleeding in massively transfused patients with fibrinogen concentrations less than 80–100 mg/dL or when fibrinogen concentrations cannot be measured in a timely fashion (12,13)

EMERGENCY MANAGEMENT

Acute Resuscitation

Hemorrhagic shock is the most common form of shock observed in injured children. Rapid identification and treatment of hemorrhagic shock is one of the core principles in the ABCs of trauma resuscitation. In a study of all trauma deaths occurring in the city and county of Denver, exsanguination was the second leading cause of acute (<48 hours) deaths (39). In the acute phase of resuscitation, the recognition of acute blood loss and shock is dependent upon an accurate assessment of clinical indices of organ function and perfusion. The American College of Surgeons Committee on
<table>
<thead>
<tr>
<th></th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood loss [blood volume (%)]</td>
<td>&lt;15%</td>
<td>15–30%</td>
<td>30–40%</td>
<td>&gt;40%</td>
</tr>
<tr>
<td>Clinical findings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart rate</td>
<td>&lt;100</td>
<td>&gt;100</td>
<td>&gt;120</td>
<td>&gt;140</td>
</tr>
<tr>
<td>Blood pressure</td>
<td>Normal</td>
<td>Normal</td>
<td>Hypotension</td>
<td>Severe hypotension</td>
</tr>
<tr>
<td>Respiration (tachypnea)</td>
<td>No</td>
<td>Mild</td>
<td>Moderate</td>
<td>Severe</td>
</tr>
<tr>
<td>Mentation</td>
<td>Anxious</td>
<td>Combative</td>
<td>Confused</td>
<td>Lethargic</td>
</tr>
<tr>
<td>Skin</td>
<td>Warm</td>
<td>Cool</td>
<td>Mottled</td>
<td>Pallor</td>
</tr>
<tr>
<td>Capillary refill (sec)</td>
<td>&lt;5</td>
<td>5–10</td>
<td>10–15</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Urine output</td>
<td>1–3 mL/kg</td>
<td>0.5–1 mL/kg</td>
<td>&lt;0.5 mL/kg</td>
<td>Negligible</td>
</tr>
<tr>
<td>Resuscitation</td>
<td>Rapid</td>
<td>Transient</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Vital signs</td>
<td>Return to normal</td>
<td>Improvement, then</td>
<td>Remain abnormal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>recurrent tachycardia,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>hypotension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blood preparation</td>
<td>Type and crossmatch</td>
<td>Type-specific</td>
<td>O-negative</td>
<td></td>
</tr>
<tr>
<td>Blood transfusion risk</td>
<td>Low</td>
<td>Moderate–high</td>
<td>Immediate</td>
<td></td>
</tr>
</tbody>
</table>

*Source:* Modified from Ref. 40.
Trauma has developed a useful classification of hemorrhagic shock based on systemic signs (Table 1) (40). Estimates of blood loss are based on parameters of cardiovascular, respiratory, central nervous system, and renal function. Furthermore, the response to initial fluid resuscitation suggests the degree of blood loss, the rate of ongoing bleeding, and the likelihood of the need for blood transfusion. A rapid response to fluid administration suggests minimal blood loss (class I) and a low probability of blood transfusion. A transient response suggests moderate and ongoing blood loss (classes II and III) and a moderate to high need for blood. If no response to initial fluid resuscitation is observed then severe blood loss (class IV) is likely and immediate transfusion is indicated.

If signs and symptoms of shock are present, a bolus of 20 mL/kg of crystalloid solution is rapidly administered and assessment repeated. If signs of shock continue another crystalloid bolus is given. External hemorrhage should be controlled with pressure and fractures splinted to reduce ongoing blood loss. Minimal or no response to crystalloid administration and the absence of obvious bleeding suggests internal hemorrhage. In this setting acute blood transfusion is indicated. O-negative or non–crossmatched-type PRBC’s are administered in 10–20 mL/kg boluses and preparation is made for prompt operative intervention to control further blood loss. The use of O-negative or non–crossmatched-type specific blood is equally safe for emergency volume resuscitation but should be reserved only for these situations. Fully crossmatched blood is associated with the lowest risk of unexpected hemolytic reactions, but generally requires 30 to 45 minutes to prepare. In life-threatening situations blood resuscitation should not be delayed while awaiting crossmatch. It must be kept in mind that the use of greater than one-half blood volume of O-negative blood complicates later crossmatching. If the patient is subsequently given type-specific blood there is a significant risk of hemolytic transfusion reaction. For this reason, the use of O-negative blood should be limited to less than 25% of the estimated blood volume. In situations when this is not possible, O-negative blood should be continued until the patient is stable.

**Massive Transfusion**

Selected patients will suffer near exsanguination and require massive transfusion until hemorrhage is controlled. The mortality in patients requiring massive transfusion following blunt trauma exceeds 50%. Half of these succumb within the first 24 hours (41). Long-term outcome in survivors appears excellent (42). Transfusion of greater than one blood volume within a 24-hour period is defined as massive transfusion and associated with a number of hematologic complications. The primary complication following transfusion to this degree is coagulopathy. As blood loss approaches 1.5 blood volumes, platelets and clotting factors become diluted. Platelet count decreases to approximately 40% from baseline with replacement of one blood volume, 60% with two blood volumes, and 70% with three blood volumes. Microvascular bleeding generally occurs at a platelet count <50,000/mL.

Clinically important dilution of clotting factors also occurs after replacement of 1.5 blood volumes. A PT or PTT value >1.8 times control is 96% specific for microvascular bleeding. Conversely, a PT <1.3 times control has a 94% predictive value for the absence of microvascular bleeding. The most sensitive predictors of microvascular bleeding are platelet count less than 50,000/mL and a fibrinogen less than 0.5 g/L (43). Microvascular bleeding in the setting of massive transfusion is most likely due to significant thrombocytopenia, clotting
factor dilution, and hypofibrinogenemia and is therefore an indication for platelet, factor, and fibrinogen replacement.

DEFINITIVE MANAGEMENT
Operative Intervention
Perhaps the most effective measure to limit blood transfusion therapy is the elimination of further bleeding by surgical intervention. Any child with suspected thoracic, abdominal, or vascular injury who is refractory to resuscitation should be taken promptly to the operating room. Given the success of nonoperative management of solid organ injury in children, one must be vigilant in recognizing the child who is continuing to bleed and requires operative therapy. In general, any child with a known solid organ injury in the abdomen who remains hemodynamically unstable despite adequate fluid resuscitation, or requires \( >1/2 \) blood volume replacement within the first 24 hours, has continuing bleeding and requires a laparotomy. Clinical variables in patients with splenic injury suggesting the need for surgical intervention include hypotension in the field or ED, tachycardia in the ED, initial hematocrit less than 30, multiple injuries, or the need for blood transfusion in the ED (44).

Once operative control is achieved, additional measures can be employed to reduce the need for blood transfusion. The use of fluid warmers, heated ventilatory circuits, and active warming devices reduce the risk of hypothermia and the coagulopathy associated with decreased body temperature. Further surgical measures and techniques like argon beam coagulation, collagen hemostatic agents, fibrin sealant, abdominal packing, vascular isolation, or arteriography with embolization have all been effectively employed in the management of surgical bleeding. The basis for deciding to transfuse the patient intraoperatively is less clear. Remember, elective surgical procedures have been safely performed in adults with severe anemia (hemoglobin \(<7\) g/dL) who refuse blood on religious grounds, provided normovolemia is maintained (34). The decision to transfuse should be based on an assessment of the patient’s condition, estimate of blood loss prior to surgical control, and ongoing blood loss.

Endpoints of Resuscitation
The conventional endpoints of resuscitation—return of normal heart rate, blood pressure, and urine output—may be all that are necessary in the previously healthy injured child with normal cardiopulmonary function. Base deficit (BD) and lactate appear to accurately reflect the hemodynamic and tissue perfusion changes associated with hemorrhagic shock. Increases in BD parallel oxygen transport parameters such as \( \alpha-\upsilon \) \( O_2 \) difference, \( DO_2 \), and oxygen consumption. Similarly, lactate levels and BD can be used to guide resuscitation (45,46). Injury survivors with moderate to severe BD improve their BD within four hours and normalize their BD by 16 hours. Non-survivors fail to improve their BD to \(-6\) or better, despite ongoing resuscitation (46). Moreover, transfusion requirements appear increased with more severe BD. In severely injured patients, transfusions were required within 24 hours of admission in 72% of patients with a BD \( \leq -6 \) versus 18% of patients with a BD \( \geq -6 \) (45).

Endpoints of resuscitation should not rely solely on BD or lactate level. Mikulascheck demonstrated that if treatment decisions were guided by BD or anion gap, incorrect treatment would occur in up to one-half of patients (47).
Persistent lactic acidosis suggests occult hypoperfusion. In a prospective study of trauma patients with two consecutive lactic acid levels >2.5 mmol/L who underwent invasive monitoring and resuscitation, Blow found a correlation between lactic acidosis and poor cardiac performance. Patients with persistent hypoperfusion despite resuscitative efforts demonstrated 43% mortality (48). The normalization of end organ and tissue perfusion as measured by serum lactate is perhaps the most reliable perfusion marker available (49).

**Recovery**

The recovery phase of injury until the time of discharge is the period when the greatest reduction in transfusion can be accomplished without compromising the patient. In the absence of ongoing blood loss, equilibration of the fluid compartments rarely produces significant changes in the hematocrit. Critically ill patients with hemoglobin concentrations less than 9 g/dL, randomized to a restrictive strategy in which transfusion was administered only for hemoglobin less than 7 g/dL or to a liberal transfusion strategy in which hemoglobin concentrations were maintained greater than 10 g/dL, demonstrated that a restrictive strategy of red cell transfusion results in a lower 30-day mortality in patients who are <55 years of age, less acutely ill, and without significant cardiac disease (7).

During the recovery period the decision to transfuse should be made only on the basis of symptoms or signs of ischemia. In general, children are not at risk for myocardial ischemia and rarely manifest signs of anemia (dyspnea, fatigue, and tachycardia). Blood draws should be minimized or eliminated, particularly if the patient is afebrile, asymptomatic, and tolerating a diet. In children with isolated splenic injury, Shafi found that after an initial drop in hematocrit within the first 24 hours post-injury, the hematocrit remained stable and returned to baseline by day six (23).

**COMPLICATIONS OF TRANSFUSION**

**Transfusion Reaction**

Transfusion reactions may be broadly classified into nonhemolytic and hemolytic reactions. Nonhemolytic reactions are common (1:100) and occur as the result of an allergic reaction to white blood cells or plasma proteins. In general, nonhemolytic reactions are mild, causing only fever, urticaria, and skin rash. In rare instances, life-threatening severe bronchospasm and anaphylaxis can occur. If a nonhemolytic transfusion reaction is suspected, the transfusion should be discontinued and the symptoms managed with antihistamines, epinephrine, and steroids, as indicated.

Hemolytic transfusion reactions may be acute or delayed. Hemolysis occurs when recipient antibodies react with donor red blood cell antigens. Delayed reactions (1:1000) result from antibodies to the transfused blood that arose from prior transfusion or isoimmunization from pregnancy and were not detected by routine antibody assay. Fatal acute hemolytic reactions (1:250,000–1:1,000,000) are caused by ABO incompatibility and most often result from either clerical or administration errors. Delayed hemolytic transfusion reactions (1:260,000) should also be considered serious and potentially life threatening. They accounted for 10% of all transfusion deaths between 1976 and 1985 (2). A hemolytic transfusion reaction is characterized
by the rapid onset of fever, chills, rigors, chest or abdominal pain progressing to respiratory distress, and circulatory shock. Hemoglobin is present in the plasma and urine. Renal failure may ensue. Once recognized, the transfusion should immediately be discontinued. Aggressive resuscitation should be instituted to support the circulation and achieve a urine output of >60 mL/hr.

Transfusion-Transmitted Disease

Viral infection, the most feared complication, is the most common cause of late death from transfusion (Table 2). The first descriptions of transfusion-associated HIV infection occurred in late 1982. Improved screening and detection has reduced the current frequency of HIV infection to approximately to 1/250,000–1/2,000,000 units. The most common serious viral infection is hepatitis C (HCV), estimated to occur in 1/30,000–1/150,000 units. Eighty-five percent of posttransfusion HCV infections become chronic, 20% of infected patients develop cirrhosis, and 1% progress to hepatocellular carcinoma. Hepatitis B (HBV) infection is estimated to occur in 1/30,000–1/250,000 units. In 1975 new screening tests were implemented, reducing transfusion-transmitted HBV infection. The HBV now accounts for only 10% of all cases of posttransfusion hepatitis. Acute disease develops in 35% of persons infected with HBV. Up to 10% will develop chronic infection.

Bacterial infection due to contamination most often occurs following platelet transfusion (1/12,000 units), but can also occur following RBC transfusion (1/500,00 units). The difference in frequency is attributed to storage of platelets at 20–24°C, which facilitate bacterial growth, while red blood cells are generally stored at much lower temperatures. The most common organism associated with RBC contamination is Yersinia enterocolitica, while Staphylococcus aureus, Klebsiella pneumoniae, Serratia marcescens, and S. epidermidis infections are most frequently observed in platelet-associated infection (2).

Metabolic Complications

Children may be more susceptible than adults to metabolic complications with rapid transfusion because of the higher ratio of transfused blood-to-blood volume.

Table 2 Estimated Risks of Transfusion per Unit in the United States (1999)

<table>
<thead>
<tr>
<th>Event</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Febrile reaction</td>
<td>1:100</td>
</tr>
<tr>
<td>Bacterial contamination</td>
<td></td>
</tr>
<tr>
<td>Platelets</td>
<td>1:12,000</td>
</tr>
<tr>
<td>Red blood cells</td>
<td>1:500,000</td>
</tr>
<tr>
<td>Viral infection</td>
<td></td>
</tr>
<tr>
<td>Hepatitis A</td>
<td>1:1,000,000</td>
</tr>
<tr>
<td>Hepatitis B</td>
<td>1:30,000–1:250,000</td>
</tr>
<tr>
<td>Hepatitis C</td>
<td>1:30,000–1:150,000</td>
</tr>
<tr>
<td>HIV</td>
<td>1:200,000–1:2,000,000</td>
</tr>
<tr>
<td>Delayed hemolytic transfusion reaction</td>
<td>1:1000</td>
</tr>
<tr>
<td>Fatal hemolytic transfusion reaction</td>
<td>1:250,000–1:1,000,000</td>
</tr>
</tbody>
</table>

Source: Adapted from Ref. 2.
Children are prone to hypothermia and may become profoundly hypothermic with the infusion of cold fluids and blood products. Hypothermia not only increases metabolic demand but also worsens coagulopathy. Infants and small children should be maintained in a warm environment and given warmed fluids and blood products. Rapid infusion can also produce severe electrolyte disturbances. Hypocalcemia or hyperkalemia may arise after large- or rapid-volume infusion and, therefore, serum electrolytes should be periodically evaluated.

**RED BLOOD CELL SUBSTITUTES**

Due to the risks and costs of blood transfusion, efforts have been directed toward the development of hemoglobin-based red cell substitutes. Red cell substitutes do not transmit viral pathogens and have lower viscosities than blood while maintaining the same-oxygen carrying capacity of allogenic blood. Free hemoglobin has an extremely high oxygen affinity that renders it ineffective for tissue oxygenation. Furthermore, once outside the protective red cell membrane the hemoglobin tetramer disassociates into its component \( \alpha \) and \( \beta \) dimers, which are potentially nephrotoxic. Polymerization of bovine, human, and recombinant hemoglobin results in synthetic hemoglobin with a \( P_{50} \) of natural hemoglobin, a plasma half-life up to 30 hours, and normal oncotic pressure (50). The absence of a red cell membrane eliminates the need for blood typing and crossmatching, as well as the immunologic effects attributed to surface antigens or white blood cells, platelets, and debris present in red blood cell units.

One unit (500 mL) of synthetic, polymerized, stroma-free hemoglobin (Poly SFH-P) is characterized by hemoglobin concentration of 10 g/dL, \( P_{50} \) of 28–30 torr and t\(_{1/2}\) of one day. A phase-II trial of Poly SFH-P demonstrated its safe use in acute trauma (51). A prospective, randomized trial of Poly SFH-P in trauma patients demonstrated that the use of a red blood cell substitute for the treatment of acute blood loss reduced the need for red blood cell transfusion, while maintaining parameters of oxygen transport (4). The most recent trial of Poly SFH-P confirms the ability of red blood cell substitutes to maintain oxygen-carrying capacity in the setting of acute hemorrhagic shock, even with transfusion requirements up to 20 units (52). Mortality (25%) was substantially lowered at critical hemoglobin levels \( \leq 3 \) g/dL relative to historic controls (64.5%) who refused red blood cells on religious grounds. Remarkably 9/12 patients who sustained lethal blood loss (RBC Hb \( \leq 1 \) g/dL) survived with the administration of Poly SFH-P and resultant total hemoglobin concentration (RBC Hb + Poly SFH-P) 7–10 g/dL.

Although these results are encouraging, the abrupt end of the diaspirin cross-linked hemoglobin (DCLHb) trial suggests that the various red blood substitutes under development are not homogenous. Unlike the Poly SFH-P trials, a phase-II trial of DCLHb administration was associated with a 72% increase in morbidity (Multiple Organ Dysfunction Score) and a threefold fold increase in mortality in the treatment group (46%) relative to the control group (17%) (53). It is speculated that selected red blood substitutes (e.g., DCLHb) bind nitric oxide, which causes the undesirable side effects of vasoconstriction and pulmonary hypertension. Nevertheless, efforts to develop a safe and effective red cell substitute continue given the advantages of a readily available, oxygen-carrying, resuscitative fluid that eliminates the delay and risks of allogenic blood.
REFERENCES

10
Pediatric ICU Management

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ICU CARE

Trauma continues to be the leading cause of death in the first several decades of life. Those surviving an accident but suffering from significant trauma will frequently need intensive care. The criteria for intensive care unit (ICU) admission will vary from institution to institution, but some commonality can be suggested. Those with multi-system trauma or hemodynamic instability will benefit from intensive care. Others with a Pediatric Trauma Score of seven or less; isolated but significant head trauma and an altered mental status; liver, or splenic lacerations of grade III or greater; significant pancreatic injuries, multiple orthopedic injuries; and injuries, that may not be readily cared for on the ward because of local institutional factors may best be cared for initially in the ICU.

MONITORING

Basic monitoring is required for all pediatric trauma patients in the ICU. This includes measurement of vital signs: determination of heart rate and respiratory rate, continuous electrocardiography, noninvasive blood pressure determination, and temperature measurement. According to recent pediatric literature, pulse oximetry should be considered a fifth vital sign, and capnography should also be included for intubated patients (1).

Cardiovascular Monitoring

Usually, noninvasive blood pressure monitoring is utilized in the pediatric population. Noninvasive monitoring in the child may be quite accurate if the proper cuff size is utilized. The American Heart Association has set guidelines for proper cuff fit. They recommend a cuff whose width is 40% of the circumference at the midpoint of the limb or 20% greater than the diameter of the extremity (2). The attending trauma team must also be aware of the age-related norms for blood pressures (Table 1).
In most modern pediatric intensive care units (PICU), automated arterial blood pressure devices are utilized. These units measure heart rate and systolic, diastolic, and mean arterial blood pressure. Pitfalls of noninvasive monitoring include:

1. Diastolic pressures tend to be slightly higher with the noninvasive devices.
2. Dysrhythmias and wide variations in blood pressure over a short time frame may be missed.

Access for invasive blood pressure monitoring may be accomplished in all children. This is performed either through percutaneous arterial cannulation or by arterial cutdown. The usual site in children is the radial artery. However, in an emergent situation in a crowded trauma bay, the ICU, or operating room the quickest access may be percutaneous cannulation of the femoral artery (3). After stabilization in the PICU the arterial site may be changed to the radial artery. Pitfalls of invasive monitoring include limb ischemia (femoral artery), cannula compression, and kinking or clot formation. It is therefore wise to correlate invasive with noninvasive monitoring in the critically ill trauma patient. Benefits of invasive monitoring include continuous direct waveform display of the arterial blood pressure and access for arterial blood sampling for blood gases.

Electrocardiography (ECG) monitors the heart rate and rhythm of cardiac conduction. Rhythm disturbances associated with trauma may include atrial tachycardia, ventricular tachycardia (subarachnoid hemorrhage), persistent sinus bradycardia (cerebral hypoxia/arrest at the scene/airway obstruction/tracheal disruption/increased intracranial pressure secondary to head trauma/hypothermia due to cold exposure), and sinus tachycardia (hypovolemic shock). Also, many teenage trauma patients have taken drugs that alter the ECG: tricyclic antidepressants, cocaine, opiates, and amphetamines.

**Oxygen Saturation**

Pulse oximetry is currently being advocated as an accurate, simple, and noninvasive method of measuring the oxygen saturation of arterial blood. It is based on the spectrophotometry of oxygenated hemoglobin, which absorbs infrared light at the 940 nm wavelength and transmits red light at the 660 nm wavelength. The pulse oximetry probe has two light-emitting diodes that pass light at these wavelengths through the perfused tissue to a photodetector on the other side. The photodiode then compares the amount of infrared, red, and ambient light that reaches it and calculates the oxygen saturation (SaO2) (2). A small sensor (probe) is placed on the finger, toe, earlobe, forehead, or any convenient place. Most devices demonstrate the SaO2 as well as pulse rate continuously.

The pulse oximeter has been demonstrated to reflect moderate hypoxia (SaO2 < 89%) before an increase in ventilatory drive is demonstrated (1). This, as well as its noninvasive, continuous monitoring of the SaO2, has made it a critical tool in the management of critically ill patients.

**Table 1 Abnormal Vital Signs**

<table>
<thead>
<tr>
<th></th>
<th>RR</th>
<th>Pulse</th>
<th>BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infant</td>
<td>&gt;40</td>
<td>&gt;160</td>
<td>&lt;60</td>
</tr>
<tr>
<td>Toddler</td>
<td>&gt;30</td>
<td>&gt;140</td>
<td>&lt;75</td>
</tr>
<tr>
<td>School age</td>
<td>&gt;25</td>
<td>&gt;120</td>
<td>&lt;85</td>
</tr>
<tr>
<td>Adolescent</td>
<td>&gt;20</td>
<td>&gt;110</td>
<td>&lt;90</td>
</tr>
</tbody>
</table>

In most modern pediatric intensive care units (PICU), automated arterial blood pressure devices are utilized. These units measure heart rate and systolic, diastolic, and mean arterial blood pressure. Pitfalls of noninvasive monitoring include:

1. Diastolic pressures tend to be slightly higher with the noninvasive devices.
2. Dysrhythmias and wide variations in blood pressure over a short time frame may be missed.

Access for invasive blood pressure monitoring may be accomplished in all children. This is performed either through percutaneous arterial cannulation or by arterial cutdown. The usual site in children is the radial artery. However, in an emergent situation in a crowded trauma bay, the ICU, or operating room the quickest access may be percutaneous cannulation of the femoral artery (3). After stabilization in the PICU the arterial site may be changed to the radial artery. Pitfalls of invasive monitoring include limb ischemia (femoral artery), cannula compression, and kinking or clot formation. It is therefore wise to correlate invasive with noninvasive monitoring in the critically ill trauma patient. Benefits of invasive monitoring include continuous direct waveform display of the arterial blood pressure and access for arterial blood sampling for blood gases.

Electrocardiography (ECG) monitors the heart rate and rhythm of cardiac conduction. Rhythm disturbances associated with trauma may include atrial tachycardia, ventricular tachycardia (subarachnoid hemorrhage), persistent sinus bradycardia (cerebral hypoxia/arrest at the scene/airway obstruction/tracheal disruption/increased intracranial pressure secondary to head trauma/hypothermia due to cold exposure), and sinus tachycardia (hypovolemic shock). Also, many teenage trauma patients have taken drugs that alter the ECG: tricyclic antidepressants, cocaine, opiates, and amphetamines.

**Oxygen Saturation**

Pulse oximetry is currently being advocated as an accurate, simple, and noninvasive method of measuring the oxygen saturation of arterial blood. It is based on the spectrophotometry of oxygenated hemoglobin, which absorbs infrared light at the 940 nm wavelength and transmits red light at the 660 nm wavelength. The pulse oximetry probe has two light-emitting diodes that pass light at these wavelengths through the perfused tissue to a photodetector on the other side. The photodiode then compares the amount of infrared, red, and ambient light that reaches it and calculates the oxygen saturation (SaO2) (2). A small sensor (probe) is placed on the finger, toe, earlobe, forehead, or any convenient place. Most devices demonstrate the SaO2 as well as pulse rate continuously.

The pulse oximeter has been demonstrated to reflect moderate hypoxia (SaO2 < 89%) before an increase in ventilatory drive is demonstrated (1). This, as well as its noninvasive, continuous monitoring of the SaO2, has made it a critical tool in the management of critically ill patients.
component of PICU monitoring in the pediatric trauma patient. It provides a continuous reflection of hemoglobin saturation and provides the trauma surgeon with knowledge that sufficient oxygen is being delivered to the injured tissues.

A disadvantage of pulse oximetry has been decreased accuracy at low saturations (defined as $\text{SaO}_2 < 70–75\%$). New generations of pulse oximeters perform better without deterioration of performance at saturations $<75\%$. However, it is still recommended that frequent measurements of $\text{PaO}_2$ should be done at lower saturations (4). If the oxygen saturation is below 70% on multiple pulse oximeter determinations then the arterial blood should be sampled because the true oxygen saturation is usually underestimated by most oximeters. Other disadvantages of some pulse oximeter models include motion artifact, placement of sensor below blood pressure cuff, and poor tissue perfusion of a distal extremity (3,5).

When elevations of carboxyhemoglobin (COHb) are seen in the setting of carbon monoxide (CO) poisoning, the pulse oximetry reading remains in the normal range, despite markedly reduced actual oxygenated hemoglobin ($\text{O}_2\text{Hb}$). This is because COHb does not absorb light at the infrared wavelength (940 nm), while it does transmit red light (wavelength 640 nm). As a result, the pulse oximeter cannot differentiate between the COHb and $\text{O}_2\text{Hb}$ at the red wavelength, and the combined value is applied to the calculation of the oxygen saturation. As a result, the pulse oximeter overestimates the actual oxyhemoglobin saturation ($\text{SaO}_2$) so that it is unreliable in patients with CO poisoning (6).

Ventilation

End tidal carbon dioxide (EtCO₂) monitoring, known as capnometry, is a noninvasive method for measuring the $\text{PaCO}_2$ in expired gas. Similar to pulse oximetry-measuring devices, the exhaled gas passing through a sampling chamber, which has an infrared light source on one side and a photodetector on the other, measures the carbon dioxide ($\text{CO}_2$). $\text{CO}_2$ absorbs light at the infrared wavelength (940 nm). The $\text{CO}_2$ present in the expired gas may be calculated from the amount of infrared light that reaches the photodetector. EtCO₂ is a reflection of alveolar ventilation, metabolic rate, and the pulmonary circulation. It also may be helpful in transport of the injured patient to and from the PICU for early detection of endotracheal tube dislodgment (7). It is currently recommended by several sources, including the American Academy of Pediatrics, that all children who are intubated and being transported have an EtCO₂ (8).

MANAGEMENT OF PICU TRANSFUSIONS

In the unstable trauma patient, hemoglobin and hematocrit should be measured every four hours and one hour after every transfusion until vital signs stabilize and urine output is adequate. To restore blood volume and $\text{O}_2$-carrying capacity to a pediatric trauma patient that has lost a large volume of blood, it is essential to transfuse one unit quickly in larger children (>25 kg) or 10–15 mL/kg of blood in smaller children. Packed red blood cells are the product of choice for patients with moderate acute blood loss. For severe hemorrhage, plasma substitutes are required when packed red blood cells are transfused to compensate for dilution of coagulation proteins.

Massive transfusions that involve replacing an amount of blood equal to the patient’s blood volume in 24 hours involve several risks. These include citrate toxicity, electrolyte imbalance, and decreased release of oxygen to the tissues resulting
from decreased 2,3 disphosglycerate content, pulmonary microembolism, decreased core temperature, and thrombocytopenia/disseminated intravascular coagulation (DIC). The total blood volume in a child is approximately 75 mL/kg. If this amount of blood has been given to a child in a 24-hour period or less then early treatment of the side effects of massive transfusion should be initiated. For every blood volume lost, it is often necessary to administer fresh frozen plasma (20 mL/kg), sodium bicarbonate (1–3 meq/kg if pH <7.3), calcium chloride 10% (10–20 mg/kg if ionized calcium <2), and platelets (platelet count <50,000/uL). In children, 0.1 unit of platelet concentrate/kg usually increases the platelets an increment of 40,000/uL (3,9). Transfusion pumps equipped with warming units should be used when large amounts of blood and crystalloid are transfused to decrease the incidence of hypothermia. In addition, most PICU beds have thermal blankets and external warming sources to minimize heat loss.

NUTRITION

Although gastric and colonic motility may be impaired for several days after trauma or stress, small intestinal motility and absorptive function remain intact. A prospective, randomized study by Moore and Jones demonstrated that enterally fed patients had fewer complications after major abdominal trauma than patients receiving total parenteral nutrition (10). A recent study by Jackson, et al. demonstrated that early enteral feeding in PICU patients was feasible, well tolerated, and cost-effective without the risk of aspiration or abdominal distension. Bedside nasal jejunal tubes were passed and caloric requirements were met within 48 hours in most patients (11,12). Placement of the tubes may be checked by portable kidney, ureter, and bladder (KUB) films and, if passage is difficult, may be performed under fluoroscopic guidance with minimal sedation in the fluoroscopy suite. In conclusion, elemental feedings should be initiated early in the pediatric trauma patient and are preferred over parenteral nutrition. If full enteral feeds are not tolerated then parenteral nutrition should be instituted to meet the caloric needs of the patient, and a small amount of jejunal feeds can be continued to maintain gut integrity.

COMMONLY USED MEDICATIONS

Table 2 shows the commonly used medications.

ACUTE RESPIRATORY FAILURE

Acute lung injury leading to respiratory insufficiency is a frequent complication found in the trauma patient. Its etiology is varied and includes atelectasis, aspiration, infection, the acute respiratory distress syndrome (ARDS) as well as others. Of these ARDS has the most potential for significant morbidity and mortality. Therapy may be as simple as supplying oxygen and pulmonary physiotherapy or as complicated as providing extracorporeal life support (ECLS). The pulmonary injury preceding ARDS may be direct (pulmonary contusion and smoke inhalation) or indirect (shock and sepsis). It is important to understand the differences in both their effects as well as how each can be best treated.
Pathophysiology

In an early description Asbaugh et al. termed the clinical picture of progressive hypoxemia, tachypnea, and generalized patchy pulmonary infiltrates, in the absence of cardiac failure ARDS (13). These signs and symptoms are usually presented within one to four days of the original inciting event. This clinical entity describes a final common pathway with definable lung pathology from a wide spectrum of significant injuries. Early beliefs were that ARDS results in a disseminated and homogeneous pulmonary process, as suggested by conventional chest X rays (CXR) (Fig. 1). It has since been shown with computed tomography (CT) that this is not so (Fig. 2) (14,15). CT scans in patients with ARDS reveal the presence of atelectasis and edema in the more dependent portions of the lungs. This is felt to be due to compression of lung tissue. Nondependent portions of the lungs have an increase in edema but are well aerated and thus receive an inordinate amount of the minute ventilation. This is because gases all flow via the path of least resistance. As the syndrome progresses, so does the opacification on CXR.Gattionni et al. showed that as little as one third of the lung is actually ventilated and called this condition “baby lung” (16). Mechanical ventilation in this clinical setting leads to regional over-distension of nondependent lung, reduces capillary perfusion, increases pulmonary dead space, and exacerbates the already present ventilation perfusion mismatch.

It has also been shown that mechanical ventilation itself can lead to lung injury (17,18). Initially termed barotrauma, this injury may more appropriately be due to volutrauma. Webb and Tierney have also shown that regional over-distension of alveoli with mechanical ventilation leads to injury (19). This is most closely associated with high peak inspiratory pressures, greater than 40 cm H2O, and repeated opening and closing of collapsed alveoli. This alveolar over-distension leads to stress failure of alveolar capillary membranes, which leads to increased microvascular permeability and edema. Although the evidence is circumstantial, it is felt that this volutrauma
on top of the existing ARDS significantly complicates the syndrome. A recent multicenter study showed a significant difference in mortality and ventilator days when lung protective strategies (tidal volume <6 cc/kg and plateau pressures <30 cm H₂O) were used (20).

**Etiology**

Two groups of patients with ARDS are differentiated by the etiology of their pulmonary disease. A primary lung insult such as pneumonia may lead to a reduction in lung but not chest wall compliance. Here, consolidation is the main pathology. These patients are less responsive to lung recruitment measures such as positive end expiratory pressure (PEEP) and prone positioning. These patients are more susceptible to regional

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**Figure 1** Chest X ray CXR showing diffuse bilateral pulmonary infiltrates.

**Figure 2** CT scan showing the inhomogeneity of ARDS.
hyperinflation so that peak pressures must be watched very closely. Indirect causes of ARDS, such as trauma and sepsis, lead to secondary lung injury. These patients have a reduction in both their lung and chest wall compliance. The major pathologic findings are interstitial edema and alveolar collapse. These patients are usually more responsive to PEEP and prone positioning. If not careful, however, these measures may put them at risk for hemodynamic instability.

**Diagnosis**

Making the diagnosis of ARDS is not usually difficult if one considers it in those patients who have suffered significant trauma or develop sepsis or pneumonia following trauma. Physicians do not universally agree on all of the necessary findings but there are some commonalities. The American European Consensus Conference attempted to simplify this and includes:

1. an acute onset,
2. a \( \text{PaO}_2 / \text{fraction of expired oxygen (FiO}_2) < 300 \)
3. bilateral pulmonary infiltrates on CXR,
4. pulmonary capillary wedge pressure (PCWP) < 18 mmHg or no clinical evidence of left atrial hypertension (21).

**Clinical Course**

There is a series of phases in the course of ARDS. The initial phase is characterized by tachypnea and dyspnea with hypocarbia from hyperventilation. The partial pressure of oxygen (\( \text{pO}_2 \)) is usually normal. Microscopically there is neutrophil sequestration and platelet aggregation within the pulmonary vasculature. Within 12 to 24 hours progressive hypoxemia and worsening respiratory symptoms develop. A chest X ray will show bilateral infiltrates. There is worsening endothelial injury and increased permeability with leaky capillaries. Neutrophils marginate to the interstitium, where there is already an abnormally high protein content. Damage to the alveolar epithelial integrity continues and fluid floods the alveolar space. There is continued fibrin and platelet aggregation and worsening microvascular occlusion. At this point the clinical entity is still reversible if the initiating factors are discovered, treated, and eliminated. The next phase occurs if there are repeated or sustained insults. This takes place over the next several days. Respiratory failure continues with an increase in the ventilation perfusion mismatch and intrapulmonary shunting. Hypoxemia is now more severe and less responsive to increases in FiO\(_2\). This necessitates increased ventilation support in the face of worsening pulmonary compliance. Continued infiltration with neutrophils and now mononuclear cells, lymphocytes, and fibroblasts worsen the interstitial milieu. Surfactant destruction occurs as well as further alveolar collapse. Macrophages release monokines, which activate other inflammatory cells, thus worsening the entire picture. The final phase is more chronic in nature. There is a worsening pulmonary fibrosis, and with recurrent pneumonias, lung compliance and gas exchange fail to improve. The usual endpoint is significant morbidity if not mortality.

**Management**

There is no specific therapy for ARDS. Most measures are directed towards support of the patient’s respiratory status as well as the treatment of any underlying problems, such as pneumonia and sepsis. In the past most respiratory therapies were directed
toward normalization of blood gases. Today, most critical care physicians attempt to achieve adequate gas exchange and prevent further lung injury, which may assist with lung healing. Mechanical ventilation is probably the most important supportive therapy in treating patients with ARDS. Criteria for its utilization include hypoxemia unresponsive to supplemental O₂ and the need to recruit atelectatic alveoli. On occasion continuous positive airway pressure (CPAP) will be adequate; however, there are several limitations with this type of assistance. It requires a very tight-fitting mask and a very cooperative patient. If the amount of pressure required exceeds 10 cm H₂O, then the success rate is not high.

**Oxygenation**

Once a patient requires mechanical ventilation, manipulating the FiO₂ and the positive end-expiratory pressure is used in an attempt to treat hypoxemia. Increasing the FiO₂ does not always work. This is especially true when there is significant shunting within the lungs. In this situation utilizing PEEP may be beneficial. It may be used to recruit atelectatic alveoli, increase functional residual capacity, decrease the shunt fraction, increase the volume of ventilated parenchyma, redistribute alveolar edema, and decrease diffusion distances (22). The PEEP is only supportive, however, and is not therapeutic. Its prophylactic use probably does not change the course of ARDS. It does not decrease the amount of alveolar edema and at high levels >10–12 cm H₂O it may be detrimental. It increases mean airway pressure and intrathoracic pressure and decreases venous return, which may lead to a decrease in cardiac output. It may also impact intracranial pressure as well as hepatic and renal perfusion. These complications are rare if PEEP is kept below 10 cm H₂O. If higher levels of PEEP are necessary then the use of a Swan–Ganz catheter or oximetric pulmonary artery catheter should be considered. The best level of PEEP can be calculated from static pressure volume curves (Fig. 3) (23). Looking at the lower and higher inflection points facilitates setting both the best PEEP and peak inspiratory pressures. This limits overdistension on inspiration and alveolar collapse on expiration, which may prevent the alveolar stretch injury associated with repeated opening and closing of alveoli with inflation and deflation.

![Figure 3](image-url)  
*Figure 3* An inflation pressure versus volume curve showing the upper (peak inspiratory pressure point) and lower (ideal PEEP) inflection points.
Ventilation

In the past, average volumes of 10–15 cc/kg were used in attempts to adequately ventilate patients. More recently evidence suggests that this is more than is really necessary (20). Six to ten cc/kg may be adequate. Much of the consolidated lung will not ventilate, so the portions of lung that can be ventilated are actually overstretched and damaged. We attempt to keep our peak inspiratory pressures <40. In some trauma patients (indirect lung injury) it is the chest wall that may be noncompliant. If this is the case then higher pressures may be better tolerated and necessary. The ability to maintain gas exchange is often difficult while staying within airway pressure and tidal volume guidelines. The question to ask is whether to change the guidelines or gas exchange expectations. Normocapnia may not be possible and it may be necessary to accept higher levels of partial pressure exerted by CO2 in mmHg (pCO2). This idea of permissive hypercapnia is not new. Sudden elevations in pCO2, however, are also detrimental and result in cardiac depression, increases in intracranial pressure, and may worsen intracellular acidosis. An absolute endpoint is uncertain but a pH as low as 7.2 seems to be well tolerated. This often requires heavy sedation and even paralysis.

Ventilation Modes

The two common modes of ventilation are based on airway pressure and tidal volume, respectively. Each has advantages and disadvantages. Pressure control allows for rapid variable flow and provides peak inspiratory pressure throughout the entirety of the inspiratory time. Volume control allows for a constant tidal volume and minute ventilation regardless of the changes in pulmonary compliance. There are some new modes that allow for a combination of both and also allow for changes breath to breath. Pressure-regulated volume control is one that sets a target tidal volume and inspiratory time and allows the ventilator to adjust the flow rate. Waveform and peak inspiratory pressure vary from breath to breath as pulmonary compliance, resistance, and patient cooperation change. This is our preferred method of ventilation in the more critical patients with ARDS.

High-frequency ventilation allows for continual high airway pressures, very low tidal volumes, and very fast rates. Gas exchange occurs via Brownian motion. These modes are helpful as trials when other modes fail, as well as in cases of persistent pneumothoraces or chronic bronchopleural fistulas. Their efficacy in the pediatric patient with ARDS has not been shown.

Prone Positioning

Prone positioning was tried first by Brian 25 years ago and seems to be quite popular in Europe (24). The idea is to reduce ventilation perfusion inequality by redistributing blood flow from unventilated areas of lung to those with a more normal ventilation-perfusion ratio (V/Q) match. It may also recruit previously atelectatic lung areas. The patient is rotated from the supine to the prone position on a schedule whose time interval varies from institution to institution from every hour to once a day. Patient repositioning is labor-intensive and this effort must be monitored closely. Pressure points must be protected and the most common complication is dislodgement of lines and endotracheal tubes, which can be a serious problem if the patient has just been placed in the prone position.
Nitric Oxide

Nitric oxide (NO), initially named endothelium-derived relaxing factor, has been shown to dilate pulmonary arteries and has been used extensively in treating pulmonary hypertension. Its use in ARDS is based on two principles. First is the treatment of pulmonary hypertension, and the second is to direct blood flow towards ventilated alveoli, thus decreasing the ventilation perfusion mismatch. Initially, studies by Roissant et al. showed an improvement in oxygenation, reduced pulmonary artery pressure, and reduced shunt fraction (25). It appears though the ideal dose range is between 1 and 10 ppm (26). Its use is well tolerated and the adverse reactions are few and limited. Papazian demonstrated a beneficial effect of inhaled NO when combined with prone positioning (27). Each modality increased the PaO₂/FiO₂, but the highest change was found when the two were combined.

Partial Liquid Ventilation

Perfluorocarbons have been investigated for years due to their significant affinity for oxygen. Recently, they have been used clinically in treating ARDS in both Phase 2 and 3 trials. Perflubron is one such chemical that has low viscosity, low surface tension, high density, and a high oxygen solubility and CO₂-carrying ability. Partial liquid ventilation is a technique where a volume of chemical equal to the functional residual capacity of a patient is used in combination with conventional ventilation. The perfluorocarbon’s high density assists its ability to collect in the dependent portions of the lung, which are poorly ventilated. With this characteristic it has been shown to displace alveolar transudate within the dependent consolidated lung, thus recruiting alveoli. Exudate is then lavaged out of the lung, clearing cellular debris and mucous plugs. The most recent multicenter trial looking at its use in ARDS in adults has closed and the data are not yet available.

Steroids

Corticosteroids have been shown to modulate a number of mediators, which participate in the inflammatory cascade that is a component of ARDS. Most agree that their use in the early phases of ARDS has no benefit. We believe, however, that their efficacy in the later fibroproliferative phase of ARDS has still not been answered. Meduri et al. has shown positive effects of their use in those who have failed to respond to conventional ventilation after seven days (28).

Extracorporeal Membrane Oxygenation (ECMO)

When all of the above interventional modalities fail to show improvement in patients with ARDS, their survival has most likely been reduced to 20% to 30%. A trial of ECMO is warranted in this instance and some would argue that it should be considered sooner rather that later. The survival as reported by the Extracorporeal Life Support Organization is between 50% and 60% in, pediatric patients with respiratory failure (29). In short, ECMO supports the patient’s pulmonary function (venovenous) or pulmonary and cardiac function (venoarterial) in hopes that lung rest and healing can take place. It is not in the scope of this chapter to explain in detail the intricacies of ECMO, which can be found in one of the textbooks written on this subject (30).
REFERENCES


Nutritional Support for the Pediatric Trauma Patient

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INTRODUCTION

Trauma is accompanied by a set of metabolic aberrations that are profound but predictable. Over 65 years ago Sir David Cuthbertson described the fundamental aspects of this metabolic response to injury in adults (1). Although the metabolic sequelae of trauma in children qualitatively resemble those of adults, marked quantitative differences exist.

An understanding of the metabolic events that accompany trauma is the first step in nutritional support therapy. An individualized determination of nutrient requirements must be made and an appropriate route of delivery selected. Nutritional support of the injured child should be instituted promptly and be designed to limit the deleterious consequences of structural protein loss while facilitating wound healing and the immune response.

THE METABOLIC RESPONSE TO TRAUMA

During the period immediately following severe injury, aggressive fluid, electrolyte, and blood replacement is often required for survival. This period is termed the “ebb phase” of the metabolic response to trauma and is characterized by a decrease in cardiac output and a reduction in metabolic rate. Once the patient has been adequately resuscitated, the “flow phase” of injury is entered. The metabolic response during the flow phase is summarized in Figure 1 and consists of an increase in net muscle protein breakdown and the enhanced movement of amino acids through the circulation. This provides the amino acids needed for the rapid synthesis of proteins for the inflammatory response and tissue repair. Those amino acids not used for protein synthesis are channeled through the liver to create glucose from their carbon skeletons by gluconeogenesis. Glucose requirements are effectively met by this mechanism. In a coupled hepatic process the amino portions of the amino acids are cleaved and detoxified by the urea cycle. There is a marked rise in the circulation of hepatically derived acute-phase proteins (i.e., C-reactive protein, fibrinogen,
haptoglobin, alpha-1 antitrypsin, and alpha-1 acid glycoprotein) and a concomitant decrease in hepatically derived nutrient transport proteins such as albumin and retinol-binding protein.

The metabolic response to major trauma is associated with a consistent hormonal and cytokine profile regardless of the specific pattern of injury. Traumatized patients demonstrate a very transient decrease in insulin concentrations followed by a persistent elevation. Despite higher insulin levels, which, in theory, should promote anabolism, accelerated net protein breakdown continues. This may be explained, in part, by the elevated concentrations of the catabolic hormones (glucagon, catecholamines, and cortisol) found during the period of acute injury. Increases in the cytokines interleukin-6 (IL-6) and tumor necrosis factor, both of which are released by activated macrophages, also occur. IL-6 levels are correlated with increased protein turnover, protein catabolism and the synthesis of acute phase proteins, and increased mortality.
(2,3). The release of IL-2, IL-8, gamma interferon, and many growth factors is also known to augment the immunologic and hormonal response to injury. The catabolism of skeletal muscle to generate the amino acids needed for wound healing and to produce glucose for energy production is an excellent short-term adaptation in children. However, it cannot be sustained for long periods due to the lack of body protein stores. The progressive loss of skeletal muscle protein leads to respiratory compromise, cardiac dysfunction, increased susceptibility to infection and, ultimately, increased mortality (4). Hence minimizing the protein loss associated with trauma is of major clinical importance.

**METABOLIC RESERVES**

The most striking difference in body composition between the healthy adult and the healthy child is the quantity of protein available in times of injury. As a percentage of body weight the protein stores of adults are twice those of neonates (Table 1). Lipid stores are also decreased in children compared to adults, while carbohydrate reserves are constant across age groups. Not only do neonates and children have reduced stores, they have much higher baseline requirements. The resting energy expenditure for neonates is up to three times that for adults, and protein requirements may be 3.5 times the requirement for adults (8). Thus, critically ill children are more susceptible to the deleterious effects of protracted catabolic stress. The prompt institution of nutritional support, as soon as the patient has been adequately resuscitated, is prudent. In general, any child with significant trauma who will not be eating adequately within three days should be considered for nutritional support.

**NUTRITIONAL NEEDS**

Once a decision has been made to commence nutritional support in the injured child an accurate individualized determination of nutrient requirements is needed. This assessment should include estimates of protein, total energy, carbohydrate, lipid, electrolyte, and micronutrient needs.

**Protein Requirements**

Amino acids are the key building blocks required for growth and tissue repair. The vast majority of amino acids reside in proteins, with the remainder being in the free amino acid pool. Proteins themselves are not static as they are continually degraded and synthesized in a process termed “protein turnover.” The reutilization of amino acids released from protein breakdown is extensive. Protein turnover contributes to

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The Body Composition of Neonates, Children, and Non-obese Adults as a Percent of Total Body Weight</th>
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<tr>
<td>Age</td>
<td>Protein (%)</td>
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<td>Neonates</td>
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</tr>
<tr>
<td>Children (age 10 years)</td>
<td>15</td>
</tr>
<tr>
<td>Adults</td>
<td>18</td>
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*Source: Based upon the data of Refs. 5–7.*
protein synthesis more than twice the amount of amino acids derived from protein intake. In traumatized children, such as those with severe burn injury, or in ill children with cardiorespiratory failure requiring extracorporeal membrane oxygenation (ECMO), protein turnover is twice that of normal children (9). Generally, in severe illness amino acids are redistributed away from skeletal muscle to injured tissues, cells involved in the inflammatory response, and the liver. Acutely needed enzymes, serum proteins, and glucose (by way of gluconeogenesis) are thus synthesized. A salient advantage of high-protein turnover is that it allows for the immediate synthesis of proteins needed for the inflammatory response and tissue repair. The process does require energy, hence either an increase in resting energy expenditure or a redistribution of energy normally used for growth is required. Although critically ill children demonstrate both an increase in whole-body protein degradation and whole-body synthesis, it is the former that predominates. Thus, these patients manifest net negative protein balance, which clinically may be noted by weight loss and skeletal muscle wasting.

The catabolism of skeletal muscle to generate glucose is necessary as glucose is the preferred energy source for the brain, red blood cells, and renal medulla. Illness enhances gluconeogenesis in adults, children, and neonates. On a per kilogram body weight basis, gluconeogenesis seems to be particularly elevated in very small children (presumably because of their relatively large brain-to-body-weight ratio) (10). Interestingly, the provision of dietary glucose is relatively ineffective in quelling endogenous glucose production in the stressed state (11).

Without elimination of the inciting stress for catabolism, the progressive loss of diaphragmatic and intercostal muscle as well as cardiac muscle may cause cardiopulmonary failure. Fortunately, amino acid supplementation does improve protein balance. The mechanism for this change in ill patients appears to be an increase in protein synthesis with little change in protein degradation (12).

The amount of protein required to optimally enhance protein accretion is higher in unwell than in healthy children. Infants demonstrate 25% higher protein degradation after surgery, 100% increase in urinary nitrogen excretion with bacterial sepsis, and 100% increase in protein breakdown if they are ill enough to require ECMO (9). The provision of dietary protein sufficient to optimize protein synthesis, facilitate wound healing and the inflammatory response, as well as to preserve skeletal muscle protein mass, is the single most important nutritional intervention in injured children. The quantity of protein (or amino acid solution) administered in critical illness should be 2–3 g/kg/day for infants up to the age of one year and 1.5 g/kg/day for older children. Certain severely stressed states (i.e., severe burn injury) may require additional protein supplementation (2.0–2.5 g/kg/day). Excessive protein administration should be avoided because toxicity, particularly in patients with marginal renal and hepatic function, is possible. Even relatively well neonates fed protein allotments of 6 g/kg/day have developed azotemia, pyrexia, a higher incidence of strabismus, and lower IQ (13,14).

Two important issues regarding the protein metabolism of critically ill children remain to be elucidated. At present there is no specific recommendation possible regarding any special amino acid composition that may be of specific benefit to severely injured children (15). The use of enteral glutamine supplementation (with and without other “immune enhancing” nutrients such as arginine, omega-3 fatty acids, and nucleotides) has been used in an effort to limit septic complications associated with trauma. However, this approach remains investigational and larger-scale studies are needed (16,17). Similarly, quelling the extreme protein catabolism found
in children with major injuries utilizing hormonal modulation, particularly insulin administration, is also being actively investigated (18).

Energy Requirements

A careful appraisal of energy requirements in critically ill children is required as both too much and too little energy may have potentially deleterious consequences. Inadequate caloric intake will result in poor protein retention, especially if protein administration is marginal. In contradistinction, the provision of excess glucose calories in critically ill patients results in increased carbon dioxide (CO₂) production rates (hence exacerbating ventilatory failure) and a possible paradoxical increase in net protein degradation (15,19).

The severity and duration of the illness or injury governs the energy needs of critically ill patients. Recent data suggest that energy needs are far less than previously thought for most types of trauma. The resting energy expenditure in the flow phase of injury is increased by 50% in children with severe burns. However, it returns to normal during convalescence (20). If illness increases work of breathing, such as in neonates with bronchopulmonary dysplasia, a persistent elevation in energy expenditure up to 25% over expected values is evident (21). Newborns undergoing major operations have only a transient 20% increase in energy expenditure that returns to baseline levels within 12 hours and remains at baseline unless major complications develop (22,23). Adequate anesthetic and analgesic management also plays a significant role in muting the stress response, as evidenced by neonates undergoing patent ductus arteriosus (PDA) ligation who do not manifest any discernable increase in resting energy expenditure postoperatively with fentanyl anesthesia and subsequent intravenous analgesia (24). Adult intensive care unit patients also do not have an elevation of resting energy expenditure over expected values (25). Head injury produces a variable elevation in resting energy expenditure, presumably due to a marked rise in circulating catecholamines. Again patients who are sedated, in phenobarbitol coma, or have been given neuromuscular relaxants manifest no such elevation in energy expenditure (26).

Total energy requirements include resting energy expenditure, energy needed for physical activity, and diet-induced thermogenesis. Resting energy expenditure itself includes the caloric requirement for growth. Although critically ill children have increased protein turnover, their growth is often halted during extreme physiologic stress. Additionally, levels of physical activity are typically low following severe injury. The mean energy expenditures of critically ill neonates on ECMO were found to be nearly identical to age- and diet-matched, non-stressed controls (27). The critically ill cohort did, however, have a greater variability in energy expenditure (27). Further, a surfeit of calories in critically ill neonates does not necessarily result in improved protein accretion (15). Thus, for practical purposes the recommended dietary caloric intake for healthy children affords a reasonable starting point for critically injured patients (28). Table 2 outlines safe caloric provisions for injured children at various ages. Enterally fed traumatized children, as a rule, require a further 10% increment in calories due to obligate malabsorption. In any injured child with protracted illness the actual measurement of resting energy expenditure, by portable indirect calorimetry, is advised due to the high-interindividual variability in energy expenditure. Predictive equations used in conjunction with stress factors to account for degree of illness have been shown to be inaccurate in determining individual energy expenditures in intensive care unit patients and are not recommended (25).
Once protein needs have been met, both carbohydrate and lipid energy sources have similar beneficial effects on net protein synthesis in ill patients (29). A rational partitioning of these energy-yielding substrates is predicated upon the knowledge of carbohydrate and lipid utilization in trauma.

**Carbohydrate Requirements**

Glucose production and availability is a priority in ill children. Injured and septic adults have a threefold increase in glucose turnover and oxidation and an elevation in gluconeogenesis (30,31). An important feature of the metabolic stress response is that the provision of dietary glucose does not halt gluconeogenesis; consequently, the catabolism of muscle proteins continues (11). It is clear, however, that a combination of glucose and amino acids effectively improves protein balance in illness primarily by augmenting protein synthesis (32).

In early nutritional support regimens for surgical patients, glucose and amino acid formulations with minimal lipid (the minimum needed to obviate fatty acid deficiency) were often utilized. Energy allotments well over normal dietary requirements were also often given. The excess glucose was converted to fat, resulting in a net generation of CO2. The synthesis of fat from glucose has a respiratory quotient (RQ), defined as the ratio of CO2 produced to O2 consumed, of about 0.87. In clinical situations, this high RQ is not attained, as glucose is never purely used for fatty acid synthesis. Nonetheless, the provision of excess glucose results in an elevated RQ increasing the ventilatory burden for the child. The mean RQ in postsurgical neonates fed a high glucose diet is approximately 1.0, while comparable neonates fed with less glucose, and lipids at 4.0 g/kg/day, have an RQ of 0.83 (29). In contrast to glucose metabolism, excess lipids are merely stored as triglycerides and do not result in an augmentation of CO2 production. Utilizing high glucose total parenteral nutrition, hypermetabolic adult patients fed excess caloric allotments have a 30% increase in O2 consumption, a 57% rise in CO2 production, and 71% elevation in minute ventilation (19). Thus, avoidance of overfeeding and the utilization of a mixed fuel system of nutrition employing both glucose and lipids to yield energy is theoretically and practically useful in stressed patients, many of who also have respiratory failure. Such an approach also often obviates problems with hyperglycemia in the relatively insulin-resistant ill child.

**Lipid Requirements**

Lipid metabolism, like protein and carbohydrate metabolism, is generally accelerated by illness and trauma (32). Initially, during the brief ebb phase following...
trauma or in early septic shock, lipid utilization is compromised and triglyceride levels rise as the metabolism of intravenously administered lipids falls. In the flow phase of the injury response, adult patients demonstrate lipid turnover rates that are two- to fourfold higher than comparable controls and proportionate to the degree of injury (33,34). The increased lipid turnover after injury involves the cycling of free fatty acids and glycerol into the synthesis and hydrolysis of triglycerides. Both metabolic processes result in a stream of substrates through the plasma pool that may be reflected in a modest elevation in the resting metabolic rate. Approximately 30% to 40% of the released fatty acids are oxidized for energy, which results in RQ values post-injury in the vicinity of 0.8. This suggests that free fatty acids are, in fact, the prime source of energy in trauma patients. When subjected to uncomplicated abdominal surgery, infants and children have a reduction in RQ and a decline in plasma triglycerides, implying an increased oxidation of free fatty acids (35). The glycerol, released along with the free fatty acids from triglycerides, may be converted to pyruvate that is then, in turn, utilized as a glucose precursor. As with other catabolic processes in illness and trauma, the provision of dietary glucose does not decrease glycerol clearance nor diminish lipid recycling.

Normal ketone body metabolism is markedly altered by severe injury. Acetyl coenzyme A (CoA) is the product of incomplete fatty acid and pyruvate oxidation, which through a condensation reaction within the hepatocyte forms the ketone bodies acetoacetate and B-hydroxybutyrate. In starved healthy subjects, a major adaptation to preserve skeletal muscle mass is the use of ketone bodies generated by the liver as an energy source for the brain (which cannot directly oxidize free fatty acids). However, in the three-day period following trauma there is a negligible elevation in serum ketone body levels when compared to healthy fasting subjects (36). This observation may be understood in light of serum insulin levels, as ketogenesis is inhibited by even low concentrations of the hormone, a phenomenon evident to physicians in the absence of ketotic problems in type II diabetes. Hence, the high insulin concentrations seen in severe injury ablate the ketotic adaptation to starvation.

The energy needs of the injured patient are met largely by the mobilization and oxidation of free fatty acids. However, ill children have limited lipid stores. Thus, they may evolve biochemical essential fatty acid deficiency within one week if administered a fat free diet (37,38). In infants, linoleic and linolenic acid are considered essential, with arachidonic acid and docosahexaenoic acid deemed as possibly, conditionally essential. When there is a lack of dietary linoleic acid, the formation of arachidonic acid (a tetraene) by desaturation and chain elongation cannot occur and the same pathway entrains available to oleic acid to form 5,8,11-eicosatrienoic acid (a triene). A triene-to-tetraene ratio of greater than 0.4 suggests essential fatty acid deficiency. The clinical syndrome consists of dermatitis, alopecia, thrombocytopenia, susceptibility to bacterial infection, and failure to thrive (37,38). To obviate essential fatty acid deficiency in injured children, a sufficient allotment of linoleic acid and linolenic acid is recommended.

The parenteral provision of commercially available lipid solutions to traumatized children obviates the risk of essential fatty acid deficiency and results in improved protein utilization without significantly increasing carbon dioxide production or metabolic rate (39). These advantages are balanced by some potential risks of excess administration: hypertriglyceridemia, increased infections, and decreased alveolar oxygen diffusion capacity (40–42). Although the evidence is far from conclusive, the possible adverse effects of lipid administration have resulted in most centers
starting lipid supplementation in ill children at 0.5 gm/kg/day, and advancing over a period of days to 2–4 gm/kg/day, while closely monitoring triglyceride levels. Lipid administration is usually restricted to a maximum of 30% to 40% of total calories, although this practice has not been validated by clinical trials.

**Electrolyte Requirements**

Electrolyte requirements ($Na^+, K^+, Cl^-, HCO_3^-, Ca^{2+}$) must be evaluated frequently in the critically injured patient. Simultaneous serum and urine electrolyte determinations often yield information regarding the renal conservation of particular salts. In addition to routine electrolyte monitoring, careful attention to phosphate and magnesium levels is needed as hypophosphatemia may lead to thrombocytopenia and respiratory muscle dysfunction, while magnesium deficiency can cause cardiac arrhythmias. Renal failure will result in the retention of phosphate, so nutritional allotments must be reduced accordingly. Frequently, head injured patients have an iatrogenically induced respiratory alkalosis. If a metabolic alkalosis is also present due to active diuresis or gastric suction, Cl$^-$ administration should be used to correct the alkalosis. Alkalemia tends to inhibit respiratory effort, drive potassium into cells, and decrease ionized calcium by increasing the affinity of albumin for calcium. Metabolic acidosis is sometimes present in traumatized children with hypotension or ischemic injuries. The provision of acetate instead of Cl$^-$ in the parenteral nutrition solution may combat this metabolic problem. The provision of excess acetate at 1 milliequivalent/kg over 24 hours is usually a safe adjunct to other measures to limit metabolic acidosis.

**Vitamin and Trace Mineral Requirements**

Vitamin and trace mineral metabolism in injured pediatric patients has not been well studied. For the neonate and child, the fat-soluble vitamins A, D, E, and K, as well as the water-soluble vitamins ascorbic acid, thiamine, riboflavin, pyridoxine, niacin, pantothenate, biotin, folate, and vitamin B$_{12}$ are all required and are routinely administered. Since vitamins are not stoichiometrically consumed in biochemical reactions but rather act as catalysts, the administration of large supplements of vitamins in stressed states is not logical.

The trace minerals that are required for normal development are zinc, iron, copper, selenium, manganese, iodide, molybdenum, and chromium. Trace minerals are usually used in the synthesis of the active sites of an ubiquitous and extraordinarily important class of enzymes called metalloenzymes. Like vitamins, metalloenzymes act as catalysts. Hence, unless there are excessive losses such as enhanced zinc loss with severe diarrhea, large nutritional requirements would not be anticipated in illness. The vitamin and trace mineral needs of healthy children and neonates are well defined in the literature (28). These levels have been used in traumatized patients, and little evidence exists that they are nutritionally inadequate. In children with severe hepatic failure, copper and manganese accumulation occurs; thus, parenteral trace mineral supplementation should be limited to once per week.

The pharmacologic use of vitamins and trace minerals in pediatric illness is controversial. Reviews of both vitamin and trace mineral toxicity clearly demonstrate that excessive dosage is a health risk (43,44).
ROUTES OF NUTRIENT PROVISION

In the traumatized child the enteral route of nutrient provision is preferable to the parenteral route whenever the gastrointestinal tract is functional. Enteral nutrition is physiologic, safer, and cheaper (45). If there is a concern regarding aspiration, the use of post-pyloric feeding tubes placed at the bedside or by interventional radiology is a very useful adjunct to the nutritional management of the injured child. Continuous feedings using standard 1 kcal/mL formulas can adequately nourish the majority of patients. Carefully controlling the enteral infusion rate and avoiding bolus feeding until tolerance is established usually obviate diarrhea. If diarrhea persists stool cultures are sent for routine pathogens and Clostridium difficile toxin. At the time of extubation, feeds are held for a period of 6 to 12 hours. It is also our policy not to feed patients enterally who are hypotensive or have evidence of bowel obstruction in order to limit the risk of spontaneous small bowel necrosis associated with rapid enteral feeding (46).

If the gastrointestinal tract is not functional and parenteral nutrition is necessary, central venous access is sought so that concentrated solutions that obviate fluid overload can be safely administered. Percutaneously placed intravenous lines that are threaded centrally are the preferred means of administration. Central access may be placed at the bedside in most intensive care unit patients. Groin lines are not favored for nutritional therapy, because of their propensity for infection. Once gastrointestinal activity has been reestablished the patient can usually be converted to enteral nutrition within a two- to three-day time period.

SUMMARY

Injured children are particularly susceptible to the loss of lean body mass and its attendant increased morbidity and mortality. Critical illness results in increased protein, carbohydrate, and lipid utilization and net negative protein balance. The judicious administration of carbohydrates, lipids, vitamins, trace minerals, and particularly protein, preferably through an enteral route, can optimize wound healing and reduce or even eliminate the consequences of this catabolic response.

REFERENCES

Anesthesia for Pediatric Trauma

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INTRODUCTION

The role of anesthesia in pediatric trauma extends far beyond the operating room to include the emergency department, the radiology suite, the intensive care unit, and the acute pain service. In an ideal world, pediatric anesthesiologists are readily available to provide any or all of these services at any time. However, only a minority of children are treated at specialized pediatric trauma centers where these services exist (1). This makes it imperative that all physicians and surgeons involved in the care of children be familiar with the salient considerations for the successful management of the airway and anesthetic in the traumatized child.

The essential elements in the successful management of trauma include the diagnosis and treatment of primary injuries and the avoidance of secondary injury. Early recognition of primary injuries with rapid control of the airway and replacement of the circulating blood volume remain the cornerstones for a successful resuscitation of the pediatric trauma victim. Secondary injuries, which result from hypoxia and hypotension, are important determinants of morbidity and mortality after trauma, particularly in the presence of trauma to the head (2).

Successful treatment of the traumatized child requires a thorough knowledge of the anatomical and physiological features that distinguish children from adults. These differences diverge as the age difference increases, with neonates presenting the greatest clinical challenge. This chapter provides a practical review of the airway and anesthetic management of the traumatized child.

AIRWAY MANAGEMENT

The principles of airway management include optimization of gas exchange and protection of the airway. To achieve these principles, the airway requires protection from aspiration of blood, gastric contents, and foreign bodies. The following delineates a management strategy to achieve these principles.
Anatomic and Physiologic Considerations

Developmental changes in the anatomy of the upper airway are most dramatic in children in the first eight years of life. At birth, a number of unique features of the airway may complicate its management. Neonates and infants have large head–body ratios, manifested primarily through a relatively large occiput. The large occiput naturally raises the head into the “sniffing” position, a position that facilitates direct laryngoscopy and intubation. The epiglottis in the neonate is long and floppy, a feature that necessitates lifting the epiglottis in order to view the laryngeal inlet (3).

The high compliance of the chest wall in neonates and infants may be attributed to the soft, non-calcified ribs. The ribs articulate with the vertebrae and sternum at right angles, resulting in “bucket-handle” chest wall excursions that are less efficient than those in adults and increase the work of breathing. The diaphragm is the major respiratory muscle in infants, as the intercostal muscles are poorly developed. The diaphragm is oriented horizontally and cephalad, reducing its mechanical advantage, and contains fewer fast oxidative (type I) muscle fibers than in adults, so that fatigue and respiratory failure occur earlier in infants (3). Excursion and efficiency of the diaphragm may be further compromised if large volumes of air are swallowed and gastric distension ensues. To resolve this problem, an orogastric or nasogastric tube should be inserted to decompress the stomach. The greater compliance of the chest wall and paucity of elastin in the alveolar walls in neonates increases the closing capacity of the lungs compared with adults. The greater alveolar ventilation to fractional residual capacity (FRC) ratio in neonates (5:1) compared with adults (1.5:1) may be attributed to the greater metabolic rate in neonates (4–6 mL/kg of oxygen per minute) than in adults (2–3 mL/kg of oxygen per minute) (3). Together these differences in compliance and metabolic rate may contribute to intrapulmonary shunting, rapid hemoglobin oxygen desaturation, and hypoxia in the apneic infant.

Physiological and anatomical changes continue during the first few years of childhood. Neonates and infants two to six months of age are obligate nasal breathers. As full term infants mature beyond six months of age, they gradually convert from nasal to mouth breathing, particularly in the presence of airway obstruction. In contrast, preterm infants remain obligate nasal breathers well beyond six months of age. Blood, mucus, or nasogastric tubes present in the nasal passages may significantly obstruct airflow and lead to hypoxia in obligate nasal breathers. Nasal intubation may traumatize enlarged adenoids in children, resulting in blood or lymphoid tissue that contaminate the oropharynx or tracheal tube. Tonsillar enlargement may obstruct the airway and/or limit visualization of the larynx, although this is usually limited to children greater than two years of age. A history of snoring in an otherwise healthy child should alert the physician to the possibility of enlarged adenoids or tonsils.

The state of the dentition should be carefully inspected before instrumenting the airway. Facial trauma may dislodge or loosen teeth. Laryngoscopy can also traumatize the teeth, both directly and indirectly. Sustained pressure to the alveolar ridge of the maxilla may result in defects in mineralization of the primary teeth. However, transient pressure on the alveolar ridge, which is the most common clinical scenario, has not been associated with maldevelopment of secondary dentition (3).

Management of the Pediatric Airway

All anesthetic equipment should be inspected and operational before the child arrives in the operating room/trauma room. A working source of oxygen and airway
suction, as well as backup supplies, should be available. The oxygen source should have high flow capabilities (15 L/min for maximum oxygen delivery) and include a self-inflating bag-valve-mask device in both pediatric and adult sizes. Both sizes of bags are required as low-volume bag devices deliver inadequate tidal volumes to infants with reduced lung compliance and limit the inspiratory phase in children with atelectasis (4).

A full range of sizes of oropharyngeal and nasopharyngeal airways, masks, laryngoscopes, tracheal tubes, and stylets should be immediately available, together with ancillary equipment to manage the difficult airway or a failed intubation. Oropharyngeal and nasopharyngeal airways may be employed as temporary measures to relieve airway obstruction before tracheal intubation. It is crucial to select the appropriate sized airway, as an airway that is either too small or too large may obstruct the laryngeal inlet by downfolding the epiglottis or displacing the tongue caudally. The size of the oral airway may be estimated by the distance between the angle of the mandible and the lips. Similarly, the distance from the tip of the nose to the tragus of the ear may estimate the size of a nasopharyngeal airway.

The choice of laryngoscope blade for intubation depends on the child’s age. A straight blade, usually a Wisconsin or Miller 0–1 blade, is recommended for neonates, infants, and children up to four years, and a Miller 2 blade for ages four to eight years. Other straight blades, such as the Wis–Hippe, Flagg, and Robertshaw, have a wider flange, which allows greater control of the tongue in toddlers and young children (5). These blades displace the tongue to the left and lift the epiglottis, thereby exposing the larynx. A curved MacIntosh blade may be used for older children (>6 years), in whom the laryngeal inlet may be visualized by lifting the tongue.

Several methods are available for estimating the appropriate size for an uncuffed tracheal tube in children (Table 1). A 3.0 [internal diameter (ID) in mm] tube should be used in term neonates up to the age of three months, a 3.5 tube up to the age of nine months, and a 4.0 tube 9 to 18 months of age. Thereafter, the following formula may be used:

\[
\text{ID size (mm)} = \left[ \frac{\text{Age (yr)}}{4} \right] + 4 (\text{or } 4.5)
\]

The diameter of the distal phalanx of the fifth digit and the diameter of the external nares have also been used to guide tube size, since they approximate the diameter of the cricoid ring (6). Tracheal tubes one-half size larger and smaller than

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<td><strong>Age</strong></td>
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^Fiberoptic bronchoscope.
that selected according to the above guidelines must be available. A tube of the appropriate size should pass through the cricoid ring without resistance, i.e., force should never be applied to insert the tube beyond the cords. If force is not used, the presence of an audible leak during inspiration is not required. Conversely, if a large leak is present at peak airway pressures, a larger tube should be used to ensure adequate alveolar ventilation.

Cuffed tracheal tubes are increasingly popular, replacing uncuffed tubes in infants and children. Uncuffed tracheal tubes have been the standard in children less than eight years of age because the external tube diameter fits the internal lumen of the cricoid ring, the narrowest part of the neonatal airway. The shift in practice from uncuffed to cuffed tubes can be expected to decrease the frequency of multiple intubations (as a result of too large a leak around the tube) and the incidence of inadequate alveolar ventilation (7). Although it is commonly held that cuffed tracheal tubes protect the airway from aspiration, this notion has been challenged (8). The cuffed tube that corresponds to the correctly sized uncuffed tube is 0.5 mm ID smaller than the latter. The following formula may also be used (7):

\[
\text{ID size}(\text{mm}) = \left[ \frac{\text{Age (yr)}}{4} \right] + 3
\]

Although a smaller ID may compromise ventilation in the spontaneously breathing child, most traumatized children are mechanically ventilated. In children six to eight years of age and older, cuffed tubes are routinely used. The integrity of the cuff should always be tested before tracheal intubation. After intubation, the cuff should be inflated until there is no audible leak at a peak inspiratory pressure of 20 cm H\textsubscript{2}O or no leak according to the flow-volume loop. The polyvinyl chloride tracheal tubes currently in use are high-volume–low-pressure cuffs that are designed to minimize tracheal ischemic injury. Nonetheless, overinflation of the cuff could lead to mucosal ischemia and subglottic stenosis, or if positioned immediately below the glottic opening, recurrent laryngeal nerve injury (9). The cuff should be deflated and reinflated periodically to preclude cuff overinflation.

The position of the tube within the trachea may be estimated by several techniques. For uncuffed tubes less than 5 mm ID, the tip of the tube lies at mid-tracheal level when the thick black line that lies 2–3 cm from the distal tip is aligned at the vocal cords. For children greater than two years of age, the following formula estimates the appropriate length of an oral tube at the central incisors:

\[
\text{Length (cm)} = \left[ \frac{\text{Age (yr)}}{2} \right] + 12
\]

If a nasal tube is used, the required length is 2–3 cm longer than that recommended by the above formula. The tube position should be confirmed by auscultation of the chest and lungs and chest X ray. For the chest X ray, the tip of the tube should lie at the T2 level.

Although nasotracheal intubation may be discouraged as the first-line mode of intubation in the emergency room, it is the preferred mode for transport of children with instrumented airways and for management in the pediatric intensive care units. Nasally placed tubes are less likely to be dislodged during transport and are better tolerated during prolonged mechanical ventilation in children. To minimize the risk of airway trauma during nasal intubation, immersing the distal 2–3 cm of the tubes into hot sterile water for a brief period should soften the tips of these tubes.
Airway Control

The first priority of trauma management is to assess the integrity of the airway. In the conscious child, the ability to vocalize and answer questions confirms a patent airway and also provides an indication of the child’s neurological status. In the unconscious child, the airway must be assessed quickly. Supplemental oxygen should be administered by mask, using a self-inflating bag-valve-mask device with an oxygen flow of 15 L/min. A pulse oximeter on a digit or toe will provide a reliable indication of hemoglobin oxygen saturation, providing the limb is adequately perfused. Alternative sites for the oximeter in infants and young children include the cheek, tongue, and ear.

Abnormal breath sounds, such as gurgling, snoring, or stridor, and the use of accessory muscles, the presence of a tracheal tug, and a paradoxical “see-saw” pattern of breathing are indicative of partial upper airway obstruction. The absence of any audible sounds may indicate complete airway obstruction or a patent airway. An obstructed airway should be managed by applying anterior pressure to the coronoid process of the ascending ramus of the mandible at the base of the external auditory canal (jaw thrust maneuver), as this avoids inadvertent cervical spine displacement (10). This maneuver subluxes the mandible anteriorly and rotates the temporomandibular joint. In the unconscious child, foreign matter should be cleared from the airway using judicious suctioning of the oropharynx. In neonates and infants up to three months of age, the nasal passages should be suctioned using a small tracheal catheter, as fewer than half of these obligate nasal breathers revert to oral breathing in the presence of nasal obstruction (11).

A nasopharyngeal or oropharyngeal airway may be used to temporarily maintain upper airway patency until a definitive airway is established. Before inserting the airway, the child’s level of consciousness should be assessed since the presence of an airway may induce gagging and vomiting. Nasopharyngeal airways are better tolerated than oropharyngeal airways in responsive patients. These airways should be inserted without excessive force to prevent damage to the nasal passages, which may cause epistaxis or precipitate laryngospasm. If the airway cannot be maintained despite these maneuvers, immediate tracheal intubation is required.

The indications for urgent tracheal intubation are:

1. airway obstruction, unrelieved by simple maneuvers,
2. apnea,
3. cardiac arrest,
4. major shock,
5. altered or decreasing level of consciousness (GCS < 8)—resulting in an inability to protect the airway and/or requirement to control alveolar ventilation (increasing carbon dioxide tension).

Severe head injury is by far the most common indication for emergency tracheal intubation. When the trachea must be intubated urgently, a choice must be made between the oral or nasal route. A decision regarding the route of intubation depends on the child’s injuries, the physician’s ability, and the anticipated duration of intubation. In the majority of cases, oral intubation is the preferred route when the airway must be secured rapidly, particularly in the presence of hypoxia and/or hypercapnia. However, transport and nursing of a child who is orally intubated is more difficult and challenging. In contrast to oral intubation, nasal intubation takes more time to perform, may be associated with significant bleeding from
the nasopharynx, and may transiently increase intracranial pressure (ICP). If the airway must be secured rapidly, particularly for hypoxia and hypercapnia, the oral route is preferred. Nasal intubation is contraindicated in the presence of a basal skull fracture because of the risk of an intracranial intubation.

An anesthetic is indicated for children who require intubation in the trauma room. Cardiorespiratory arrest and shock are the only situations in which an anesthetic may not be required to secure the airway (12). Details of the anesthetic used for intubation are discussed under the section Pharmacological Agents for Induction and Maintenance of Anesthesia.

Understanding the proper technique for laryngoscopy will facilitate and speed the maneuver in an emergency situation and minimize the risk of damage to teeth. Although the choice of blade depends on the individual’s training and equipment availability, we use straight blades for children up to six to eight years of age and curved blades thereafter. When using a straight blade, the blade should be inserted into the right side of the mouth (at the lateral commissure) and passed over the lateral incisors and/or bicuspids. This avoids damage to the central incisors. The tip should be directed toward the midline, passed under the epiglottis, and then lifted to uncover the vocal cords. For those less experienced with straight blades, the blade should be passed into the esophagus and pulled back until the vocal cords drop into view like the curtains at the end of a stage show. During laryngoscopy, the long axis of the handle of the blade should be directed towards the junction of the ceiling and wall at the opposite end of the room in order to distract the mandible from the maxilla, using extension of the elbow rather than rotation of the wrist. This technique is particularly effective for difficult airways. When using a curved blade, the blade should be introduced into the mouth over the central incisors and the tip advanced towards the base of the tongue. When positioned in the vallecula, the blade is lifted using the same elbow action as with a straight blade. The closely adherent epiglottis is lifted with the tongue, thereby exposing the vocal cords.

Intubation of the trachea is best confirmed by directly visualizing the tube between the vocal cords. Other confirmatory signs include the capnogram, the rise and fall of the chest and abdomen during positive-pressure ventilation, auscultation of bilateral breath sounds over the lung fields, the presence of condensation in the tube during exhalation, and the absence of breath sounds over the epigastrium. The measurement of end-tidal carbon dioxide concentrations (PetCO₂) in exhaled gas, or capnography, has become the standard in the operating room for verifying correct tube placement, although under some conditions, this monitor may be unreliable and yield false positive results (13). For example, PetCO₂ may be observed in as many as 33% to 45% of cases of esophageal intubations. However, in such cases, PetCO₂ decreases progressively and rapidly with sequential breaths (14). In the presence of a diminished or absent pulmonary blood flow (i.e., during cardiac arrest), the PetCO₂ will be markedly diminished or zero. Indeed, the return of PetCO₂ has been shown to closely reflect the return of spontaneous circulation during cardiopulmonary resuscitation (15). In the “ideal” lung, where ventilation and perfusion are well matched, PetCO₂ is usually 3–5 mmHg less than arterial carbon dioxide tension (PaCO₂) (16). In order to validate the PetCO₂ measurement, it should be compared to the PaCO₂. Many variables contribute to a large arterial–end-tidal CO₂ difference (ΔPaₐtCO₂) in children, including fresh gas flow rate in the breathing circuit, type of breathing circuit, sampling site of the exhaled gases, and sampling flow rate in side stream capnography (17).
Dead space ventilation is the most likely cause of a $\Delta P_{a-e\text{CO}_2}$, and may result from severe respiratory failure, cardiac arrest, pulmonary or systemic hypoperfusion, air embolism, and pulmonary thromboembolism (16). Newer disposable colorimetric carbon dioxide detection devices may be used where formal capnography is unavailable. These devices have been shown to accurately verify correct tube placement within six ventilated breaths during emergency intubation and have been validated in children (18,19).

For those children whose tracheas are already intubated when they arrive in the emergency department, the position of the tip of the tube should be checked immediately, as out-of-hospital resuscitation is associated with a greater incidence of unsuccessful intubations, and dislodgement or migration of the tube during transport (20).

Cervical Spine Stabilization

Of the cervical spine injuries that occur in the general population, fewer than 10% occur in children (21). Upper cervical injuries occur more frequently in children less than nine years of age, and lower cervical injuries occur in children 10 to 16 years of age (22). A cervical spine injury should be suspected in all cases of neurotrauma, as 30% to 53% of cervical spine injuries are associated with intracranial pathology (23,24).

The mechanism of the neurological insult associated with cervical spine injuries in children differs from that in adults. In children $<10$ years of age, the head is disproportionately large and the intervertebral ligaments are lax. As a result, sudden deceleration and acceleration movements cause the head to flex or extend acutely on the supple cervical spine. These movements result in upper cervical injuries, ligamentous injury, and/or spinal cord injury without radiographic abnormality, known by the acronym Spinal Cord Injury Without Radiographic Abnormality (SCIWORA) (22). Accordingly, it is imperative that cervical spine immobilization be instituted and maintained until a cervical injury has been ruled out in children with suspected head and/or neck injuries. Cervical spine injuries should be assessed both clinically (neck pain, pinpoint tenderness over the spinous processes, or a palpable step or change in orientation of the vertebrae) and radiographically (step changes in the alignment of vertebrae, widening or narrowing of the intervertebral spaces, and compression/fractures of vertebrae). A rigid collar and support device (backboard, beanbags/towels/blocks, and tape) have been advocated for children with suspected cervical spine injuries although no technique has been shown to provide superior protection from further injury (25,26).

Immobilization of the cervical spine assumes particular significance during management of the airway. Inadvertent manipulation of the neck during laryngoscopy may exacerbate spinal injuries, although there is a dearth of evidence to support this notion. The size and position of the cervical collar must be checked while the airway is secured, because a collar that is too loose or incorrectly applied may not stabilize the spine. In emergency airway management in children with suspected cervical injuries, the airway must be secured without compromising the child’s neurological status. Neither the jaw thrust maneuver nor insertion of an oral or nasal airway has been shown to exacerbate cervical spine injuries (27). Bag-valve-mask ventilation should be performed with the cervical collar and/or sandbags in place. However, if the cervical collar restricts the ability to control the airway, particularly during laryngoscopy and intubation, then the front of the collar should be carefully removed while manual in-line immobilization of the cervical spine is maintained.
Current recommendations regarding cervical immobilization and airway management are empirical. To date, no studies have compared the effects of different methods of advanced airway management on neurological outcome in children with cervical spine injuries. The current Advanced Trauma Life Support \textsuperscript{R} guidelines for emergency airway management recommend orotracheal intubation with manual in-line immobilization. In vivo and cadaveric studies in adults during laryngoscopy and intubation, the greatest degree of cervical spine movement occurs at the atlanto-occipital junction and C1-2 junction, with progressively less movement at lower spinal levels (28,29). Evidence from cadaveric models of cervical spine injury also suggests that axial traction may be more effective than in-line immobilization in reducing movement at the atlanto-occipital junction, although neither method of stabilization reduces movement in the subaxial cervical spine (28). Until there is clinical evidence to support any particular intervention, it would seem prudent to continue with the current ATLS \textsuperscript{R} guidelines when emergent laryngoscopy and intubation are indicated.

In a conscious, cooperative, and stable child with a suspected cervical injury who requires non-emergent intubation for diagnostic interventions or surgery, fiber-optic intubation under sedation/anaesthesia is the preferred technique.

### Rapid Sequence Induction

The decision to intubate the trachea in the trauma room requires careful consideration, as the incidence of complications associated with emergency tracheal intubation outside the operating room is greater than under controlled conditions in the operating room (30).

All traumatized patients, whether children or adults, are assumed to have a full stomach by virtue of delayed gastric emptying and the likelihood that an ileus exists, which are well-known consequences of severe injury and pain. Crying, with subsequent air swallowing, and bag-valve-mask ventilation may further distend the stomach in infants and young children. Therefore, the most widely utilized and safest technique to secure the airway is to use a rapid sequence induction (RSI).

The RSI technique consists of several defined steps:

1. preparation and preoxygenation,
2. induction of anaesthesia,
3. cricoid pressure.

Preparation for RSI includes the presence of two trained and dedicated assistants, one to provide in-line immobilization of the neck and the other to administer medications and apply external pressure to the cricoid ring. A Yankauer suction catheter should also be available in the event regurgitation occurs.

Preoxygenation with a tight sealing mask minimizes the risk and severity of desaturation by filling the functional residual capacity with oxygen. Desaturation is likely to occur in association with the apneic period that occurs during induction of anesthesia, laryngoscopy, and intubation. The optimal period of preoxygenation depends on the child’s age and concurrent illness, with the minimum period being 100 seconds (31). Unless the child is apneic before induction of anesthesia, positive-pressure ventilation during preoxygenation should be avoided as inadvertent gastric insufflation distends the stomach and increases the risk of regurgitation. Many children, however, will not tolerate a tight-fitting mask. A less intrusive technique such as blowing oxygen over the face is a reasonable alternative.
The application of cricoid pressure has been considered an essential element of RSI, although there is no evidence that it prevents aspiration in children with full stomachs. Whether visualization of the larynx in infants and children is improved with the application of cricoid pressure also remains controversial (32). In view of its inherent risks and only theoretical benefits, RSI and, in particular, cricoid pressure needs to be reevaluated from an evidence-based perspective.

Before commencing RSI with cricoid pressure, it is important to ensure that there are no contraindications to its use. The contraindications to cricoid pressure are either absolute or relative (Table 2). Only a trained assistant should apply cricoid pressure after the cricoid ring is located. Recommendations regarding the timing of application of cricoid pressure, the force that is required, and the preferred technique (single-handed vs. bimanual) are based on studies in adults since comparable data in children are lacking (32–34). Current evidence suggests that after preoxygenation but immediately before induction, a force of 20 N should be applied to the cricoid ring. This force should be increased to 30 N as consciousness is lost (32). A force of 30 N is the force required to indent a new tennis ball by a single digit or the pressure applied to the nasal bone that brings tears to the eyes. A description of how to correctly apply cricoid pressure is described below. Once applied, cricoid pressure should be maintained until the tube is secured within the trachea, the cuff (if present) has been inflated, and the presence of a capnogram/alveolar ventilation has been verified. Excessive or incorrectly applied cricoid pressure may compress the child’s airway, compromise the view of the glottic inlet, and increase the difficulty of intubation, especially in infants and young children in whom the trachea is more malleable and easily compressed. If the larynx cannot be visualized while cricoid pressure is applied, the force should first be reduced and then, if necessary, completely released until the glottic opening can be visualized.

The use of single-handed versus bimanual cricoid pressure remains controversial. Single-handed pressure involves stabilizing the cricoid cartilage with the thumb and middle finger while pressure is applied to the cricoid ring with the index finger. The bimanual technique uses the same single-hand maneuver plus a second hand that is placed behind the neck to apply counterpressure. However, recent studies failed to demonstrate the superiority of bimanual over single-handed cricoid pressure (34). Although it has been postulated that bimanual cricoid pressure provides better support for the cervical spine, thereby reducing the possibility of damage to the cord during cricoid pressure Criswell et al. found no neurological sequelae after RSI with the single-handed cricoid pressure technique in 73 patients with cervical spine inju-

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Contraindications to Cricoid Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute</td>
<td>Lack of knowledge&lt;br&gt;缺乏知识&lt;br&gt;缺乏专业知识&lt;br&gt;缺乏设备&lt;br&gt;缺乏培训人员&lt;br&gt;困难的气道&lt;br&gt;呕吐&lt;br&gt;难于呼吸到肺&lt;br&gt;Active vomiting&lt;br&gt;主动呕吐&lt;br&gt;空气道—骨折的环状软骨，气道内异物&lt;br&gt;食管—Zenker’s diverticulum，气道内尖锐异物&lt;br&gt;颈椎—不稳定性或骨折的椎骨，气道内尖锐异物</td>
</tr>
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</table>
ries (35,36). Regular and ongoing training of personnel in the correct application of cricoid pressure using mannikins or weighing scales is perhaps the most important factor governing successful use of the technique.

After the airway has been secured, a wide-bore orogastric tube should be inserted to decompress the stomach.

The Difficult Airway

Early recognition of the child with a difficult airway should prevent the potentially devastating consequences of a failed intubation and inability to ventilate the lungs. While the majority of infants and children have a normal airway, certain pediatric syndromes as well as head and neck trauma may be associated with abnormal upper airways that can make intubation a formidable task (Table 3). In the case of children with syndromes, the parents should be asked about a history of difficult intubations during previous anesthetics. The child may also wear a medic alert bracelet that indicates preexisting medical problems, including a difficult airway. Ideally, previous medical records and anesthetic charts should be reviewed before embarking on a plan to secure a difficult airway. In the emergency setting, however, there is often a dearth of details about existing airway problems. If so, we must rely on our clinical assessment.

Table 3  Pediatric Syndromes Associated with a Difficult Intubation

<table>
<thead>
<tr>
<th>Anatomic abnormality</th>
<th>Syndrome</th>
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<tbody>
<tr>
<td>Microstomia</td>
<td>Hallerman Streiff</td>
</tr>
<tr>
<td></td>
<td>Trisomy 18</td>
</tr>
<tr>
<td></td>
<td>Freeman–Sheldon</td>
</tr>
<tr>
<td>Macroglossia</td>
<td>Down syndrome</td>
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<tr>
<td></td>
<td>Beckwith–Wiedemann syndrome</td>
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<tr>
<td></td>
<td>Cherubism</td>
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<tr>
<td></td>
<td>Mucopolysaccaridoses</td>
</tr>
<tr>
<td>Mandibular hypoplasia/micrognathia</td>
<td>Achondroplasia</td>
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<tr>
<td></td>
<td>Cornelia de Lange</td>
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<tr>
<td></td>
<td>Cri du chat</td>
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<tr>
<td></td>
<td>Goldenhar</td>
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<tr>
<td></td>
<td>Hallerman Streiff</td>
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<td></td>
<td>Pierre Robin</td>
</tr>
<tr>
<td></td>
<td>Treacher–Collins</td>
</tr>
<tr>
<td></td>
<td>Trisomy 18</td>
</tr>
<tr>
<td></td>
<td>Turner (XO)</td>
</tr>
<tr>
<td>Limited excursion of the mandible</td>
<td>Temperomandibular joint dysfunction</td>
</tr>
<tr>
<td></td>
<td>(congenital, traumatic, and inflammatory)</td>
</tr>
<tr>
<td></td>
<td>Muscle disorders (malignant hyperthermia,</td>
</tr>
<tr>
<td></td>
<td>myotonia)</td>
</tr>
<tr>
<td></td>
<td>Integumentary/fascia disorders (neoplasm,</td>
</tr>
<tr>
<td></td>
<td>infection, scleroderma, and postirradiation)</td>
</tr>
<tr>
<td></td>
<td>Neurologic injury</td>
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<tr>
<td></td>
<td>Atypical response to succinylcholine</td>
</tr>
<tr>
<td>Limited neck extension</td>
<td>Klippel Feil</td>
</tr>
<tr>
<td></td>
<td>Post-surgery</td>
</tr>
<tr>
<td></td>
<td>Postirradiation</td>
</tr>
</tbody>
</table>
Physical examination of the head and neck in children usually provides evidence of a difficult airway. Although several predictors of a difficult airway in adults have been reported, none are valid in children (37–39). Therefore, physical examination of the airway in children should attempt to identify those characteristics that are associated with a difficult airway, including:

1. microstomia,
2. limited excursion of the mandible,
3. retrognathia/micrognathia,
4. intraoral pathology (bleeding, infection, and foreign body),
5. distorted airway anatomy (oropharyngeal or tracheobronchial disruption),
6. limited neck movement, particularly extension.

Management of a child with an anticipated difficult airway requires the skills of a specialized pediatric anesthesiologist. If the child is a neonate or infant, a pediatric surgeon or otolaryngologist should also be available to provide a surgical airway if required, as needle cricothyrotomy and transtracheal jet ventilation in this age group are fraught with potentially fatal complications (i.e., barotrauma and pneumothorax) and must be used with great caution. A portable unit that contains specialized airway equipment should be immediately accessible in the trauma room. However, we prefer to transfer the child to the operating room to secure the airway. In order to become familiar and proficient with the available equipment for managing difficult airways in children, experience with the equipment should be acquired in children with normal airways under controlled conditions.

Two personnel trained in airway management, preferably two anesthesiologists, should be available to deal with an anticipated difficult airway. A two-person intubation technique is one in which the first person performs the laryngoscopy with one hand and applies posterior pressure on the thyroid cartilage to bring the laryngeal inlet into view with the second hand. The second person then inserts the tracheal tube under direct visualization (3). Alternatively, the first person may perform the laryngoscopy and insert the tracheal tube while the second applies posterior pressure to the thyroid cartilage. We prefer the former arrangement.

The insertion of a malleable stylet into the tube may facilitate orotracheal intubation in patients with an anterior larynx, or limited mouth opening. The stylet stiffens the tube and maintains its hockey-stick shape, in order to slide the tip of the tube under the epiglottis and through the vocal cords. The stylet should never extend beyond the tip of the tube as it could damage the mucosa or perforate the trachea.

The laryngeal mask airway (LMA) has become an important device in the management of difficult airways in children, as it often provides a good airway and can be utilized as a conduit to facilitate tracheal intubation (Table 4). Although blind intubation of the trachea has been performed successfully via an LMA, this technique is more likely to fail in children, where the aperture of the LMA approximates the laryngeal inlet in only 27% to 41% of cases (40–42). Consequently, the use of a flexible fiberoptic bronchoscope is recommended to facilitate insertion of the tube via the LMA. The newer “intubating LMA” (LMA-Fastrach, LMA North America Inc., San Diego, California, U.S.A.) was designed as a conduit to facilitate tracheal intubation (43). The recommendation that a neutral head position be maintained for both insertion and intubation means that this device may be more appropriate in patients with suspected cervical spine pathology.
The LMA cuff should be lubricated with gel before insertion. With the cuff deflated or partially deflated and the aperture facing caudad, the LMA should be advanced across the hard palate using the index finger as a guide over the back of the tongue. When resistance is felt, the LMA is abutting against the upper esophageal sphincter. The cuff should then be fully inflated.

The LMA does not “protect” the airway from regurgitation and aspiration as it does not seal the airway. A new prototype, the Proseal LMA, has an improved laryngeal seal and a secondary tube, which acts as a conduit for passage of a gastric tube and regurgitation of gastric fluid (44).

The Trachlight®/C213 is a useful device that illuminates the laryngeal inlet transtracheally as a guide for blind tracheal intubation. An appropriately sized tracheal tube is mounted onto the stylet, and the stylet is then introduced into the oropharynx. Under low-level lighting, a characteristic red glow is seen over the anterior neck as the cricothyroid membrane is transilluminated.

The Bullard laryngoscope, which combines fiberoptic illumination with a rigid laryngoscope, is available in both adult and pediatric sizes. An appropriately sized tracheal tube is mounted onto a metal stylet attached to the scope. The advantage of this scope is that laryngoscopy and intubation can be performed with minimal manipulation of the cervical spine and less mouth opening (4 mm) compared to conventional laryngoscopy. In addition, a side port allows insufflation of oxygen during laryngoscopy.

Flexible fiberoptic bronchoscopy using a combination of intravenous “conscious” sedation and topical airway anesthesia is the technique of choice for intubation of adult patients with a difficult airway. However, children rarely cooperate enough to use this technique, particularly with the added stress of trauma. Accordingly, for children who are fasting, fiberoptic intubation is performed with the child anesthetized. This ensures that spontaneous ventilation is maintained until the airway has been secured. An appropriately sized tube is mounted onto the proximal part of the well-lubricated bronchoscope, and the scope is introduced into the nose or mouth. The nasal route usually provides a straighter and more direct route to the laryngeal inlet.

### Table 4  LMA Characteristics

<table>
<thead>
<tr>
<th>LMA size</th>
<th>Patient weight (kg)</th>
<th>Maximum cuff volume (mL)</th>
<th>Largest ETT&lt;sup&gt;a&lt;/sup&gt; (ID, mm)</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
<td>&lt;5</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>1.5</td>
<td>5–10</td>
<td>7</td>
<td>4.0</td>
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<tr>
<td>2.0</td>
<td>10–20</td>
<td>10</td>
<td>4.5</td>
</tr>
<tr>
<td>2.5</td>
<td>20–30</td>
<td>14</td>
<td>5.5</td>
</tr>
<tr>
<td>3.0</td>
<td>30–50</td>
<td>20</td>
<td>6.0 cuffed</td>
</tr>
<tr>
<td>4.0</td>
<td>50–70</td>
<td>30</td>
<td>6.0 cuffed</td>
</tr>
</tbody>
</table>

<sup>a</sup>Largest ETT that will pass through the lumen of the LMA.

Failed Intubation

The inability to secure the airway after induction of anesthesia is one of the most stress-provoking and dangerous events in anesthesia, especially when the patient is a child. An immediate “call for help” should be sent to the appropriate departments
in the hospital (especially the OR and ICU) to mobilize all the necessary medical and surgical personnel who may be required to assist in securing the airway.

If the child can be ventilated with a face mask, a non-emergent path is followed. Intubation difficulties may be attributed to incorrect positioning of the head and neck, excessive cricoid pressure, an inappropriate laryngoscope blade, resistive muscle tone, or inexperience of the laryngoscopist (45). A second “optimal” attempt at intubation using conventional laryngoscopy should be made once these factors have been optimized. In the trauma patient, however, the optimal “sniff” position usually recommended for intubation may be contraindicated, as it may potentially cause a cervical spine injury. The number of attempts at conventional laryngoscopy should be minimized to avoid bleeding and laryngeal edema. If the “optimal” attempt at conventional laryngoscopy fails, other nonsurgical intubation techniques for the difficult airway (LMA, Bullard laryngoscope, flexible fiberoptic bronchoscope, and lightwand) should be considered. If these also fail, mask ventilation should continue until the child resumes spontaneous ventilation and awakens or a surgical airway should be established.

It is imperative that ventilation be maintained between attempts at intubation, using either a mask or LMA. Whether ventilation is spontaneous or controlled is moot, so long as ventilation occurs. Failure to ventilate may be explained by airway obstruction in the oropharynx or at the glottis or beyond. If the airway is obstructed at the oropharynx, then maneuvers to clear the airway should be performed. If one person cannot ventilate, then a second person should be recruited to assist. The primary person performs a “jaw thrust” maneuver and holds the face mask in position with both hands, while the assistant squeezes the reservoir bag. Alternatively, the assistant may perform the jaw thrust maneuver while the primary person positions the face mask with one hand and squeezes the reservoir bag with the other. An oropharyngeal and/or nasopharyngeal airway may help. If mask ventilation is still inadequate, an LMA should be inserted immediately. If this establishes a clear upper airway, the LMA can be used as a conduit for tracheal intubation. If ventilation remains obstructed, repositioning of the LMA should be attempted. If the lungs cannot be ventilated, then the obstruction is likely at the level of the glottis or beyond (i.e., laryngospasm or a foreign body). A surgical airway is required immediately.

Percutaneous needle cricothyrotomy and transtracheal jet ventilation (TTJV) are not recommended in the emergency management of the pediatric airway. Cricothyrotomy is technically more difficult to perform, especially in neonates and infants, in whom the cricothyroid membrane is poorly defined. Furthermore, the risks of direct needle trauma to structures surrounding the trachea, and of barotrauma, pneumothoraces, pneumomediastinum, and pneumoencephaly from insufflation with a high-pressure oxygen source, may lead to catastrophic complications. Cricothyrotomy should only be used as a last resort in cases of life-threatening airway obstruction and inability to ventilate by any other means.

**Laryngotracheal Trauma**

Laryngotracheal trauma is a rare but potentially fatal injury. It may result from falls, motor vehicle accidents (MVAs) gunshot injuries, and strangulation (46). Respiratory distress, massive subcutaneous emphysema, stridor, and hoarseness should alert the physician to the possibility of such an injury (47,48). Muscle relaxation must be administered judiciously as positive pressure ventilation may not be
possible. In some instances, an urgent tracheostomy may be required to reestablish or preserve the airway. Instrumentation of such a traumatized airway should never be attempted without a surgeon present, in case complete laryngeal or tracheal transection occurs.

PHARMACOLOGICAL AGENTS FOR INDUCTION AND MAINTENANCE OF ANESTHESIA

The choice of agent for induction of anesthesia depends on the hemodynamic and neurological status of the child, the patency of the airway, and the familiarity of the physician with the agents. Although there is agreement that even severely traumatized patients require sedation and analgesia for tracheal intubation and surgery, there is little consensus as to the preferred agents. The combination of a rapid-acting general anesthetic, a neuromuscular blocking agent, and a potent opioid is recommended to induce anesthesia and rapidly secure the airway in children. These agents should be injected into a fast-flowing intravenous solution to ensure a rapid onset of action after normovolemia has been established. A preinduction dose of atropine (20 mg/kg) is recommended to minimize the risk of bradycardia associated with the vagal responses to laryngoscopy in neonates and infants, and to succinylcholine in all infants and children.

Sedative-Hypnotic Agents

For hemodynamically stable children, thiopentone, an ultra–short-acting barbiturate, or propofol, an alkyl phenol, ensure a rapid and predictable onset and offset of anesthesia. For hemodynamically unstable children, smaller doses of thiopentone and propofol should be used, as these agents depress myocardial contractility and dilate peripheral vascular beds in a dose-dependent manner. Alternatively, ketamine or etomidate may be used.

Thiopentone has traditionally been advocated as the induction agent of choice in head injury because it produces dose-dependent reductions in cerebral metabolic rate and oxygen consumption (CMRO$_2$), which results in a reflex decrease in cerebral blood flow (CBF) and a parallel decrease in ICP. Thiopentone also attenuates the increase in ICP associated with laryngoscopy and intubation and maintains cerebral autoregulation and the response to changes in arterial carbon dioxide tension (49). The recommended induction dose of thiopentone in a hemodynamically stable child is 4–5 mg/kg in neonates, 7–8 mg/kg in infants, and 5–6 mg/kg in children greater than one year of age (50,51).

Propofol produces similar changes in Control Nerrons System dynamics as thiopentone (52,53). Recent evidence suggests that propofol may also act as a free radical scavenger, providing protection of the CNS during periods of anoxia (54). Another advantage of propofol is its potent antiemetic effect although this is not an important issue in traumatized children (55).

The cardiovascular effects of propofol are similar to those of thiopentone (56). Hypotension is particularly prominent after rapid bolus administration. An increase in central vagal tone, leading to bradycardia and asystole, has been reported following coadministration of other vagotonic agents (57). This may be attenuated by pretreatment with atropine. The induction dose of propofol in hemodynamically stable children is 3–5 mg/kg in infants and 2–3 mg/kg in older children (58).
Adverse effects associated with propofol, including anaphylactoid reactions, pain on injection, bacterial contamination, and hyperlipidemia, are related to the lipid emulsion in which it is formulated (59). Pain on injection can be minimized by pre/coadministration of 1% lidocaine (0.2 mg/kg) or an opioid (60). Opisthotonic posturing, myoclonic movements, and seizure-like activity have been observed after propofol administration, although no electroencephalographic (EEG) abnormalities have been documented (59).

Continuous propofol infusions are being used increasingly for maintenance of anesthesia and sedation. In the operating room, propofol may be utilized as part of a total intravenous anesthetic regime when inhalational anesthesia is contraindicated. Outside the operating room, propofol infusions are commonly used for sedation in the radiology suite, for diagnostic endoscopic procedures, and in the intensive care unit, where the favorable pharmacokinetic profile (rapid redistribution and clearance) is associated with a shorter time to wakeup and extubation (61). Various dosing regimens have been proposed: an initial loading dose of 2.5 mg/kg, followed by infusion rates ranging from 2 to 15 mg/kg/hr (61,62). However, no regimen is perfect and infusion rates should be titrated to effect. The coadministration of opioids significantly reduces infusion requirements (63). Prolonged continuous propofol administration has been associated with metabolic acidosis, bradyarrhythmias, and fatal cardiac failure in young children in the intensive care unit (64). While the specific causes of death in these reports remain unknown, postulated risk factors include high doses of propofol (>4 mg/kg/hr), prolonged administration (>48 hours), age less than four years, and intercurrent respiratory tract infection. Recent evidence from one child suggests that chronic propofol administration may impair fatty-acid oxidation, which leads to failure of the mitochondria and end-organ damage (65).

In hemodynamically unstable children, two other induction agents may be used: ketamine (2 mg/kg) or etomidate (0.2–0.4 mg/kg). Ketamine, a racemic mixture of two enantiomers, produces anesthesia via dissociation of the thalamocortical and limbic systems. It also confers profound analgesia and amnesia. N-methyl-D-aspartate (NMDA) receptor antagonism is responsible for most of its CNS effects; however, interactions with non-NMDA glutamate, opioid, cholinergic, and monoaminergic receptors may also be important (66). The cardiovascular stability of ketamine is due to sympathomimetic stimulation, since it has a direct, negative inotropic effect on the heart. The sympathomimetic effects produce increases in both heart rate and blood pressure (67). Respiratory function and protective airway reflexes are well preserved during ketamine administration. It is the only intravenous agent with bronchodilator activity.

In the past, ketamine has been contraindicated in closed head injury, purportedly because of an increase in intracranial pressure (ICP). However, recent evidence suggests that ketamine does not increase ICP if blood pressure and ventilation are controlled (68). Furthermore, NMDA receptor antagonists play a neuroprotective role in head injury (69). Ketamine has fallen into disfavor because of a high incidence of dysphoric psychotomimetic phenomena (hallucinations and vivid dreams) associated with emergence from anesthesia. These phenomena are dose-related, occur more commonly in the elderly, and may be attenuated by pretreating the patient with a small dose of a benzodiazepine such as midazolam.

Etomidate has been used for many years to induce anesthesia in adults. However, there is little clinical information regarding its use in children. Etomidate is unique in that it decreases cerebral metabolic rate, cerebral blood flow (CBF), and ICP, while maintaining cerebral perfusion pressure (CPP). By preserving sympathetic
outflow, etomidate is associated with minimal change in hemodynamics (70). The respiratory effects of etomidate are biphasic, with an initial short period of hyperventilation, followed by respiratory depression or apnea.

The side effects of etomidate include myoclonic activity (coughing and hiccoughing), pain on injection, phlebitis, and adrenocortical suppression. The myoclonic activity is not associated with epileptiform EEG changes. However, focal EEG activity may increase in some patients with preexisting epilepsy (71).

Adrenocortical suppression is a major limitation to the routine use of etomidate. In the early 1980s, a number of deaths in critically ill patients were linked to the use of prolonged infusions of etomidate in the intensive care unit (72). This phenomenon has also been demonstrated following a single induction dose of etomidate in children undergoing cardiac surgery, although no detrimental clinical effects were observed (73).

Benzodiazepines are the most widely utilized agents for sedation in the pediatric population. They are agonists at inhibitory gamma-aminobutyric acid (GABA) receptors in the limbic system. Antegrade amnesia is one of the major benefits associated with the use of these agents, so that children will have little or no memory of unpleasant procedures. Benzodiazepines also have little effect on cardiorespiratory function at clinical doses. For many years, diazepam was the agent of choice. However, prolonged sedation resulting from a long elimination half-life (12–24 hours) and active metabolites led to the development of agents with a shorter duration of action.

Midazolam, the only water-soluble benzodiazepine, has a rapid onset of action and short half-life (two to four hour). It is two to four times more potent than diazepam. It is less effective than thiopentone as an induction agent for general anesthesia but is used extensively for sedation in the pediatric intensive care unit where continuous infusion rates of 0.05–0.2 mg/kg/hr have been shown to be effective (74,75). The coadministration of opioids is usually necessary to provide analgesia postoperatively or for painful investigations.

Lorazepam has an intermediate half-life (4–12 hours) and duration of action. It may be administered intermittently (0.05–0.1 mg/kg) or via continuous (IV) infusion (start at 0.025 mg/kg/hr) (75). Lorazepam is metabolized by glucuronyl transferase, not the P450 system. Therefore, it may be more appropriate in children with advanced liver disease, or those on drugs that alter the P450 system (anticonvulsants, rifampicin, and cimetidine).

The benzodiazepines are the only hypnotic agents for which there is a specific antagonist. Flumazenil (Romazicon®) is a GABA receptor antagonist whose safety and efficacy has been verified in children (76). As flumazenil has a shorter half-life than any of the benzodiazepines, re-sedation may occur following bolus administration. The recommended dose of flumanzenil is 5–10 μg/kg, followed by an infusion of 2–10 μg/kg/hr.

**Neuromuscular Blocking Agents**

Neuromuscular blockade reduces the incidence of airway-related complications during emergency intubation (77). In addition, neuromuscular blockade is associated with small but significant reductions in oxygen consumption and energy expenditure in critically ill children who are mechanically ventilated in the intensive care unit (78). Two classes of neuromuscular blockers exist: depolarizing and non-depolarizing agents.
Succinylcholine, the only depolarizing neuromuscular blocking agent available for clinical use, is the drug of choice for RSI, because it has both a rapid onset and ultrashort duration of action. The recommended dose is 2 mg/kg IV or 4 mg/kg IM for infants and children. The intramuscular route should only be used where intravenous access is unavailable as this route has a delayed onset of action.

Succinylcholine has been associated with increases in ICP in animal studies, although this has never been reported in humans. There is also evidence to suggest that the magnitude of the small increase in ICP after succinylcholine administration is reduced in patients with neurological injury (79). The increase in ICP associated with coughing and retching during laryngoscopy as a result of inadequate anesthesia and neuromuscular blockade is of far greater magnitude and clinical concern than the theoretical changes in ICP attributed to succinylcholine. Furthermore, potential increases in ICP may be effectively controlled by pretreatment with thiopentone or propofol, a synthetic opioid, and other adjuvants such as lidocaine (1.5 mg/kg).

Over the past decade, the routine use of succinylcholine in children has been brought into question due to a small number of reported deaths related to hyperkalemia (80). These cardiac arrests occurred in young males with undiagnosed myopathies. Failure to diagnose hyperkalemia as the etiology of these malignant arrhythmias and to protect the heart from the arrhythmogenic effects of hyperkalemia by administration of intravenous calcium chloride resulted in difficult resuscitations and deaths. Other adverse effects associated with its use in children include bradycardia, malignant hyperthermia, masster muscle rigidity, and myalgia. Contraindications to succinylcholine are listed in Table 5. Despite these potential problems, succinylcholine remains the preferred neuromuscular blocking agent when the airway must be secured emergently.

Non-depolarizing muscle relaxants may be used to facilitate intubation in circumstances where succinylcholine is contraindicated or unavailable. Among those relaxants currently available, the intermediate-acting agent rocuronium has the most favorable pharmacokinetic and pharmacodynamic profile for RSI. Rocuronium, a steroidal-based compound, is related structurally to pancuronium and vecuronium. In children scheduled for emergency surgery, rocuronium (1.2 mg/kg) has a rapid onset of action and similar intubating conditions to succinylcholine (81). However, recovery after rocuronium is far slower compared with succinylcholine (41 ± 13 vs. 5.2 ± 1.9 min) (82). Thus, the use of rocuronium is limited to circumstances in which

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Contraindications to Succinylcholine</th>
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<tbody>
<tr>
<td>Absolute</td>
<td>Previous history of malignant hyperthermia</td>
</tr>
<tr>
<td></td>
<td>Central core disease</td>
</tr>
<tr>
<td></td>
<td>Difficult airway</td>
</tr>
<tr>
<td>Relative</td>
<td>Muscular dystrophy, Beckers</td>
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<tr>
<td></td>
<td>Chronic denervating injury</td>
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<tr>
<td></td>
<td>Chronic myopathy or neuromuscular disease</td>
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<td></td>
<td>Burns (beyond 48 hr)</td>
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<tr>
<td></td>
<td>Massive tissue injury</td>
</tr>
<tr>
<td></td>
<td>Preexisting hyperkalemia</td>
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<tr>
<td></td>
<td>Plasma cholinesterase deficiency</td>
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</table>
the airway is not compromised and rapid return of spontaneous ventilation is unim-
portant. Rocuronium will precipitate thiopentone from solution as will vecuronium
and other non-depolarizing relaxants, if the two are mixed or administered sequen-
tially. The intravenous tubing should be flushed of thiopentone before the relaxant is
administered.

Maintenance of neuromuscular blockade can be achieved with a variety of
intermediate long-acting agents administered as intermittent boluses or via a contin-
uous infusion. The choice of agent depends primarily on the duration of blockade
required and the child’s cardiovascular, hepatic, and renal function. Pancuronium
(0.05–0.1 mg/kg) is a long-acting agent often used in infants and young children, as
its vagolytic effects attenuate anesthesia-induced bradycardias. It has a prolonged dura-
tion of action in patients with hepatic or renal dysfunction. Vecuronium (0.05 mg/kg)
has an intermediate duration of action in children and adults. However, in infants
the duration is prolonged, being similar to that of pancuronium (83). Vecuronium
(0.1–0.15 mg/kg) may be used for rapid onset of action. Cisatracurium (0.08 mg/kg)
is an intermediate long-acting agent whose elimination is independent of hepatic
and renal function. Both vecuronium and cisatracurium have minimal cardiovascular
effects.

Opioids
Analgesia is an integral part of the management of injured children. Inadequate
analgesia during painful procedures has been shown to have a negative impact on
subsequent procedural pain (84). Pain management is dealt with in the following
chapter of this book; therefore, only the specific issues pertaining to the use of
opioids in airway management and neurotrauma are discussed here. The relative
potencies and the recommended bolus doses of opioids are shown in Table 6.

Opioids are commonly used during induction of anesthesia to minimize the
sympathetic response to laryngoscopy and intubation. Nowhere is this more impor-
tant than in the setting of neurotrauma, where a sympathetically mediated increase
in ICP may have disastrous consequences. The most common opioids used in this
setting are the synthetic opioids, which have a rapid onset and short duration of
action. Fentanyl is the most commonly utilized agent as it is readily available in most
operating rooms and emergency departments. Alfentanil and sufentanil are short-
acting analogues of fentanyl. Remifentanil is a relatively new ultrashort-acting
opioid, which differs from the other agents in that it is rapidly metabolized by
ubiquitous tissue and plasma esterases. Remifentanil has a half-life of approximately
eight minutes, necessitating its administration by continuous intravenous infusion.
The dose of remifentanil is 0.25–1.0 μg/kg/min, depending on the other agents being

<table>
<thead>
<tr>
<th>Opioid</th>
<th>Potency</th>
<th>Dose (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphine</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Meperidine</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Alfentanil</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>Fentanyl</td>
<td>100</td>
<td>0.001</td>
</tr>
<tr>
<td>Sufentanil</td>
<td>1000</td>
<td>0.0001</td>
</tr>
<tr>
<td>Remifentanil</td>
<td>Infusion only</td>
<td></td>
</tr>
</tbody>
</table>

Table 6  Relative Potencies of Synthetic Opioids and Recommended Initial Bolus Dosage
administered. All opioids confer hemodynamic stability, although at higher doses their use may be associated with significant bradycardia. Chest wall rigidity may also occur after both high-dose (25–50 μg/kg) and low-dose (3–5 μg/kg) fentanyl in neonates. This may also occur with remifentanil (85). The administration of a neuromuscular blocker attenuates this phenomenon, while naloxone (20–40 μg/kg) reverses it.

Opioids are often used to abate the sympathetic response to laryngoscopy and intubation. Alfentanil (15 μg/kg) or remifentanil (1 μg/kg), administered immediately before induction, have been shown to attenuate the hemodynamic response to intubation in children undergoing elective surgery (86). In contrast, fentanyl (2 μg/kg) must be given five minutes before laryngoscopy and intubation to attenuate the hemodynamic responses (87).

The effect of these agents on ICP and CPP is controversial. A number of studies in adults with raised ICP have demonstrated a transient increase in ICP and a reduction in mean arterial pressure and CPP after bolus injections of fentanyl, sufentanil, and alfentanil (68,88). It has been suggested that high-dose opioids should be avoided in patients with severe head injury, unless mean systemic arterial pressure (MAP) and CPP can be maintained (89). Comparable data for the effects of opioids on ICP and CPP in children are lacking.

**ASSESSMENT AND MANAGEMENT OF SHOCK**

**Assessment of Hypovolemia**

Recognition of the signs of hypovolemic shock in children requires an understanding of the underlying physiological differences between children and adults.

Cardiovascular function and compensatory mechanisms to maintain cardiac output in young children differ from those in adults. In young children, a decrease in preload is compensated for by an increase in heart rate, rather than stroke volume. A high resting sympathetic tone in children preserves a relatively normal blood pressure in spite of a significant loss of intravascular volume (30–40%). As a result, hypotension is a late sign of uncompensated shock. The adequacy of tissue perfusion can be assessed by determining the child’s level of consciousness, rate of capillary refill, central and peripheral pulses, and urine output. These indicators are of greater importance in assessing the hemodynamic status of a child than the blood pressure.

External blood loss is easy to recognize and quantify, whereas internal hemorrhage may be insidious, occult, and life threatening in children. Intra-abdominal, intrathoracic, and pelvic hemorrhage are well-known causes of shock in both adult and pediatric trauma. In infants and young children, retroperitoneal and intracranial hemorrhage are not uncommon causes of hypovolemic shock. However, hypovolemia may remain unrecognized until induction of anesthesia, after which circulatory collapse rapidly occurs.

The signs of hypovolemic shock relative to the degree of blood loss are shown in Table 7.

**Intravenous Access**

Venous access may prove extremely difficult in the hypovolemic child. Not only are the peripheral veins small and collapsed, but in children between six months and two years of age, a layer of subcutaneous fat further obscures superficial veins. The
preferred sites for peripheral venous access include the dorsum of the hand and foot, the saphenous vein, and the cephalic vein on the posterolateral aspect of the antecubital fossa (90). In neonates, superficial scalp veins are also potential sites for cannulation, although inadvertent arterial cannulation may cause spasm if certain drugs are infused (i.e., thiopental). Two large-bore intravenous lines are preferred to allow rapid infusion of intravenous fluids. The “60-second rule” ensures that time is not wasted gaining access in peripheral veins. If peripheral venous access has not been established within this time period, alternative sites should be sought.

When attempts at peripheral access have failed, central venous or intraosseous access should be sought. Placement of a short, wide-bore cannula in the femoral, internal jugular, or subclavian vein facilitates the rapid infusion of a large volume of fluid. The use of conventional central venous catheters is not recommended because of their physical limitation to large volume blood flow. The femoral vein may be the safest and easiest site for venous cannulation in an emergency situation, as it may be located quickly, medial to the femoral artery. Femoral cannulation offers several other advantages, including the avoidance of the Trendelenburg position, which is particularly important for the head-injured child, and avoidance of the potential complications of thoracic cannulation (pneumothorax, hemothorax, chylothorax, carotid/subclavian artery puncture, arrhythmias, pericardial, or intrapleural infusion).

Intraosseous access is an effective way to establish vascular access in traumatized children. Insertion of a large-bore needle into the bone marrow gains entry to the systemic circulation (91). Intraosseous access should be reserved for infants and children less than five years of age because in older children the cortical bone hardens, the medullary space becomes progressively smaller, and the red marrow is gradually replaced with yellow fatty marrow. Several commercially available needles are readily available. However, any strong, large-bore needle with a stylet can be used. The recommended needle size for infants less than 18 months of age is 18 to 20 gauge and for older children is 13 to 16 gauge (92). The preferred insertion sites are the anteromedial aspect of the proximal tibia (one finger breadth distal to the tibial tuberosity), distal femur (2–3 cm proximal to the condyle), distal humerus (1 cm superior to the malleolus), and iliac crest (on the inferior aspect of the iliac crest). Any drug or solution that is available for intravenous administration can be given via the intraosseous route.

Table 7  Signs of Hypovolemia in Infants and Young Children

<table>
<thead>
<tr>
<th></th>
<th>&lt;20a</th>
<th>25a</th>
<th>40a</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVS: heart rate</td>
<td>Tachycardia</td>
<td>Tachycardia</td>
<td>Tachy (\Rightarrow) bradycardia</td>
</tr>
<tr>
<td>BP Normal</td>
<td>May be normal, distal pulses weak, thready</td>
<td>Hypotension</td>
<td></td>
</tr>
<tr>
<td>Skin: temperature Cool</td>
<td>Cool</td>
<td>Cold</td>
<td></td>
</tr>
<tr>
<td>Color Normal, however capillary refill slow</td>
<td>Cyanosis, mottled</td>
<td>Pale</td>
<td></td>
</tr>
<tr>
<td>Urine output Small decrease</td>
<td>Oliguria</td>
<td>Anuria</td>
<td></td>
</tr>
<tr>
<td>CNS Irritable</td>
<td>Confused, lethargic</td>
<td>Comatose</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Refers to % blood loss.
Source: Adapted from Ref. 97.
Intravenous Fluid Therapy

In the trauma room, the choice and volume of intravenous fluid should be tailored to the child’s needs. A cookbook approach to this issue is inappropriate and may lead to inadequate or excessive fluid resuscitation, both of which may be detrimental. The hemodynamic status should be frequently reevaluated during the resuscitation to ensure appropriate fluid management. Control of hemorrhage is an important primary factor in a successful resuscitation. External hemorrhage requires immediate direct control, and internal hemorrhage requires emergent surgical control in the operating room. Fluid resuscitation is an interim measure to reestablish and maintain intravascular volume until blood loss can be controlled. While fluid restriction or low-volume fluid resuscitation has previously been advocated to reduce cerebral edema after traumatic brain injury, this practice is currently under reevaluation as the importance of maintaining an adequate CPP is increasingly appreciated (93).

The administration of boluses of isotonic crystalloid solutions, such as normal saline or lactated Ringer’s solution, is standard first-line therapy in the majority of pediatric emergency departments. Lactated Ringer’s is often used, as large volumes of normal saline may cause a hyperchloremic metabolic acidosis (94). However, large volumes of lactated Ringer’s solution may transiently cause a serum lactatemia and hyponatremia. In infants and smaller children, fluids should be administered via a burette to attenuate the risk of transfusing excessive volumes of fluid.

Hypotonic and glucose-containing solutions are contraindicated in traumatized children as they may lead to increased free water, hyponatremia, and hyperglycemia. The avoidance of glucose-containing solutions is particularly relevant in head injury. Early hyperglycemia occurs frequently after head injury and is a reliable indicator of both severity of head injury and outcome (95). In children, particularly those less than two years of age, the initial serum glucose on admission is related to the Injury Severity Score (96). Glucose-containing solutions should only be used to prevent or treat hypoglycemia, not for volume resuscitation. Glucose-containing solutions should be administered via a separate intravenous line to avoid administering a large bolus.

The role of hypertonic saline solutions in trauma remains controversial. There is increasing evidence to suggest that judicious use of hypertonic saline may be effective, particularly in the management of head injury, burns, and in neonatal/pediatric resuscitation where the delivery of smaller volumes of fluid may be beneficial (97). However, hypertonic fluids are not routinely used for resuscitation because of the theoretical risk of central pontine myelinolysis, a potential sequela of rapid correction of severe hyponatremia (98). Of greater concern, however, is the increased risk of bleeding noted in several experimental models of uncontrolled hemorrhage following hypertonic saline resuscitation (99,100).

The choice of fluid for resuscitation, the crystalloid–colloid controversy in trauma resuscitation, remains contentious. Colloids restore normovolemia using smaller volumes of fluid and maintain colloid oncotic pressure, thereby reducing interstitial edema in the periphery and lungs. However, an increase in capillary wall permeability with leakage of colloid into the interstitium theoretically may worsen the edema. Albumin 5% is the most commonly utilized colloid in pediatric resuscitation. Synthetic colloids have only marginally displaced albumin’s popularity. This has been due in part to their side effects. Dextrans 40 and 70 and hetastarch may cause anaphylactic/anaphylactoid reactions or, if administered in large volumes, a coagulopathy (97). In contrast, the newest synthetic colloid, pentastarch, which is
currently available in Canada, is not associated with any of these side effects. Up to 25 mL/kg pentastarch may be used in children.

Crystalloids are less expensive than colloids, readily available, and are not associated with any of the complications attributed to colloids. While there may be a greater likelihood of interstitial edema with excessive volumes of crystalloids compared with colloids, mortality is similar with both. A recent systematic review purported that resuscitation with large volumes of crystalloid may reduce mortality in multi-trauma patients (101). At the present time, the optimal fluid therapy for trauma resuscitation remains unknown.

In the past, hemodynamic variables alone were utilized to guide fluid transfusion. More recently, measurements of global organ perfusion, including lactic acid concentration and base excess measurements, have also been used (102,103). Recognition that regional hypoperfusion may exist in spite of adequate global perfusion has led to even newer techniques, such as measurement of gastric mucosal pH, to guide fluid management (104). The relevance of these newer technologies in guiding fluid therapy during resuscitations is constantly evolving.

**Perioperative Management of Pediatric Trauma**

Following the initial resuscitation in the trauma room, children may require urgent surgery. Thermal homeostasis may be achieved using the following techniques, in order of descending priority (105,106):

1. **Active warming** by maintaining a high ambient temperature using a radiant heater, circulating water mattress, and forced-air warming device (Bair Hugger®). Forced-air devices are extremely effective but may cause burns if manufacturer’s guidelines are not followed. In particular, the temperature of these devices should be reduced when warming children in shock.

2. **Intravenous fluid warming**, using a countercurrent heat exchange warmer (Hotline, Level One Inc., Rockland, Massachusetts, U.S.A)

3. **Passive insulation** using blankets (cotton or reflective space)

A nasopharyngeal or rectal temperature probe should be used to monitor core temperature throughout the resuscitation and in the operating room.

Urine output is an important indicator of circulatory volume status and renal function. A Foley catheter should be inserted as soon as the child is anesthetized, unless genital trauma is present.

Insertion of an intra-arterial line facilitates continuous blood pressure monitoring and intermittent blood sampling. However, insertion may be difficult if shock is present and should not delay surgical intervention to control bleeding. A 22G cannula should be used in infants and children <5 years old, while a 20G cannula should be used in older children. The most common site for insertion is the radial artery, although other superficial vessels, including the axillary, dorsalis pedis, posterior tibial, femoral, and brachial arteries, may be utilized. The brachial artery, being a single artery, is less desirable as thrombosis may cause limb ischemia. In children who are in shock, femoral arterial cannulation may prove more successful. A baseline arterial blood gas analysis will provide important information regarding adequacy of ventilation, acid–base status, electrolytes, and hemoglobin concentration.

Transfusion therapy is dealt with in another chapter; however, major trauma dictates that blood products should be available in the operating room prior to
the commencement of surgery. All intravenous fluids should be administered via a countercurrent warming device to reduce blood viscosity and prevent hypothermia. Prolonged shock, hypothermia, and massive transfusion (>1 blood volume in 24 hours) may result in coagulopathy, electrolyte abnormalities, and acid–base disturbances. Replacement of clotting factors should be guided by coagulation indices. Hyperkalemia and hypocalcemia are the most frequently observed electrolyte abnormalities after rapid transfusion of banked blood. While hyperkalemia does not usually cause clinical problems in children (unless rapid and massive transfusion occurs via a centrally placed catheter), hypocalcemia may occur independent of the route of administration and cause sudden hypotension and profound myocardial depression. Clinically relevant hypocalcemia, confirmed by a low plasma ionized calcium, should be treated with 0.2–0.3 mL/kg of 10% calcium chloride or 0.5 mL/kg of 10% calcium gluconate, repeated as often as necessary until rapid transfusion is no longer required and the calcium level stabilizes.

Shock and regional hypoperfusion lead to metabolic acidosis, which may be exacerbated by large volumes of chloride-containing solutions (0.9% saline, albumin) and stored blood (107). Base deficit has been shown to correlate with injury severity, and a base deficit < −8 meq/L is a strong predictor of mortality (108). Frequent blood gas analysis will help to guide therapy. Treatment of acidosis should focus on volume resuscitation and optimization of ventilation. The use of sodium bicarbonate is rarely indicated.

ANESTHESIA FOR NEUROTRAUMA

Head injuries are present in 75% of traumatized children and account for 70% of trauma-related deaths (109). A relatively large head that is balanced on a flexible cervical spine predisposes the child to flexion/extension injuries to the neck and head. The injury may be focal or diffuse, penetrating or blunt. In contrast to adults who sustain focal injuries after neurotrauma, children usually sustain diffuse injuries that are associated with a 50% or greater mortality rate (110).

The negative impact of hypoxemia and hypotension on secondary brain injury is well recognized. Apnea is common immediately following severe head injury and is directly related to the amount of energy transmitted to the brainstem at the time of impact (111). The ensuing hypoxia, hypercarbia, and acidosis, in combination with a stress-related catecholamine surge, result in considerable cerebral and cardiac dysfunction. Strategies that optimize cerebral oxygen delivery and perfusion are of the utmost importance in the resuscitation of these children.

Ventilatory Management and Control of ICP

Airway protection, adequate oxygenation, and control of ventilation (PaCO₂) are the prime objectives of airway control in the head-injured child. The brain is an obligate aerobic organ that depends on a constant supply of oxygenated blood for optimal function. Therefore, the ABCs of trauma resuscitation must always take precedence over concerns for ICP.

Under normal conditions, CBF is autoregulated to maintain constant blood flow over a range of mean arterial pressure from 60 to 150 mmHg. CBF is also coupled to metabolic requirements, with PaCO₂ and PaO₂ being the most critical mediators of vascular resistance (112). Until recently, the major cause of diffuse
cerebral swelling and intracranial hypertension after head injury has been attributed to hyperemia. However, CBF values in normal and head-injured children now indicate that hyperemia may be less common than previously thought (113). Consequently, the routine use of hyperventilation to reduce ICP has been questioned.

Using xenon-enhanced computed tomography (CT) scans, Skippen et al. demonstrated a strong relationship between hyperventilation and regional cerebral ischemia in children with isolated severe head injury (114). During ventilation to normocapnia (PaCO₂ = 4.7–5.3 kPa or 35–40 Torr), 29% of children exhibited evidence of ischemia in one or more areas of the brain. This incidence increased to 59% during hyperventilation to a PaCO₂ of 3.3–4.7 kPa (25–35 Torr), and to 73% at PaCO₂ levels below 3.3 kPa (25 Torr). Moderate hyperventilation is recommended to selectively control transient episodes of acute intracranial hypertension in order to prevent cerebral herniation (115,116). It should be noted that the salutary effects of hyperventilation are transient, as renal compensation establishes a new acid–base set point, with arteriolar tone returning to normal within 48 hours (112). Careful monitoring of minute ventilation and end-tidal carbon dioxide levels is essential to avoid inadvertent hyperventilation and dangerously low levels of arterial carbon dioxide tension.

Cerebral Perfusion Pressure

The concept of CPP, defined as the difference between the MAP and the ICP, is integral to the management of blood pressure in head trauma. With the introduction of ICP monitoring, CPP has become a standard measure of the adequacy of oxygen delivery to the brain. Current evidence from studies of adults with head trauma suggests that a minimal CPP of 60–70 mmHg is required to maintain adequate cerebral perfusion (117). Comparable data in children are lacking. Nonetheless, systemic hypotension is a strong predictor of morbidity and mortality after head injury, independent of age and hypoxia (118). Early placement of an intra-arterial catheter to provide continuous blood pressure monitoring is recommended in order to prevent hypotension and to facilitate arterial blood gas analysis.

Adjunctive Therapies to Lower ICP

In addition to hyperventilation, mannitol, an osmotic diuretic, is first-line therapy to control severe intracranial hypertension. Mannitol decreases ICP and increases CPP and jugular venous oxygen saturation by shrinking brain cell volume via an osmotic effect (119,120). This effect is offset, in part, by a transient increase in systemic blood pressure and decrease in blood viscosity. The net effect is an increase in CBF, followed by compensatory vasoconstriction and a reduction in ICP. If administered too rapidly, mannitol may transiently vasodilate the cerebral vasculature and paradoxically increase ICP. To obviate this effect, mannitol (0.25–1.0 g/kg IV) should be given slowly (over approximately 10 minutes). Repeat doses of mannitol are contraindicated in the traumatized patient, as mannitol may accumulate in the brain and exacerbate the cerebral edema. Careful monitoring of intravascular volume, serum osmolality, and serum sodium concentration is essential to optimize the benefits of mannitol.

The loop diuretic furosemide is also used to decrease the volume of the brain, either alone (0.5–1.0 mg/kg) or in combination with mannitol (0.15–0.3 mg/kg). The combination of both diuretics is more effective in lowering ICP than either singularly, although profound dehydration and electrolyte disturbances may occur. Monitoring of volume status and serum electrolytes is essential to preclude complications.
The use of barbiturates to treat intracranial hypertension is controversial. Thiopentone (2-4 mg/kg IV) may be used to treat an acute increase in ICP. Eisenberg et al. demonstrated that barbiturates are highly effective in treating refractory intracranial hypertension that is unresponsive to cerebrospinal fluid (CSF) drainage, hyperventilation, and mannitol (121). Pentobarbital coma has been used to induce coma after brain swelling. However, the high doses required to produce coma and burst suppression on the EEG frequently cause significant hypotension, which may further compromise CPP and necessitate inotropic support. Furthermore, thiopentone therapy has not been shown to improve neurological outcome.

ANESTHESIA FOR THORACIC TRAUMA

Thoracic injury in the pediatric population is usually the result of blunt trauma, as penetrating trauma accounts for less than 10% of thoracic injuries (122). Chest trauma in children is a marker of injury severity and is associated with a high mortality rate. A retrospective study of 1356 trauma patients from a private pediatric hospital over a 2.5-year period showed a 1% incidence of chest injuries and a mortality rate of 22%. When extrathoracic injury, especially head and neck injuries, complicates thoracic trauma, the mortality (29%) is sevenfold greater than when the injuries are restricted to the chest (4.3%) (123). Similarly, the association of a pulmonary contusion with severe head injury in children leads to a poorer neurological outcome (124).

Immediate treatment of life-threatening injuries, such as tension pneumothorax, open pneumothorax, massive hemothorax, flail chest, and cardiac tamponade, may be required on the basis of clinical examination alone. Securing the airway is the first priority, although tension pneumothorax and cardiac tamponade may require emergent needle decompression under local anesthesia prior to induction of general anesthesia and tracheal intubation.

Pulmonary Contusion and Chest Wall Injury

Pulmonary contusion is a common finding in patients who sustain severe blunt chest injuries. Although children with such injuries were thought to have a more favorable outcome than adults, a recent review suggests that this is not the case (125). Alveolar hemorrhage and parenchymal destruction are maximal during the first 24 hours after injury and usually resolve within seven days (126). The diagnosis of lung injury may be made clinically; however, it is usually confirmed by chest X ray. CT is highly sensitive in identifying pulmonary contusion and may help predict the need for mechanical ventilation.

The elasticity of the bony and cartilaginous thoracic skeleton of a child produces different patterns of injury compared with those seen in adult trauma. Significant pulmonary and mediastinal injury may occur in the absence of rib fractures. However, if rib fractures are present, the severity of injury in children is far greater, and an underlying pulmonary contusion is likely (127). In the presence of first rib fractures, with or without subcutaneous emphysema, a bronchial tear should be considered.

Respiratory distress is common after lung trauma, with hypoxemia and hypercarbia generally increasing over the first 72 hours. The management of patients with pulmonary contusion usually involves supportive respiratory measures to optimize gas
exchange. Early detection and prevention of injury progression provide the greatest chance for survival. Avoidance of fluid overload, oxygen therapy, and a low threshold for mechanical ventilation are useful therapeutic guidelines. Shorter inspiratory times result in faster respiratory rates in infants and children. For mechanical ventilation, standard ventilatory settings include an inspiratory-to-expiratory (I:E) ratio of 1:2, a respiratory frequency of 10 to 14 in adolescents, 14 to 20 in children, and 20 to 30 in infants. However, ventilatory parameters often need to be altered according to the end-tidal carbon dioxide and arterial blood gas measurements.

A large gas leak around an unsealed tracheal tube can lead to a loss of volume during the inspiratory phase of mechanical ventilation and compromise alveolar ventilation if the pulmonary compliance is low. Changes in head position may further exacerbate the leak. Accordingly, it is imperative to monitor both inspiratory and expiratory volumes and arterial carbon dioxide tension in order to monitor the alveolar ventilation.

In neonates and infants, pressure-limited, time-cycled ventilation is commonly employed to avoid excessive, inflation pressures and barotrauma. However, any reduction in chest compliance, or the increase in compliance of the ventilator circuit, will compromise the delivered tidal volume and alveolar ventilation. Therefore, most ventilators are equipped with alarms and respiratory monitoring to ensure that an adequate minute ventilation is achieved.

A low level of positive end expiratory pressure (PEEP) has been advocated to reduce pulmonary atelectasis and restore resting lung volume during general anesthesia. As little as 5 cm H2O of PEEP has been shown on CT scans to prevent or reverse atelectasis in dependent regions of the lungs in healthy children (128). Recent evidence suggests that the use of low-volume, pressure-limited ventilation in combination with high levels of PEEP may improve outcome in children with adult respiratory distress syndrome (ARDS) (129). Reductions in both the tidal volume and respiratory frequency increase carbon dioxide tension, known as permissive hypercapnia, which may protect against ventilator-induced lung injury and improve oxygenation and lung compliance (130). A long inspiratory phase (inverse ratio ventilation) has also been advocated.

Volume-limited ventilators are more often used in older children to deliver a constant tidal volume independent of changes in chest compliance. A reduction in the conductance of the breathing circuit (kinked or blocked tracheal tube) or pulmonary compliance will lead to high inflation pressures and an increased risk of barotrauma. Normal values for tidal volume in awake, spontaneously breathing children range from 6–8 mL/kg. However, larger tidal volumes of 10–15 mL/kg are required under anesthesia, due to a reduction in the resting lung volume, uneven distribution of ventilation, and an increase in physiologic dead space. Only the I:E ratio and respiratory frequency should be set before connecting the ventilator tubing to the tracheal tube. The volume and flow should be set very low initially, and then gradually increased until the desired inspiratory pressures (<20 cm H2O) and chest excursion are achieved. The inability to accurately deliver small tidal volumes with volume-limited ventilators has restricted their use to children greater than 10 kg in weight.

Complications of pulmonary contusion include pneumonia and ARDS. However, the overall incidence of ARDS in children admitted with pulmonary contusion or multiple trauma is relatively low (<3–14%) (131,132). In some children with severe lung injury, however, gas exchange may deteriorate despite optimal conventional ventilatory management. Alternative therapies include high-frequency ventilation,
prone ventilation, nitric oxide, liquid ventilation, and extracorporeal membrane oxygenation (ECMO) (130).

**Blunt Cardiac Injury**

Blunt cardiac injury is rarely seen in children with multisystem trauma. Myocardial contusions are the most common lesion; however, wall disruption and valvular lesions may occur (133). Although clinical signs such as absence of heart sounds are suggestive of cardiac injury, the diagnosis is usually made by 12-lead electrocardiography (ECG) or 2D echocardiography (ECHO). However, a normal ECG does not rule out the possibility of cardiac injury (134). The presence of rib fractures and pulmonary contusion on chest radiograph should give rise to a clinical suspicion of occult myocardial damage. Measurement of myocardial creatine phosphokinase (CPK-MB), although often performed, correlates poorly with both ECG and ECHO findings of cardiac injury (135). Troponin may be a better predictor of cardiac injury.

If hemopericardium progresses to cardiac tamponade, induction of anesthesia becomes extremely hazardous, as preload becomes restrictive. Controlled ventilation is also poorly tolerated as the increase in intrathoracic pressure further restricts preload. If the tamponade is severe (the child is unable to lie down, large pulsus paradoxus), then pericardiocentesis should be performed under local anesthesia (with or without sedation). If the pericardial effusion is not severe, either sedation or general anesthesia may be induced, but in either case, spontaneous ventilation should be maintained. The sedation technique is classically ketamine, although midazolam and propofol combination have also been used. Etomidate or ketamine are ideal for induction of anesthesia, as both maintain heart rate, myocardial contractility, and systemic vascular resistance.

**Cardiopulmonary Resuscitation**

In children beyond one year of age, trauma is the leading cause of cardiac arrest (135). The prognosis for children suffering a cardiac arrest is poor, with less than 10% surviving to hospital discharge (136). In a recent study of pediatric trauma patients, the survival rate was 23.5% for children who required CPR (137). Survival rates were significantly better in children who received pre-hospital CPR, suffered blunt versus penetrating trauma, and presented with systolic blood pressures in excess of 60 mmHg. Nonetheless, of those who survived, almost two-thirds suffered significant neurological impairment.

In general, children suffer primary respiratory arrests, which are associated with a far better prognosis than primary cardiac events. Accordingly, airway management and correction of hypoxia are fundamental principles for successful CPR in children. While ventilation and oxygenation are established, a defibrillator or cardiac monitor should be attached to assess the cardiac rhythm. Cardiac compressions should continue until a carotid pulse is palpable. The mechanism by which cardiac compressions produce cardiac output is controversial, but has been attributed to direct cardiac compression, or the increase in intrathoracic pressure secondary to compression (136). Organ blood flow during cardiac compressions is significantly impaired, with animal studies demonstrating that cerebral and myocardial blood flows are only 5% to 20% of prearrest levels (138). Novel techniques, such as active compression–decompression CPR and interposed abdominal compression CPR, have been investigated during CPR in adults although no studies have been forthcoming in children (136).
Ventricular fibrillation (VF) and pulseless ventricular tachycardia are rare in children. If they occur, immediate unsynchronized defibrillation should be initiated. An energy level of 2 J/kg should be used for the first two shocks, followed by 4 J/kg thereafter. Pediatric paddles are appropriate for children below 10 kg (~1 year of age). Conducting gel pads should always be used to reduce the impedance across the chest wall. Persistent VF should prompt a reevaluation of the child’s medical and drug history, and electrolyte and acid–base status. Cardiopulmonary resuscitation should never be abandoned while there is recognizable VF.

Asystole and pulseless electrical activity (PEA) are more common in children. An initial dose of 10 μg/kg (0.1 mL of 1:10,000) of epinephrine should be administered via the intravenous or interosseous routes. If intravenous access has not been achieved, a dose of 100 μg/kg (1 mL/kg of 1:10,000 or 0.1 mL/kg of 1:1000) may be given into the lumen of the endotracheal tube. After a three-minute cycle of cardiac compressions, a further 10 μg/kg of epinephrine should be administered intravenously if spontaneous circulation has not returned. Correction of acidosis (1 mL/kg of 8.4% sodium bicarbonate), hypoglycemia (0.5 g/kg of 50% dextrose), and hypovolemia should also be considered. Other reversible causes of PEA should be identified and treated immediately (Table 8). The survival rate for traumatized children with asystole is less than 2%.

**Table 8** Reversible Causes of Pulseless Electrical Activity (PEA)

<table>
<thead>
<tr>
<th>Cause</th>
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<tr>
<td>Hypoxia</td>
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<td>Hypovolemia</td>
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<td>Hypothermia</td>
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<tr>
<td>Hyper/hypokalemia</td>
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<tr>
<td>Tamponade</td>
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<tr>
<td>Tension pneumothorax</td>
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<tr>
<td>Thromboemboli</td>
</tr>
<tr>
<td>Toxicity (drug induced)</td>
</tr>
</tbody>
</table>

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Prevention and Treatment of Trauma-Related Infection in Children

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INTRODUCTION

Trauma is a leading cause of death in children. Interventions have led to improved survival and longer hospitalization, but at the cost of an increase in infectious complications. Although the etiology and treatment of infectious complications observed in injured adults has been well studied, little has been written about trauma-related infections in children. In this chapter, we review the spectrum of infections that occur in the injured child and present guidelines for prevention and treatment of the most frequent and serious types based on the best current evidence.

STATEMENT OF THE PROBLEM

Overview

Only two studies performed since 1990 describe the overall incidence of infectious complications in injured children (1,2). These retrospective studies from large level I pediatric trauma centers give an initial overview of the problem. Although severity of injury of the patients studied in each report differs, both describe similar results regarding the frequency, type, and distribution of infections. Major infectious complications occur in about 10% of pediatric trauma patients (Fig. 1). The incidence of infection was affected little by age, sex, or mechanism of injury. Children
with infectious complications, however, were more seriously injured [as evidenced by a higher injury severity score (ISS) and lower Glasgow Coma Score (GCS)] and required mechanical ventilation twice as often as those without. While mortality is not higher in children with infectious complications, a longer length of hospital (21 vs. 6 days) and ICU (15 vs. 3 days) stays were observed in this group (2).

Data from these studies suggest that infections at sites of trauma represent about 25% of cases, while nosocomial infections, including pneumonia, bacteremia, and urinary tract infections, account for about 75% (Fig. 1) (1,2). The distinction between these two categories is important since the epidemiology, microbiology, and approaches to prevention and treatment differ. Trauma-related infections are due to the injury itself and are most often at the site of injury. These include soft tissue infection associated with a laceration, osteomyelitis related to an open fracture, or an intra-abdominal abscess following a penetrating abdominal injury. Nosocomial infections are acquired during hospitalization and are related to host compromise or therapeutic interventions. These include pneumonia, bacteremia, and urinary tract infection.

**Literature Reviews**

An extensive review of the medical literature using the Medline database since 1990 demonstrated no level-I or -II studies regarding the prevention and management of infections in injured children using the classification outlined by the U.S. Preventive Services Task Force (3). For several categories of infection, guidance can only be projected from studies performed in adult trauma patients, pediatric general surgery patients, or critically ill hospitalized children. None of the studies used to construct these recommendations were based on controlled, prospective data on type or duration of antibiotic therapy or other treatment. In addition, no study described a systematic approach for obtaining cultures at potential sites of infection. Although the antibiotic recommendations described below are based in part on culture data obtained from these studies, our recommendations need to be interpreted with
caution because they are based on retrospective reviews. In these studies, children who were treated for a potential infection may not have been cultured before antibiotics were started, leading to a lower representation of more common and important isolates. Since cultures were generally obtained from patients who failed initial antibiotic treatment, culture data will also be biased to represent more resistant or unusual isolates.

TRAUMA-RELATED INFECTIONS

Overview

The potential site of a trauma-related infection can usually be identified at the time of injury. Open extremity wounds, often associated with a fracture, are the most common trauma-related infections (53–55%), followed by intra-abdominal infections (18–36%) and central nervous system infection (9–18%) (Fig. 1) (1,2). Other less common sites of trauma-related infection reported in children include the paranasal sinuses and oral cavity. In contrast to nosocomial infections, positive cultures are usually obtained within the first few days after injury. Polymicrobial cultures are observed in almost half of infected patients (1).

Wound Infections

The risk of infection in a wound is dependent on the extent of tissue injury, the amount of initial contamination, the presence of foreign material, the body site involved, and the timeliness and adequacy of surgical wound care. Both extrinsic and indigenous microflora may contribute. Because of the diversity of traumatic wounds, generalizations about their epidemiology, microbiology, and treatment should be interpreted with caution. One study describing posttraumatic wound infection found that *Staphylococcus* species (50%) and gram-negative bacteria (33%) were the most frequent aerobic isolates followed by streptococci (17%). Most infections involving anaerobic bacteria were found to be polymicrobial (4).

Treatment of traumatic wounds should be individualized to the amount of injury, degree of contamination, body site, and time since injury. Although the diversity of these traumatic wounds precludes a uniform approach, several general principles can be used. All wounds should be debrided and irrigated to lower the microbial inoculum and remove foreign matter. Wounds associated with significant contamination or a significant delay in treatment should be left open unless cosmetic or functional considerations favor early closure. Initial antibiotic therapy of minimally contaminated wounds should cover gram-positive organisms. Treatment of more contaminated wounds or wounds treated after a significant delay should also include coverage for gram-negative bacteria and anaerobes (Table 1). The choice of empiric antibiotics can also be modified based on examination of the Gram stain obtained at the time of surgical wound treatment. Cultures should be obtained at the time of initial treatment of complex wounds, since these may give additional information needed to modify antibiotic therapy in highly contaminated wounds or wounds responding poorly to initial treatment.

Wound infections usually present with increasing pain, drainage, fluctuance, erythema, or edema (Fig. 2). For most wound infections, deep needle aspirate through an airless syringe should be submitted for aerobic and anaerobic culture before the wound is opened and treated. A deep-wound swab promptly placed into anaerobic transport medium is best if no pus can be obtained with needle and
Table 1  Recommended Empiric Treatment of Trauma-Related Infectious Complications in Children

<table>
<thead>
<tr>
<th>Category</th>
<th>Site</th>
<th>Category of infection</th>
<th>Antibiotic recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trauma-related</td>
<td>Wound</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Empiric treatment:</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Minimal contamination</td>
<td>1st generation cephalosporin</td>
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<td></td>
<td></td>
<td>Contamination or delayed treatment</td>
<td>1st generation cephalosporin + aminoglycoside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Treatment of established infection</td>
<td>Antistaphylococcal penicillin + aminoglycoside</td>
</tr>
<tr>
<td>Open fracture</td>
<td></td>
<td>Empiric treatment:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gustilo grade I or II</td>
<td>1st generation cephalosporin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gustilo grade III</td>
<td>1st generation cephalosporin + aminoglycoside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavily contaminated wound</td>
<td>1st generation cephalosporin + aminoglycoside + clindamycin</td>
</tr>
<tr>
<td>Abdomen</td>
<td></td>
<td>Empiric treatment:</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Low risk injury</td>
<td>2nd generation cephalosporin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High risk injury:</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Significant peritoneal contamination</td>
<td>Aminoglycoside + clindamycin + ampicillin</td>
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<tr>
<td></td>
<td></td>
<td>Multiple transfusions required</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Ostomy formation</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Multiple intra-abdominal injuries</td>
<td></td>
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<td></td>
<td></td>
<td>Treatment of established infection</td>
<td></td>
</tr>
<tr>
<td>Central nervous</td>
<td>system</td>
<td>Empiric treatment:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Closed fracture crossing infected sinus</td>
<td>Cefuroxime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open fracture</td>
<td>Antistaphylocal penicillin + aminoglycoside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open fracture with major contamination</td>
<td>Meropenem</td>
</tr>
</tbody>
</table>
**Treatment of established infection**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Antibiotic regimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed fracture crossing infected sinus</td>
<td>Cefuroxime + vancomycin if gram-positive cocci on smear</td>
</tr>
<tr>
<td>Open fracture with major contamination</td>
<td>Antibiotics for staphylococcal infection + aminoglycoside + vancomycin if gram-positive cocci on smear</td>
</tr>
</tbody>
</table>

**Nosocomial**

<table>
<thead>
<tr>
<th>Location</th>
<th>Antibiotic regimen</th>
</tr>
</thead>
</table>
| Lung/trachea | **GRAM STAIN**
  - First 48 hrs (trauma-related or community acquired)
    - unavailable or negative gram-negative rods
    - cefuroxime +/- azithromycin add aminoglycoside add vancomycin
  - After 48 hrs (nosocomial)
    - gram-negative rods polymicrobial
    - vancomycin + ticarcillin-clavulinate or piperacillin-tazobactam or meropenem |
| Bloodstream | Vancomycin + aminoglycoside or 3rd generation cephalosporin |
| Urinary tract | Aminoglycoside or 3rd generation cephalosporin |
| Central nervous system | Vancomycin + 3rd generation cephalosporin or meropenem |
| Sinus | **GRAM STAIN**
  - Standard
    - Cefuroxime
  - Prolonged intubation
    - Timentin-clavulinate, piperacillin-tazobactam or meropenem |
| Surgical site | Ampicillin-sulbactam |
syringe. Culture of drainage from the wound surface may be useful at times (e.g., when large numbers of group streptococci are present) but may be misleading because secondary contamination is possible, and anaerobes may not survive exposure to air. Antibiotics should be started if cellulitis is present or if the patient has shown evidence of clinical deterioration. The choice of antibiotics may be influenced by Gram stain, though initial treatment should cover gram-positive and gram-negative bacteria and anaerobes, and may be modified based on culture results (Table 1). The initial treatment of open fractures should include antibiotic therapy in addition to wound debridement and surgical repair. Early administration of antibiotics may protect against infection even if surgical intervention is delayed (5). Risk for wound infection or osteomyelitis is correlated with severity of open fracture, graded using the modified Gustilo classification (6). Cultures obtained from wounds shortly after injury are frequently polymicrobial. Isolates from the initial wounds of children with open fractures include Enterococcus species (23%), gram-negative rods (23%), Staphylococcus epidermidis (15%), Streptococcus species (15%), anaerobes (8%), and Staphylococcus aureus (5%) (7). Because initial cultures poorly correlate with those obtained in patients with infection, treatment can be limited to organisms visualized on Gram stain, found in moderate to heavy growth, or revealed to be an aggressive pathogen such as S. aureus or group A Streptococcus. Appropriate initial antibiotic coverage for open fractures includes a first generation cephalosporin such as cefazolin for Gustilo grade I or II injuries. For grade III injuries, gentamicin and clindamycin may be added, particularly for heavily contaminated wounds (Table 1).

Early indications of a superficial or deep infection in children with open fractures include increasing pain, wound or pin site erythema, wound edema, or
drainage. Radiologic changes of osteomyelitis are usually absent until the second or third week of infection. Superficial wound infections in the absence of radiographic evidence of osteomyelitis require local wound drainage. Operative debridement is required when osteomyelitis is present. Among patients with either superficial or deep infection, isolates include gram-negative bacilli (29%), Enterococcus species (24%), S. epidermidis (24%), anaerobes (12%), and S. aureus (12%) (7). Broad-spectrum antibiotic coverage with ticarcillin-clavulinate, piperacillin-sulbactam, or meropenem, to which is added an aminoglycoside such as gentamicin or tobramycin, are indicated in patients with suspected posttraumatic osteomyelitis (Table 1). Intraoperative Gram stain and cultures from bone, abscesses, and deep tissues should be obtained in all patients undergoing surgical debridement. These studies should be used to modify antibiotic therapy.

Intra-abdominal Infections

Intra-abdominal infections are the second most common trauma-related infection in children (1,2). Because data regarding the etiology and treatment of traumatic intra-abdominal infection in injured children are limited, information about the epidemiology and treatment of these infections must be extrapolated from adult studies and from infections such as those resulting from perforated appendicitis. Intra-abdominal infection is common following penetrating trauma, but also may occur after blunt abdominal trauma (8,9). The risk of infection is higher following blunt or penetrating colonic injury than following more proximal intestinal injury, probably because of the relatively higher concentration of microbial flora in the distal ileum and colon compared to the more proximal gastrointestinal tract. The principal source of infection following gastrointestinal tract injury is the endogenous microflora of the gut lumen, even following blunt injuries (9). In addition to initial peritoneal contamination, other contributing factors include multiple organ injury, multiple transfusions, and ostomy placement (9,10).

The mainstay of initial treatment for potential trauma-related intra-abdominal infection is prompt and appropriate surgical treatment. No studies have examined the risks of infection for abdominal trauma without the use of antibiotics. In addition to prompt and appropriate surgical treatment, the current practice of providing preoperative antibiotics is appropriate, even when a penetrating or blunt intestinal injury is only suspected. If exploration shows no evidence of injury, antibiotics may be discontinued. Antibiotics should be continued postoperatively when intestinal injury is present. The duration of antibiotic therapy required postoperatively, however, remains controversial, ranging from one to five days in different reports (10). Gram stains and cultures of peritoneal fluid obtained at surgery may identify patients at risk for infection, but should not be the sole factors determining the choice of perioperative antibiotics. Antibiotics should be directed against the common infecting organisms, including enteric gram-negative rods and anaerobes, including Bacteroides and Clostridium species, and anaerobic streptococci (Table 1). Initial antibiotic regimens include a second-generation cephalosporin with anaerobic coverage such as cefoxitin or a combination of an aminoglycoside and clindamycin. Ticarcillin-clavulinate or meropenem should also be adequate.

Ongoing peritonitis or an intra-abdominal abscess should be considered in any child with an unexplained fever, leukocytosis, or clinical deterioration who has undergone initial abdominal exploration for treatment of a penetrating or blunt intestinal injury. Specific evidence of an intra-abdominal infection includes persistent
or worsening abdominal pain, abdominal distension, or ileus (Fig. 2). Computed tomography (CT) or ultrasound examination of the abdomen should be performed, seeking an intra-abdominal abscess. Repeat abdominal exploration or drainage of intra-abdominal abscesses may be required. In all cases, an antibiotic regimen listed in the paragraph above should be used (Table 1). If gram-positive cocci are seen on Gram stain, vancomycin or an aminoglycoside may be added to optimize activity against methicillin-resistant *Staphylococcus* and *Enterococcus*. Isolation of resistant organisms such as extended-spectrum beta-lactamase–producing enteric rods or vancomycin-resistant *Enterococcus* requires individualized management that may benefit from consultation with an infectious disease specialist.

**Central Nervous System Infections**

Central nervous system infections are the third most common trauma-related infections in children and include meningitis, ventriculitis and subdural and epidural infections, and brain abscesses (1,2). No studies have reviewed the incidence and management of these infections in children. Diagnosis and treatment of central nervous system infection in injured children must be based on data from studies of adult trauma patients. Adult trauma patients with cerebrospinal fluid leaks, penetrating injuries, open or depressed skull fractures, or closed fractures that cross a chronically infected sinus are particularly susceptible to infection (11). When head injury is associated with a cerebrospinal fluid leak, the risk of infection may be increased up to 10-fold (11). Leaks to skin, paranasal sinuses, middle ear, or nasal passages may occur. Risk of infection also increases with the length of time that the cerebrospinal fluid leak is present (11). Since central nervous system infections may follow basilar skull fractures, the initial head CT scan of the injured child should be examined for fracture lines in the skull bases or more subtle findings of these fractures such as air–fluid levels or sinus opacification. Fine-cut CT scan and other techniques may be required to demonstrate these fractures.

Although data obtained in studies of injured children are limited, they suggest that the microbiology of central nervous system infections in injured children is similar to that observed in injured adults. The predominant organisms isolated from patients with communication between the central nervous system and respiratory tract include *Streptococcus pneumoniae*, followed by *Haemophilus influenzae* and *Neisseria meningitidis* (1,2,11). *S. aureus* is the most common organism in open skull fractures and penetrating brain injuries consistent with direct implantation of bacteria into the central nervous system as the mechanism of infection (11). As with all traumatic injuries, all open central nervous system wounds should be debrided and retained bone fragments and foreign material removed. Intraoperative cultures should be obtained to help direct antibiotic therapy and allow for more selective use of antibiotics after culture results are available. Patients who have a closed fracture crossing a known infected sinus should be treated with cefuroxime. Those patients who have experienced penetrating trauma should receive coverage for staphylococci and gram-negative bacilli using an antistaphylococcal penicillin and an aminoglycoside. When extensive contamination or residual foreign material in the brain parenchyma is observed, merepenem may be substituted for the cephalosporin to cover anaerobic organisms as well as gram-negative rods (Table 1).

A high index of suspicion for infection must be maintained when treating head injury patients since the presentation of a central nervous system infection after initial treatment may be subtle. Symptoms and signs of central nervous system infection include headache, change in mental status, vomiting, nuchal rigidity, seizures, or
cranial nerve deficits (Fig. 2) (11). Because many of these signs and symptoms may also be observed in head injury patients without infection, central nervous system infections may be difficult to identify in many patients, particularly those with severe head injuries. Whenever central nervous system infection is suspected, a head CT scan or magnetic resonance image (MRI) should be obtained, especially for patients who have had surgical treatment of an open head injury, and lumbar puncture should promptly be performed. Initial antibiotic choices are the same as those indicated above and should be modified based on Gram stain and culture results (Table 1).

NOSOCOMIAL INFECTIONS

Overview

Nosocomial infections are observed in about 7% of all pediatric trauma patients and represent the majority of these infections (1,2). Pneumonia is the most common type of nosocomial infection, followed by bacteremia and urinary tract infections (Fig. 1). Infections at these three sites represent 75% to 85% of all nosocomial infections. Other locations for nosocomial infection that have been reported include central nervous system, sinus, and surgical wound. More than one nosocomial infection is observed in 24% to 35% of patients (1,2). In contrast to those with trauma-related infections that occur early after injury, patients with nosocomial infections usually exhibit their first positive culture one to two weeks after injury. Most nosocomial infections can be directly or indirectly associated with the use of an invasive device, including endotracheal tubes, vascular catheters, urinary catheters and intracranial pressure monitoring devices (1,2).

Although no difference in age, sex, or mechanism of injury is observed, children with nosocomial infections are more severely injured as shown by higher injury severity score (ISS) and lower Glasgow Coma Scale (GCS) than those without nosocomial infections (1,2). Severe head trauma is particularly associated with the development of these infections. One study showed that the presence of a nosocomial infection was associated with an average of 16 days longer length of stay when controlling for severity of injury (1). This finding suggests that measures to prevent and treat infections in the injured child may reduce length of stay and overall cost.

Pneumonia

Although pneumonia is the most frequent nosocomial infection observed in 2.7 to 5.5% of injured children, few studies have detailed the features of pneumonia in this population (1,2,12). Higher ISS score and more severe head or chest injury are associated with subsequent pneumonia. In addition, children with nosocomial pneumonia more commonly have associated head, orthopedic, or torso injuries than those with other traumatic injuries (12).

Although decreased immune resistance associated with severe injury may increase the risk of pneumonia, the increased airway manipulation required in severely injured children may be the most important contributing factor (12). The risk of nosocomial pneumonia is increased two-to threefold among children requiring mechanical ventilation after injury. In all but 10% of pneumonia episodes, the development of infection is associated with the presence of either an endotracheal tube or tracheostomy. Pneumonia is associated with a longer duration of mechanical ventilation and intubation in both children and adults in the intensive care unit, as well as in adults with head injury (13,14). Colonization of the lower airway of
intubated adults with head injury increases with each successive day of intubation and is more rapid when sedation is increased (13). These observations suggest that clearance mechanisms such as cough and airway mucociliary action may be decreased due to head injury or sedation leading to increased lower respiratory tract infection. In contrast to adult trauma patients, the development of nosocomial pneumonia in pediatric trauma patients has not been associated with an increase in mortality. Nosocomial pneumonia, however, is associated with a two- to threefold longer length of stay (12). As with overall nosocomial infection rates, longer hospitalization

![Figure 3](image_url)

**Figure 3** Organisms isolated from pediatric trauma patients with nosocomial pneumonia early (A), up to one week, and late (B), more than one week, after injury. *Source:* Modified from Ref. 12.
may be due to the development of pneumonia or to the severity of the underlying injuries that contributed to development of these infections.

A range of bacterial and fungal organisms and viruses has been isolated in specimens obtained from injured children with nosocomial pneumonia. Chest radiograph findings of lobar or segmental consolidative pneumonia usually indicate a bacterial infection. An interstitial pattern should lead to the consideration of a viral, *Mycoplasma pneumoniae*, or *Chlamydia pneumoniae* infection. Sputum cultures containing only a single microbial pathogen are more common than polymicrobial cultures. Gram-negative bacilli represent about 60% of isolates, gram-positive bacterial organisms about 30%, and fungal and viral pathogens the remaining 10% (2,12). The microbiology of nosocomial pneumonia differs depending on whether the infection develops early or late after injury (Fig. 3) (5). Gram-positive cocci and *H. influenzae* are the most common organisms cultured from specimens obtained during the first week after injury, while gram-negative bacterial organisms predominate in cultures obtained after that time (12). Regardless of the length of stay, *S. aureus* or *Streptococcus pyogenes* toxic shock syndromes should be considered if gram-positive cocci are predominant or exclusive on Gram stain or if shock is present, especially with the presence of a rash. During influenza epidemics, oseltamivir should be added for the duration of hospitalization to both treat and prevent influenza. If the epidemic is known to be due to influenza A, amantadine or rimantadine may be used.

Clinical findings that suggest pneumonia include increased sputum production, requirement for increasing ventilatory support, and new findings on chest examination.
Minimal initial evaluation should include a chest radiograph and a sputum Gram stain and culture. Respiratory tract specimens should be collected without dilution by tracheal injection of saline. Organisms from undiluted tracheal aspirates with rare or scant growth may be of little clinical significance, except when very likely pathogens such as group A Streptococcus, probably S. pneumoniae or possibly S. aureus. When an interstitial pattern is observed on chest radiograph, rapid polymerase chain reaction testing for respiratory tract Mycoplasma or Chlamydia should be used.

Although the culture results previously described represent data obtained from one institution, these observations provide the best data available to date for empiric therapy of nosocomial pneumonia in injured children. The initial choice of antibiotics for the treatment of pneumonia can be based on the results of a Gram stain, as well as the organisms that are likely present depending on the time of diagnosis. During the first 48 hours, empiric antibiotic coverage with cefuroxime or azithromycin is appropriate. After the first 48 hours, antibiotic regimens should include an aminoglycoside when gram-negative bacilli are observed, and vancomycin when gram-positive cocci are found on Gram stain. Polymicrobial infection suspected by Gram stain results should be treated with broad-spectrum coverage using ticarcillin-clavulinate, piperacillin-tazobactam, or meropenem (Table 1). When Staphylococcal toxic shock syndrome is suspected, the addition of clindamycin and intravenous gamma globulin is usually indicated.

Measures to determine the effectiveness and required duration of antibiotic therapy for injured children with nosocomial pneumonia have yet to be established. Easily obtainable clinical variables such as physical examination, fever peak and trend; the volume, thickness, and color of sputum, and ventilator support requirements can give useful information in this regard. Additional information can be obtained from objective parameters such as serial Gram stain and culture (observing for number of polymorphonuclear cells and in vivo response of bacteria to treatment) and white blood cell indices (serial absolute neutrophil counts, absolute and relative number of immature neutrophils, toxic granulation of the neutrophils, and Dohle bodies).

**Bacteremia**

Bacteremia is the second most frequent nosocomial infection observed in injured children occurring in 1.3% to 1.9% of patients (1,2). Most blood stream infections are associated with an indwelling intravascular catheter such as a central venous or arterial line. Similar to observations made in all hospitalized pediatric patients and in pediatric intensive care unit patients, the most frequent isolate is coagulase-negative staphylococci followed by S. aureus and gram-negative bacteria (2,15,16).

The first sign of a nosocomial blood stream infection is often an unexplained fever or leukocytosis. Inflammatory changes at the site of an intravascular catheter suggest a tunneled or superficial infection (Fig. 4). Evaluation for a blood stream infection should include blood cultures through each intravascular line and from a separate peripheral site whenever possible. Quantitative or semiquantitative blood culture techniques can help differentiate line sepsis from others, or distinguish which of multiple lines may be infected. When bacteremia is suspected, initial empiric antibiotic therapy should be directed toward the most frequent isolates. Vancomycin may be used for coverage of staphylococci and an aminoglycoside or cefotaxime for gram-negative bacteria (Table 1). The choice of antibiotics can be modified after
culture results are available. When bacteremia is suspected in the setting of unexplained clinical deterioration, the suspected infected line should be removed aseptically and its tip sent for culture.

**Urinary Tract Infection**

Urinary tract infections are the third most frequent nosocomial infection occurring in 1.3% to 1.5% of pediatric trauma patients (1,2). Although data in injured children are limited, urinary tract infections in this group are most often associated with the use of an indwelling catheter or other urinary tract manipulation and are most commonly due to gram-negative bacteria. Similar findings have been reported in both hospitalized general pediatric and pediatric surgical patients (17). Although symptoms referable to the urinary tract, including abdominal or flank pain, dysuria, urinary frequency or urgency, may be observed, many injured children with urinary tract infections may have non-focal findings or may be initially asymptomatic (Fig. 4). An initial urinalysis should be obtained and a urine culture sent if this study demonstrates pyuria or bacteriuria. Initial empiric therapy should include coverage for gram-negative bacteria using an antibiotic such as an aminoglycoside or a third-generation cephalosporin (Table 1).

**Central Nervous System Infection**

Nosocomial central nervous system infection, including meningitis or brain abscess, almost always occurs in patients who have undergone a neurosurgical procedure or who have had an indwelling intracranial drainage or monitoring device. While risk factors for nosocomial central nervous system infections have not been reported in injured children, a contiguous focus of infection such as sinusitis, emergency surgery, cerebrospinal fluid drainage, cerebrospinal fluid leakage, and early reoperation have been associated with an increased chance of these infections in adults (18). A recent study demonstrated that *S. aureus* is isolated from about one-half of all postcraniotomy patients with deep infections. Other common isolates include gram-negative bacteria, coagulase-negative staphylococci, and streptococci (19).

The clinical presentation of nosocomial central nervous system infections may initially be subtle. Diagnosis is particularly difficult in patients with severe head injuries (Fig. 4). When a nosocomial central nervous system infection is suspected, a head CT should be performed to identify evidence of an intracranial abscess or other lesions requiring surgery. A lumbar puncture or fluid from any cerebrospinal fluid drain should also be obtained. Empiric antibiotic coverage with vancomycin plus a third-generation cephalosporin or meropenem (if anaerobes are suspected) should cover most organisms identified in these infections (Table 1).

**Sinusitis**

While data are not available in injured children, pediatric nosocomial sinusitis is common and has been associated with prolonged nasogastric or nasotracheal tube intubation (20,21). Aerobic organisms are found in 40% of isolates, anaerobic organisms in 25% of isolates, and mixed flora in the remaining 35% of isolates. Aerobes found in these infections include *Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *S. aureus*. Predominant anaerobes include *Peptostreptococcus* species, *Prevotella* species, and *Fusobacterium* species. Anaerobic organisms are
more frequently isolated from patients receiving mechanical ventilation for longer periods. Isolates similar to those found in the sinus are most commonly recovered from the trachea and blood (20).

Sinusitis should be suspected in patients with facial pressure or pain, headache, or purulent nasal discharge (Fig. 4). Otitis media has been associated with sinusitis in adult trauma patients (22). An evaluation for sinusitis should also be pursued in children at high risk for otitis media because of the prolonged use of simultaneous endotracheal and feeding tubes (23). Sinusitis can be confirmed by plain film or CT scan by the demonstration of marked mucosal thickening, an air–fluid level, or complete opacification of the sinus. Maxillary sinus aspirate specimens can be obtained before initiation of antibiotics. Agents such as cefuroxime or ampicillin-sulbactam should be used. Antibiotics providing additional coverage for anaerobes such as timentin-clavulanate, piperacillin-tazobactam, or meropenem should be used in patients who have been intubated for a prolonged period (Table 1).

Surgical Site Infection

Although reports describing nosocomial surgical site infections are not available in pediatric trauma patients, wound contamination and emergency or long-duration surgical procedures have been associated with higher surgical wound infection rates among children undergoing general surgical procedures (24,25). Isolates obtained from pediatric surgical patients with nosocomial wound infections include aerobic gram-negative bacteria (46%), streptococci (19%), S. aureus (15%), and anaerobes (12%) (26). The principles of diagnosis and surgical management of these infections is similar to those described for trauma-related wounds (Fig. 4). In the most severe infections, staphylococcal toxic shock syndrome, group A Streptococcus toxic shock syndromes, and necrotizing fasciitis should be considered since these require special management. Initial therapy with ampicillin-sulbactam or meropenem is usually appropriate (Table 1). If the initial Gram stain shows gram-positive cocci in clusters, vancomycin might be added. Ticarcillin-clavulanate, piperacillin-tazobactam, or meropenem might be used to include Pseudomonas if gram-negative rods predominate on the initial smear.

Recommendations for Prevention of Nosocomial Infections

While the data regarding nosocomial infections in children are limited, sufficient information is available to make initial recommendations for their prevention, diagnosis, and treatment. Development of more specific recommendations awaits the performance of larger studies in injured children. Children at risk for nosocomial pneumonia because of the need for mechanical ventilation, moderate to severe head injury, chest trauma, or multiple major injuries should be identified on admission. In addition, children with intravascular lines, urinary catheters, nasotracheal tubes, or intracranial monitoring devices, or those who undergo surgical procedures after admission are at risk for nosocomial infections and should also be identified early (Fig. 2). Prophylactic antibiotics are not indicated in patients at risk. The use of antibiotics for other reasons should be minimized to prevent development of resistant infection. These antibiotics should target as narrowly as culture results and clinical situation allow and should be continued for a well-defined length of treatment.

Standard measures to prevent the acquisition of infection such as meticulous attention to hand washing and clean care of mechanical airway devices in ventilated patients should be maintained. Since airway devices are associated with an increased
risk of infection, the need for intubation should be continuously evaluated and weighed against the risk of nosocomial pneumonia. Meticulous sterile technique should be used when placing and maintaining either intravascular lines or indwelling urinary catheters. When prolonged intubation is anticipated, conversion from nasotracheal to orotracheal intubation should be considered. Nasogastric tubes should be used only for gastrointestinal decompression and should be replaced with small-caliber feeding tubes when enteral feeding is started. The need for all invasive devices should be continuously reevaluated during hospitalization and should be removed when no longer needed (Fig. 2).

RECOMMENDATIONS FOR EVALUATION AND TREATMENT OF INFECTIOUS COMPLICATIONS

A potential infectious complication is often first suggested by the presence of fever, leukocytosis, or unexplained clinical deterioration after admission. Specific local symptoms and signs may also prompt the need for evaluation for an infectious source. Using the systematic approach outlined in Figures 2 and 4, the most likely source of infection can usually be identified and treated rapidly in the injured child. The first step should be to reevaluate all sites of injury for potential partially treated or untreated infection. Trauma-related infections are important to consider in the 48 hours after injury since most nosocomial infections occur later during hospitalization. After the first 48 hours, evaluation should focus on finding a potential nosocomial infection, particularly pneumonia, bacteremia, and urinary tract infection, since these categories are the most frequent. Since more than one infection may exist, all potential sites of infection should be considered and workup and empiric treatment may need to be directed initially at more than one site.

CONCLUSION

Infectious complications are frequent in injured children. These complications contribute to increased morbidity and a longer length of stay. The initial choice of antibiotics to prevent infection at the site of injury can be chosen knowing the most likely infecting organisms based on the site of infection, duration of hospitalization, prior antibiotics, and Gram stain of appropriate specimens. Nosocomial infections are more common than trauma-related infections and should be considered in children who are more severely injured, require invasive devices, or are hospitalized for more than two days.

REFERENCES

INTRODUCTION

Organ failure is regrettably a common result of trauma in adult populations accounting for a significant proportion of all adult trauma deaths. The trauma literature usually divides mortality into three categories, with the “third wave” representing those patients dying from multiple organ system failure and sepsis. Plotting pediatric trauma mortality against time from injury typically produces a bimodal curve (1,2). The primary curve peaks immediately after the accident and represents death at the scene or in transit to the emergency facility. The second peak occurs around three or four days later and is usually associated with head injury (3–5). Organ failure as described in relation to trauma in adults is uncommon in children. Although sepsis and multiple organ system failure are common in pediatric intensive care units, only 1.5–5% of such cases result from trauma (6–9).

Late deaths due to sepsis or multiple organ system dysfunction and failure are rare among pediatric trauma patients. The National Pediatric Trauma Registry Report of October 1997 listed 12,811 patients. Sepsis as a complication of injury occurred in 52 children (0.4%) and organ failure in 14 (0.1%). The primary cause of death (n = 418) was overwhelmingly central nervous system (CNS) injury (78.7%). There were no deaths listed as being due to sepsis, and only six as a result of multi-organ failure (1.5%) (5). This is corroborated by other studies (4,10,11).

Whether anatomy, physiology, or injury mechanisms explain this difference between adults and children is uncertain. Studies of multi-organ dysfunction syndrome (MODS), sepsis, and the systemic inflammatory response syndrome (SIRS) in the pediatric population are based mainly on non-trauma patients; their relevance for the traumatized child is not known. Studies looking at outcomes for children suffering serious traumatic injuries are limited by the use of death as the only endpoint. Although of little practical use for an individual patient, the scoring system developed in Montreal addresses this shortcoming (8,9,12).
Single organs can fail as a result of the initial traumatic insult. Measurable organ dysfunction can also be a result of secondary insults such as global ischemia due to hypoventilation or hypovolemic shock, and organ dysfunction associated with hypothermia.

Identifying endpoints for volume resuscitation in children can be difficult as unlike adults, blood pressure is maintained despite significant reduction in blood volume. Hypotension due to hypovolemia is in children a sign of impending hypovolemic cardiac arrest. Trauma units using the base deficit as a guide to adequacy of resuscitation and a gauge of injury severity should heed Kincaid’s advice that pediatric cutoffs should be less than those established for adult use. In adults less than 55 years of age without closed head injury, a base deficit of greater than \(-15\) mEq/L is associated with a 25% probability of mortality. In children without closed head injury the equivalent base deficit is \(-11\) mEq/L. In adults less than 55 years of age with closed head injury, a base deficit of \(-8\) mEq/L is associated with a 25% probability of mortality. In children with closed head injury the equivalent base deficit is \(-6\) mEq/L (13).

Conditions causing multiple organs to fail in a delayed fashion are few. Precipitating factors can include crush injuries, multiple extremity fracture, and intraabdominal compartment syndrome.

The approach to the failing organ is usually a generic response that is not related to etiology. Precipitating factors are identified and addressed, exacerbating factors are exposed and corrected, supportive measures are instituted, and complications of therapy are anticipated.

DEFINITIONS

Multiple organ system failure (MOSF) is defined as the failure of two or more organ systems in an individual following an insult to that individual (Table 1). The definitions of organ failure are variable and do not recognize the continuum of disease that may be present. For this reason, the term MODS was introduced. This syndrome is considered to be primary when the cause is directly related to the organ dysfunction (thoracic crush injury and pulmonary contusion causing respiratory failure) and secondary when the organ failure results from a generalized inflammatory response [e.g., adults respiratory distress syndrome (ARDS)] (7,9). SIRS describes the clinical response due to either non-infective or infective causes, the latter being termed sepsis, a subset of SIRS (14). Severe sepsis represents a more marked homeostatic imbalance as a result of infection, with evidence of organ dysfunction, hypoperfusion, or hypotension that responds to intravascular volume loading alone. Hypotension refractory to adequate restoration of intravascular volume, when associated with perfusion abnormalities and requiring the use of inotropes, is termed septic shock (15).

The criteria for failure of specific organ systems outlined by Wilkinson et al. are usually used in the pediatric literature (7). These are listed in Table 2. Others favor alternate criteria (16).

MODS/SIRS/SEPSIS

Prevention of the development of these syndromes commences during the resuscitative phase of trauma management. Aggressive volume resuscitation, close monitoring of tissue perfusion and oxygenation, maintenance of normothermia, stabilization of fractures,
control of hemorrhage and the avoidance of missed injuries are all-important. Where required, operative intervention needs to be timely and appropriate. “Damage control” surgery rather than definitive procedures may be indicated in some circumstances. All non-viable and contaminated tissue should be debrided. All fractures should be reduced and immobilized as soon as this is practicable. In the intensive care unit, careful tertiary surveys should be performed and repeated frequently to exclude missed injuries. Surveillance of organ function should be maintained in order that early support measures may be instituted, where appropriate. Clinicians should be alert to the development of acute infections (14).

Modalities designed to modulate the general inflammatory response of the body are experimental and largely confined to studies in the adult population (17). None can be recommended for children.

**HYPOTHERMIA**

Hypothermia has been defined as a body core temperatures below 34–35°C (18–20). Children are more prone to the development of hypothermia in the resuscitative phase

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Etymology of Syndromes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARDS</td>
<td>The adult respiratory distress syndrome first described during the 1970s refers to the usually fatal respiratory failure seen in the traumatized patient. As ventilatory support improved, ARDS was seen to be only the first of a number of organ failures to occur post-injury.</td>
</tr>
<tr>
<td>MOSF</td>
<td>A disease process characterized by the progression of a persistent hyperdynamic/hypermetabolic state to a failure of multiple organ systems, with the lungs usually being the first to fail (ARDS). This term has been supplanted by MODS largely because the term “failure” implies a quantifiable end point and a degree of irreversibility.</td>
</tr>
<tr>
<td>MODS</td>
<td>Multiple organ dysfunction syndrome as an entity allows individual organ system dysfunctions to be dynamically defined and graded; the term also reflects the concept of potential preventability and reversibility of the organ dysfunction. Primary MODS reflects organ dysfunction resulting from the primary insult, secondary MODS is the measurable clinical outcome of the SIRS that subsequently may be triggered. Primary MODS is evident in the first few days post-injury, secondary MODS usually occurs from around 7 days post-injury/insult. Individual organ dysfunctions are treated with individual supportive interventions, the effectiveness of which can be assessed in terms of alteration in organ function.</td>
</tr>
<tr>
<td>SIRS</td>
<td>The systemic inflammatory response syndrome is the pathophysiological response (to either non-infective or infective insults—the latter being termed sepsis) that causes secondary MODS. It involves the activation of inflammatory mediator cascades due to the presence of a trigger (for example endotoxin/lipid A or reperfusion-associated metabolites) and the subsequent effect the trigger has on the interaction between white blood cells and endothelium. This cellular/molecular process is difficult to assess directly; thus it is indirectly and dynamically assessed by measuring associated organ dysfunction. Theoretically, once this pathophysiological response is accurately defined and understood, cellular/molecular interventions could be developed to non-specifically modulate the associated organ dysfunction.</td>
</tr>
</tbody>
</table>
Table 2  Criteria for Defining Failure of Specific Organ Systems

<table>
<thead>
<tr>
<th>Organ system</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiovascular</td>
<td>MAP &lt;40 mmHg (infants &lt;12 mo)</td>
</tr>
<tr>
<td></td>
<td>MAP &lt;50 mmHg (children ≥12 mo)</td>
</tr>
<tr>
<td></td>
<td>HR &lt;50 beats/min (infants &lt;12 mo)</td>
</tr>
<tr>
<td></td>
<td>HR &lt;40 beats/min (children ≥12 mo)</td>
</tr>
<tr>
<td></td>
<td>Cardiac arrest</td>
</tr>
<tr>
<td></td>
<td>Continuous vasoactive drug infusion for hemodynamic support</td>
</tr>
<tr>
<td>Respiratory</td>
<td>RR &gt;90/min (infants &lt;12 mo)</td>
</tr>
<tr>
<td></td>
<td>RR &gt;70/min (children ≥12 mo)</td>
</tr>
<tr>
<td></td>
<td>PaO₂ &lt;40 torr (in absence of cyanotic heart disease)</td>
</tr>
<tr>
<td></td>
<td>PaCO₂ &gt;65 torr</td>
</tr>
<tr>
<td></td>
<td>PaO₂/FiO₂ &lt;250 torr</td>
</tr>
<tr>
<td></td>
<td>Mechanical ventilation (&gt;24 hr if postoperative)</td>
</tr>
<tr>
<td></td>
<td>Tracheal intubation for airway obstruction or acute respiratory failure</td>
</tr>
<tr>
<td>Neurologic</td>
<td>Glasgow Coma Scale Score &lt;5</td>
</tr>
<tr>
<td></td>
<td>Fixed, dilated pupils</td>
</tr>
<tr>
<td></td>
<td>Persistent (&gt;20 min) intracranial pressure &gt;20 torr or requiring</td>
</tr>
<tr>
<td></td>
<td>therapeutic intervention</td>
</tr>
<tr>
<td>Hematologic</td>
<td>Hemoglobin &lt;5 g/dL</td>
</tr>
<tr>
<td></td>
<td>WBC &lt;3000 cells/mm³</td>
</tr>
<tr>
<td></td>
<td>Platelets &lt;20,000/mm³</td>
</tr>
<tr>
<td></td>
<td>Disseminated intravascular coagulopathy (PT &gt;20 sec or a PTT &gt;60 sec in</td>
</tr>
<tr>
<td></td>
<td>presence of a positive FSP assay)</td>
</tr>
<tr>
<td>Renal</td>
<td>BUN &gt;100 mg/dL</td>
</tr>
<tr>
<td></td>
<td>Serum creatinine &gt;2 mg/dL</td>
</tr>
<tr>
<td></td>
<td>Dialysis</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>Blood transfusions &gt;20 mL/kg in 24 hr because of GI hemorrhage</td>
</tr>
<tr>
<td></td>
<td>(endoscopic confirmation optional)</td>
</tr>
<tr>
<td>Hepatic</td>
<td>Total bilirubin &gt;5 mg/dL and SGOT or LDH more than twice normal value</td>
</tr>
<tr>
<td></td>
<td>(without evidence of hemolysis)</td>
</tr>
<tr>
<td></td>
<td>Hepatic encephalopathy ≥grade II</td>
</tr>
</tbody>
</table>

Source: From Ref. 7.

Table 3  References Graded by Levels of Evidence

<table>
<thead>
<tr>
<th>Level of evidence</th>
<th>Reference number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>45</td>
</tr>
<tr>
<td>1b</td>
<td>5,9,12,15,16,19,20,23,25,29,36,44,46,47</td>
</tr>
<tr>
<td>1c</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>48</td>
</tr>
<tr>
<td>2b</td>
<td>1,3,4,6,7,8,10,11,13,18,21,33,35,41,43</td>
</tr>
<tr>
<td>2c</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>2,14,17,22,24,27,37,38,42,49</td>
</tr>
<tr>
<td>3b</td>
<td>31,39</td>
</tr>
<tr>
<td>4</td>
<td>26,30,32,34,40,50,51</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
</tr>
</tbody>
</table>

*Outlined by the Centre for Evidence-Based Medicine, Oxford University, 18 November 1999 (http://cebm.jr2.ox.ac.uk/).
of trauma management for a number of reasons. They have a large body surface area to body cell mass ratio and will transfer heat from a smaller heat sink to a cool environment at a relatively faster rate than an adult. Cooler environments exist both in the field and in the resuscitation room. Intravenous fluids and ventilator gases are often not adequately warmed during the initial resuscitation phase (21). Heat transfer can be exacerbated by vasodilatation associated with anesthetic drugs and spinal cord injury.

Hypothermia induced prior to metabolic exhaustion has been associated with improved outcome in cerebral trauma and ischemia/reperfusion injuries (20,22). Hypothermia in the trauma patient is usually a sign of metabolic exhaustion and is associated with a poor outcome. Hypothermia induces a shivering response that results in increased oxygen requirements for metabolism, increased work of breathing and respiratory alkalosis. Failure of mechanisms (such as shivering) to prevent further cooling, due to energy substrate exhaustion, causes impaired metabolic enzymatic activity (23). Oxygen consumption then falls. Arrhythmias (atrial and ventricular) have been described and are illustrated clinically by cold cardioplegia techniques. Sludging of blood increases blood viscosity and ventricular work, as does the increased peripheral vascular resistance associated with vasoconstriction. Coagulopathy occurs because clotting factors work optimally at 37°C. This coagulopathy is not reflected in laboratory studies as the specimen is typically warmed to 37°C (19,20). Impaired mental function progresses to unconsciousness as body temperature falls. A diuresis is often present despite reduced renal blood flow and reduced glomerular filtration, which may result from tubular dysfunction (24). Responses to a variety of drugs may be significantly altered by hypothermia (25). The magnitude of the insult to any one organ is unpredictable.

Hypothermia is best avoided by providing a warm environment in the field and in the resuscitation room, minimizing exposure and providing radiant heaters when exposed, heating blankets, warmed IV fluids and blood products, and warmed, humidified ventilatory gases. Active central rewarming is rarely required in the setting of pediatric trauma (26). The comparative effectiveness of these measures in adults is well established (27). Many factors have been identified as important for the effective delivery of intravenous fluids, including temperature of the fluid, rate of administration, and length of infusion tubing. Some authors recommend warming IV fluid to 37–41°C and delivering it by hand or syringe pump through short (50 cm) tubing in pediatric patients (28). The use of Level 1 warmers has been shown to be useful in pediatric patients (29). Care should be taken with fluids warmed by microwave as burns and venous thromboses have been described (30).

**ABDOMINAL COMPARTMENT SYNDROME**

This syndrome comprises organ system dysfunction resulting from raised intra-abdominal pressure. Renal, pulmonary, intestinal, and cardiovascular function are usually affected and manifested clinically by decreased urine output, increased peak inspiratory pressures, ileus, and hypotension. Intra-abdominal pressure is best quantified by the measurement of bladder pressure, with recommendations for abdominal decompression if the pressure exceeds 20 mmHg. Impaired splanchnic perfusion might be detected by gastric tonometry, but this is as yet an experimental modality in the pediatric population (16). After decompressive laparotomy, the abdominal wound is closed temporarily with an artificial patch (for example, intravenous fluid...
bags, silicone sheeting, polytetrafluoroethylene (PTFE) sheeting, or polypropylene mesh) with a view to closing the abdominal fascia at five to seven days. Complications include wound infection, patch dehiscence, intestinal fistula formation, and delayed healing by secondary intention when closure is not possible. Current pediatric data comprise case reports only (31,32).

SEVERE EXTREMITY AND CRUSH INJURIES

Extensive soft tissue trauma can be associated with renal, pulmonary, and cardiovascular dysfunction. Causes include natural disasters such as earthquakes, driveway crush injuries, and pedestrian motor vehicle accidents. Early treatment is aimed at resuscitation and fracture reduction and immobilization. The affected region is closely monitored for signs of ongoing ischemia or the development of a compartment syndrome. Hyperbaric oxygen therapy offers theoretical advantages for those patients when this modality is available (33).

Cardiovascular dysfunction is usually acute and results from reperfusion of an ischemic region and the circulation of released potassium and lactic acid. Renal dysfunction results primarily from myoglobin release and is treated by generous fluid administration, diuretics, and measures to alkalinate the urine. Sodium bicarbonate (2 mEq/kg IV as a bolus followed by a constant infusion of 2 mEq/kg over 6 hr) should maintain a urinary pH > 7. Prior to attempting to alkalinate the urine, serum electrolytes, blood pH, and osmolarity should be checked. Attempts to alkalinate the urine will be unsuccessful if hypokalemia or systemic acidosis is present. Dangers associated with attempts to alkalinate the urine include hypernatremia, hyperosmolarity, and systemic alkalosis that may precipitate hypocalcemia. Pulmonary dysfunction usually stems from the development of the acute or adult respiratory distress syndrome triggered by fat emboli and other released inflammatory mediators such as interleukin-1 tumor necrosis factor (34,35).

CHILD ABUSE

Abuse by its very nature can present as multi-organ failure. Environmental factors at presentation may include hypothermia and malnutrition. Injury to specific organs due to trauma (head injury, long bone fracture) and their delayed presentation are also important. Time delay results in presentations with established pathologies such as cerebral edema, peritonitis and abscess. Recognition of abuse is important to prevent repeat injury.

CNS DYSFUNCTION AND FAILURE

CNS dysfunction in pediatric trauma patients usually results from the initial insult, as the head is relatively large and less well supported in this age group. Factors that may exacerbate an existing injury or cause secondary dysfunction in their own right include hypoxia, hypotension, hypoglycemia, cerebral edema, electrolyte imbalance, hyperthermia, hypothermia, hepatic failure, seizures, drug administration, drug withdrawal, infections such as meningitis, and psychiatric disturbances resulting from the traumatic event. These factors should be sought and corrected when present.
Cerebral dysfunction is usually assessed clinically when possible, with modified Glasgow Coma Scale (GCS) the mainstay of assessment and documentation. Clinical changes, or the inability to assess the clinical state due to the administration of drugs during resuscitation, usually demands the acquisition of cerebral imaging to exclude an injury requiring operative intervention. Current technology favors CT scanning over MRI in the acute setting. Intracranial pressure monitoring is used to supplement clinical assessment when this is unreliable especially in comatose patients with GCS <8.

Management based on intracranial pressure monitoring is described in the chapter on brain injuries. The cerebral perfusion pressure (CPP) is calculated by subtracting intracranial pressure from the mean arterial blood pressure. A CPP greater than 70 mmHg is the target in adults; pediatric values are not defined. These pressures are usually achieved with intracranial pressures (ICPs) of less than 15–20 mmHg. Interventions based on abnormal measurements (hyperventilation, reversed-Trendelenberg posture, head and neck in neutral position, mannitol, and furosemide) usually provide time for repeat imaging and appropriate operative interventions to occur. Where no operative interventions are indicated, brain injury or death usually occurs.

Neuroprotective agents are of unproven benefit in the pediatric population (as in the adult trauma patient). Most agents experimentally show most benefit if administered prior to the traumatic insult, though some response can be noted if administered within 12 hours of the insult. Barbiturates have been used in clinical practice to reduce cerebral metabolism. Mannitol may help by both reducing intracranial blood volume and by improving the flow characteristics of blood (a rheological effect). Other agents such as calcium channel blockers are not yet advocated for use.

Brain death results in vasomotor instability and organ failure may result from a relative hypovolemia and hypoperfusion. This can be exacerbated with the onset of diabetes insipidus, which may be associated with both volume and electrolyte abnormalities. Careful management of the circulatory system and diabetes insipidus resulting from brain death is obviously important, especially if organ donation is being considered. The presence of vasomotor instability may also be caused by focal brainstem or cervical spinal cord injuries (“spinal shock”) that cause general vasodilatation, decreased peripheral vascular resistance, increased intravascular volume, and hypothermia from excessive peripheral heat loss. This usually responds to volume loading and careful management of body temperature (36).

The diagnosis of brain death has important clinical and legal implications, and has been the subject of an excellent recent review (37,38). A combination of clinical findings and confirmatory tests are used. Different legal environments may require more than one observer, a mandatory period of observation and re-examination, and mandatory use of a confirmatory test. Practitioners should be aware of the legal requirements of their local jurisdiction. It is important to recognize conditions that may mimic or hinder the diagnosis of brain death (anesthetic agents, sedatives, alcohol intoxication, hypothermia, locked-in syndrome, and Guillain–Barre syndrome).

**ACUTE RESPIRATORY DISTRESS SYNDROME**

Injury to the alveolar-capillary membrane due to inflammatory mediators results in increased membrane permeability, increased interstitial fluid, increased pulmonary vascular resistance, and decreased lung compliance. Diffusion abnormalities and intrapulmonary vascular shunts result in ventilation-perfusion mismatching, worsening
hypoxemia, and hypercarbia. Outcomes include intractable respiratory failure with death or chronic pulmonary fibrosis, although full resolution with minimal functional impairment is also possible.

Measures to prevent ARDS from developing should be implemented. Therapies to support the patient with failing lungs involve careful ventilator management to optimize oxygen delivery while avoiding barotrauma and volutrauma. Tidal volumes of 5–10 ml/kg, peak inspiratory pressures of no greater than 35–45 cm H₂O, and FiO₂ less than 60% are targets to keep in mind. Adequate functional residual capacity should be maintained with increased positive end-expiratory pressures (5–15 cm H₂O). Alterations to the I:E ratio (usually increasing the I time) may improve oxygenation and help avoid overdistension of ventilated alveoli (14). Permissive hypercarbia and judicious increases in FiO₂ to avoid oxygen toxicity to the lungs can also be helpful. Early detection and treatment of pulmonary infections are important to minimize additional damage. Careful attention to optimizing the peripheral delivery of oxygen actually taken up by unhealthy lungs is vital—cardiac function should be optimal and hemoglobin levels maintained at around 7–10 g/dL (39). Nutritional support should not be forgotten.

Unconventional ventilatory supportive measures may be available in some centers. These include extracorporeal membrane oxygenation (ECMO), high frequency oscillatory ventilation and high frequency jet ventilation, and partial or total liquid ventilation. There are no data to currently support their general use. High frequency ventilation may help when lungs have been damaged by volutrauma (and is optimally used prior to such injury).

Studies are currently underway in adults to see if nitric oxide will reduce intrapulmonary shunting and improve outcome with ARDS. As yet no pharmacological agents designed to modify the inflammatory process in ARDS has been shown to be of use. The use of ECMO in post-traumatic respiratory failure has been reported (40).

**RENAL FAILURE**

The etiology of renal dysfunction and failure is usually discussed in terms of prerenal, renal, and postrenal factors. Prerenal causes in the pediatric trauma patient include hypovolemia, cardiac tamponade, raised intra-abdominal pressure, and renal vascular injury. Renal causes of renal failure in the trauma patient may include hypoxia, hemoglobinemia, disseminated intravascular coagulopathy (DIC), myoglobinemia, sepsis, and the use of drugs such as aminoglycosides, intravenous contrast, and non-steroidal anti-inflammatory agents. Postrenal causes are unusual and might include malfunctioning Foley catheters, urethral injuries, and urinary retention due to clots in the catheter drainage system.

Avoiding the development of renal dysfunction by maintaining a normal blood volume and minimizing the use of known nephrotoxins (aminoglycosides, intravenous contrast agents) is accepted practice. The diagnosis of renal dysfunction and failure is usually anticipated when a reduction in urine output is observed, and confirmed with the presence of altered serum electrolytes, BUN, and creatinine. Therapy is initially driven by a search for the etiology of the renal failure, the removal of exacerbating factors such as drugs, and strict fluid balance management. Attempts to convert oliguric renal failure to non-oliguric renal failure via the use of furosemide (and in some instances mannitol) follow adult guidelines. Peritoneal dialysis and hemodialysis are therapies instituted when life-threatening fluid or electrolyte balances...
occur. Continuous arteriovenous hemofiltration (CAVH) is useful to control metabolic, volume and electrolyte abnormalities. Its use is limited by complications related to heparin, vascular access, and the limited ability to manage uremia in hypercatabolic patients. Continuous arteriovenous hemodiafiltration (CAVHD) and continuous veno-venous hemodiafiltration (CVVHD) will control uremia, but still have the problems associated with heparinization and vascular access. The access device and vessels used will vary with local availability and the distribution of the child’s injuries. Care must be taken to maximize the efficiency with which dialysis access is chosen so that long term options are not compromised (41,42). Acute peritoneal dialysis has been shown to be effective and safe in traumatized children and may be the best option (43).

LIVER FAILURE

Factors causing liver dysfunction and failure in the pediatric trauma patient include global causes such as hypoxia, hypotension, and sepsis; and specific factors such as Budd–Chiari syndrome, transfusion hepatitis, total parenteral nutrition (TPN) cholestasis, and acetaminophen misuse. The onset of liver failure is heralded by jaundice, the development of a bleeding diathesis, serum glucose derangements, and altered mental status. These elements are defined by serum parameters.

Massive hepatic resections are an uncommon cause of hepatic insufficiency. In this particular instance, meticulous postoperative management is vital. Careful maintenance of serum glucose and the minimization of sodium intake are important.

Therapy of liver failure is directed at the identification of etiologic factors and the modification of exacerbating factors. Close monitoring and support of serum glucose and coagulation factors are important. Nutritional approaches that reduce the intake of sodium and proteins are usually adopted. Assessment of those drugs being used that are degraded via hepatic mechanisms is important. Dialysis to alleviate hypervolemia and hyperammonemia is seldom needed. Gut flora decontamination and gut emptying with lactulose may be helpful if altered mental status is present. Liver transplant is the option of last resort, and artificial livers (either as bridging or definitive therapy) are experimental. The use of recombinant human growth hormone may be beneficial (44).

GASTROINTESTINAL FAILURE

Gastrointestinal failure is perhaps the hardest organ failure to define. Features that may be encountered include the failure of mucosal integrity and the failure of gastrointestinal motility. General factors such as hypovolemia, hypoxia, and sepsis and specific agents such as non-steroidal anti-inflammatory agents can cause mucosal failure. Mucosal dysfunction may result in bleeding, bacterial translocation, and altered nutrient absorption. Ulceration associated with head injury (Cushing’s ulcers) and burns (Curling’s ulcers) are uncommon. Troublesome motility problems include both ileus and diarrhea.

Once again, therapy is directed toward modification of etiologic factors, the use of preventive measures ( trophic feeds and antacids), and the use of supportive elements such as TPN and blood transfusion. Early enteric feeding is encouraged where possible (for example, with CNS and musculoskeletal trauma) (14,45–47). TPN is introduced if the gut is unavailable. It is clear that the metabolic needs of critically ill children differ from adults and nutritional interventions will be different (48).
PANCREATIC FAILURE

This organ dysfunction usually presents as pancreatitis that is precipitated by ischemia or direct pancreatic injury. By itself, acute pancreatitis can trigger the systemic inflammatory response syndrome (perhaps via bacterial translocation in the gut) and multi-organ failure (49). The role of necrosectomy in the absence of infection in order to avert or dampen SIRS is controversial (50,51).

DERANGEMENT OF BLOOD

DIC results from the activation and consumption of procoagulant, anticoagulant, and fibrinolytic factors. This may be precipitated by sepsis, shock, and tissue trauma that exposes thromboplastin (tissue factor) or causes the release of bacterial endotoxin. Diagnosis is made by the presence of an abnormal coagulation profile and fibrin degradation products. Supportive therapy largely consists of factor replacement [fresh frozen plasma (FFP), platelets, cryprecipitate, etc.]. The use of heparin to prevent activation relies on the presence of antithrombin-III and is controversial, as is the use of epsilon amino-caproic acid to prevent fibrinolysis. The administration of DDAVP* (a vasopressin analog) as a one-time measure to increase the expression of Von Willebrand factor in endothelial cells and platelets is unlikely to cause harm, but is of unproven benefit.

Massive hemorrhage and the resultant transfusion of blood products may be associated with deficiencies of specific blood components as well as the deleterious effects of hypothermia. The careful use of the complete blood count and coagulation studies is important to direct component replacement.

SUMMARY

The frequency of organ failure, especially due to secondary mechanisms such as SIRS, is less in the pediatric trauma population than in adults and is an uncommon cause of death. Careful diagnosis, management, and preemptive vigilance are paramount in the prevention and amelioration of organ dysfunction.

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INTRODUCTION

Head injury is a leading cause of death and acquired disability in the pediatric population. Despite this, data from well-designed clinical studies, which could be used to guide the management of children with severe traumatic brain injury, are scarce. Most of the randomized controlled trials designed to evaluate head injury have excluded pediatric patients. Because of the paucity of proven therapies in pediatric head injury, management strategies for severely head-injured children are generally extrapolated from adult studies. Because pediatric patients are not simply small adults, therapy should be based on scientific evidence that a particular type of treatment will actually improve a child’s outcome from traumatic brain injury.

Many of the therapies that are routinely employed in the treatment of adults with severe head injury have not been tested in randomized controlled trials. In fact, management strategies in the care of patients of all ages have relied in large part on expert opinion and practice experience. This has resulted in tremendous variations in the treatment and outcomes of head-injured patients, with mortality rates ranging from 25% to 60%. In an attempt to standardize the care of patients with severe head injury and ultimately improve outcome, the American Association of Neurological Surgeons and the Brain Trauma Foundation performed a thorough review of the existing head injury literature and developed evidence-based standards, guidelines, and treatment options for managing adult patients with severe head injury (1). These guidelines were designed to provide uniform practice parameters to prevent or minimize brain swelling (and the irreversible damage that occurs from this swelling) and to create and maintain a physiologic environment to maximize brain recovery. The following topics, which were deemed to have an impact on the outcome of patients with severe head injury, were addressed in this publication:

- early resuscitation,
- intracranial pressure (ICP) monitoring,
- ICP treatment threshold and methods,
- use of mannitol, barbiturates, nutrition, hyperventilation, corticosteroids, and prophylactic anticonvulsants in the treatment of head injury.
For most of the clinical practice parameters addressed in this publication, there were insufficient data to support a treatment standard. In fact, based on an analysis of all the available data, there were only three “standards of clinical care” for the treatment of severe head injury in adult patients. These included:

1. the avoidance of steroids for treating elevated ICP,
2. the avoidance of routine use of prolonged hyperventilation,
3. the avoidance of prophylactic anticonvulsants for the prevention of late post-traumatic seizures.

Focused, well-designed, and carefully implemented clinical research trials are required to upgrade clinical practice parameters to treatment standards.

Despite the fact that traumatic brain injuries are more common in pediatric trauma than in adult trauma, no specific recommendations were made in the adult guidelines regarding the treatment of traumatic brain injury in pediatric patients. A subsequent meticulous analysis of this publication for relevance to the management of severe pediatric head injury revealed even fewer recommendations for standards of care (2). In an attempt to standardize and improve treatment practice and patient outcome in pediatric patients with severe head injury, a multidisciplinary team of clinicians and researchers recently reviewed all the available data on this topic and subsequently published evidence-based practice standards, guidelines, and treatment options for the acute medical management of pediatric patients with severe traumatic brain injury (3). In the pediatric guidelines as in the adult guidelines practice standards refer to accepted principles of patient management that reflect a high degree of clinical certainty (i.e., they are based predominantly on class I data, derived from randomized controlled trials, as well as on some strong class II data, derived mainly from prospective and some retrospective studies) (1,3). In addition, practice guidelines refer to management strategies that reflect a moderate degree of clinical certainty (i.e., they are based on classes II and III data, derived from retrospective studies such as clinical series, case reports, expert opinions, and databases or registries). Finally, treatment options refer to management strategies for which the clinical certainty is unclear (i.e., they are based solely on class III data or represent the consensus of experts in areas where studies documenting more definitive levels of certainty are not available or are not possible). Besides elucidating scientific evidence that supports various treatment strategies and the rigor of the evidence, this analysis on the treatment of severe pediatric head injury revealed that pediatric head injury is under investigated and that many questions remain unanswered, especially at the class I level, regarding the optimal medical and surgical management of severe traumatic brain injury in the pediatric population (3). Thus, large, well-designed, prospective, randomized, controlled multicenter trials are still needed to investigate additional treatment modalities and provide standards of care for the management of severe pediatric head injury.

The present chapter discusses current therapeutic options for the management of severe head injury in pediatric patients. Aspects of care covered in this chapter include both prehospital and intensive management of pediatric patients with severe head injury. The management strategies described herein are based on existing scientific evidence and include recommendations from the recently published evidence-based pediatric guidelines (3). In this chapter, pediatric patients refer to patients who are 17 years of age or younger; severe head injury is defined using the Glasgow Coma
PATHOPHYSIOLOGY OF HEAD INJURY

Before proceeding with a discussion on evidence-based management strategies for the treatment of severe pediatric head injury, it is first necessary to review the pathophysiology of head injury. Severe traumatic brain injury involves two types of injury—primary and secondary. Primary injury arises at the time of the traumatic event and generates the initial damage that occurs at the moment of impact, including structural damage to neurons, supporting tissues, and blood vessels. Examples of primary injury include skull fracture, epidural and subdural hematomas, intraparenchymal hemorrhage, cortical contusions, diffuse axonal injury, and brain stem injury. In contrast, secondary injury is an evolving process that develops during the hours and days that follow the initial trauma and produces additional progressive cellular damage and dysfunction resulting from degenerative biochemical processes initiated both by the primary injury and by additional systemic insults such as hypotension and hypoxia. Secondary injury, which compounds the primary injury, occurs as a consequence of brain swelling (from acute cerebral arterial vaso-dilatation and associated increased cerebral blood volume), diffuse cerebral edema (from increased cerebral water content), elevated ICP, cerebral herniation, traumatic ischemia and/or infarction, secondary hemorrhage, hypotension, and hypoxia. Thus, only part of the damage to the brain that occurs during head trauma takes place at the moment of impact. The main goal of acute management of severe head trauma is to minimize the progression or the effects of secondary injury and thereby maximize the potential for recovery. Successful management of severe pediatric head injury requires complete and rapid physiologic resuscitation, prevention of hypotension and hypoxia, treatment of elevated ICP, and maintenance of cerebral perfusion to facilitate adequate delivery of oxygen and metabolic substrates to the brain.

The developing/maturing brain of a child undergoes changes that affect its susceptibility to both primary and secondary injury. For example, children have less cerebrospinal fluid volume, which results in less buffering capacity for changes in intracranial tissue volume and places them at risk for earlier decompensation and secondary ischemia after traumatic brain injury. Open fontanels and expandable calvarial sutures do not add buffering capacity and, therefore, are not protective in head-injured infants. Because of these and many other differences that exist between pediatric and adult patients, the treatment of head injury in the pediatric population should not be based on generalizations from studies in adults but rather should rely on scientific evidence derived from studies on pediatric patients. The remainder of this chapter focuses on evidence-based management strategies for the treatment of severe pediatric head injury.

EVIDENCE-BASED TREATMENT STRATEGIES—PRE-HOSPITAL CARE

Speed of access to definitive care and timing of the intervention relative to the initial insult play a paramount role in the survival and eventual outcome of pediatric patients with severe head injury. In support of this, several studies have reported a
decreased mortality rate in severely head-injured pediatric patients treated in pediatric trauma centers (5–8). However, as pointed out in the recently established pediatric guidelines transfer did not improve the survival of some subgroups (3). For example, patients in rural areas who were taken initially to Levels III and IV rural hospitals then transferred to a higher level of care, had a significantly increased mortality rate (9). The results of this study suggest that severely head-injured pediatric patients are more likely to survive if they are transported directly to a Level I or II pediatric trauma center than if transported first to another type of trauma center and then transferred to a pediatric trauma center. Based on this, the following recommendations were made in the pediatric guidelines (3):

1. Pediatric patients with severe traumatic brain injury should be transported directly to and treated in a pediatric trauma center if available (guideline) or to an adult trauma center staffed with qualified, pediatric-trained caregivers and equipment necessary for treating pediatric patients if no pediatric trauma center is available (option).

2. Although the literature provides strong evidence to support a role for trauma systems and pediatric trauma centers in the increased survival of pediatric patients with severe head injury, their role on the eventual functional outcome of pediatric patients with severe head injury remains unclear.

**Airway Management**

Hypoxemia, which commonly occurs during the prehospital care of severely head-injured children is associated with poorer functional outcomes in pediatric patients with traumatic brain injury (10–13). Despite this, evidence suggesting that aggressive prehospital airway management (i.e., endotracheal intubation over bag-valve-mask ventilation) improves outcome for children with traumatic brain injury is lacking (14). The pediatric guidelines make two recommendations regarding the prehospital management of airway in severely head-injured pediatric patients (3):

1. Avoid hypoxia if possible or correct it immediately by administering supplemental oxygen (guideline).

2. Perform endotracheal intubation in the prehospital setting guided by end-tidal CO$_2$ detectors and only by scene-critical care providers who are specifically trained to intubate pediatric patients (option).

If qualified caregivers are unavailable, then bag-valve-mask ventilation should be carried out until the patient reaches a trauma center staffed with the appropriately trained personnel in order to prevent life-threatening complications directly related to attempts at intubation by unqualified scene-critical care providers.

**Management of Breathing and Circulation**

In addition to the initial damage that occurs within the brain at the moment of impact, progressive cellular damage and dysfunction frequently occur in the ensuing hours and days as a consequence of degenerative biochemical processes initiated both by the primary injury and by additional systemic insults such as hypotension and hypoxia. Because of the exquisite sensitivity of the injured brain to secondary systemic and local intracranial insults, they must be avoided in order to minimize the progression of brain injury and maximize the potential for recovery (15–21).
Hypotension and hypoxia, which commonly occur in pediatric patients with severe traumatic brain injury, have the greatest negative impact on outcome, including increased morbidity and mortality (12,17,22–27). For example, in a prospective study of 200 pediatric patients the mortality rate was significantly higher in the presence of hypotension, hypoxia, or hypercarbia than it was in the absence of these factors (i.e., 55% vs. 7.7%, \( p < 0.01 \)) (23). In another study analyzing the influence of hypoxia and hypotension on mortality from severe traumatic brain injury in children hypotension on admission was associated with a mortality rate of 61%, which increased to 85% when both hypotension and hypoxia were present, compared with only 22% when patients were normotensive on admission (17). Finally, in a prospective analysis of severe traumatic brain injury in 6908 adults and 1906 children younger than 15 years of age at 41 trauma centers, hypotension was associated with significantly higher mortality rates in children and had a more harmful effect in children than in adults (25).

Hypotension in children is defined as systolic blood pressure below the fifth percentile for age or by clinical signs of shock. The lower limit of systolic blood pressure for age (i.e., the fifth percentile) can be estimated by multiplying the patient’s age in years by two, and then by adding this number to 70 mmHg (28). Because pediatric patients can maintain their blood pressure in the face of significant volume depletion and clinical signs of shock, it is imperative that the pediatric traumatic brain injury patient be monitored closely for signs of decreased perfusion, including tachycardia, urine output less than 1 mL/kg/hr, or capillary filling time greater than two seconds. Patients who exhibit such signs, even in the face of a normal blood pressure, undergo adequate resuscitation with intravenous fluids. In addition, hypotensive patients or those showing signs of decreased perfusion should undergo a thorough evaluation for extracranial sources of hypotension, including internal bleeding or spinal cord injury, and the source(s) should be corrected as rapidly as possible. Finally, there is no role for fluid restriction in the management of severely head-injured pediatric patients demonstrating clinical signs of shock (29).

Hypoxia in children is defined as \( \text{PaO}_2 < 60\text{–}65 \text{ mmHg} \), oxygen saturation <90%, apnea, or cyanosis. Hypoventilation, which results in hypercarbia, is defined as ineffective respiratory rate for age, shallow or irregular respirations, frequent episodes of apnea, or measured hypercarbia. Hypoxia and hypoventilation commonly occur in pediatric patients after severe traumatic brain injury and can have a negative impact on mortality rate and the severity of disability of survivors (22,23). Hence, it is important to obtain early airway control and to use assisted ventilation with 100% oxygen as needed in the resuscitation phase of care to avoid hypoxia and hypercarbia. Moreover, it is essential to perform continuous monitoring of oxygenation and ventilation to avoid hypoxia and hypercarbia or to detect and correct them as rapidly as possible to age-appropriate parameters.

As with all other critically injured pediatric patients, the prehospital management (i.e., in the field and during transport) of pediatric patients with severe traumatic brain injury is of paramount importance and must be optimized in order to optimize outcome. The goal of such management is to prevent secondary brain injury by obtaining early airway control and restoring oxygenation, ventilation, circulating blood volume, and blood pressure (i.e., the ABCs of resuscitation). Based on previous studies (12,17,22–27), the following recommendations were made in the pediatric guidelines (3). Treatment guidelines included recognizing and correcting hypotension as rapidly as possible with intravenous fluids and evaluating and treating all associated extracranial injuries. Treatment options included:
1. obtaining airway control in children with a Glasgow Coma Score \( \leq 8 \) or in the face of hypoventilation,
2. using assisted ventilation and 100% oxygen during the resuscitation phase of care in order to prevent hypoxemia, hypercarbia, and aspiration,
3. performing continuous assessment of oxygenation and ventilation using pulse oximetry and end-tidal CO\(_2\) monitoring and/or serial arterial blood gas measurements,
4. recognizing and correcting hypoxia as rapidly as possible,
5. monitoring blood pressure frequently and administering intravenous fluids as needed to maintain systolic blood pressure within the normal range for age.

In addition, although there are no pediatric studies to date that evaluate the effect of brain-directed therapies in the prehospital setting, such as the use of sedation, analgesia, neuromuscular blockade, mannitol, hypertonic saline, or hyperventilation, on the outcome from severe pediatric traumatic brain injury, the pediatric guidelines made the following recommendations regarding the use of these therapies (3). Specifically, they recommended as a treatment option the prehospital use of sedation, analgesia, and neuromuscular blockade to optimize transport of the pediatric patient with traumatic brain injury. However, they recommended against the prophylactic use of mannitol and hyperventilation (i.e., 25 breaths per minute in a child and 30 breaths per minute in an infant) in pediatric patients with traumatic brain injury in the prehospital setting except in euvolemic, normotensive patients exhibiting definite signs of cerebral herniation, or acute neurologic deterioration. The prehospital prophylactic use of brain-directed therapies, such as mannitol and hypertension, is not recommended because these treatment modalities can exacerbate intracranial ischemia and interfere with resuscitation. Finally, as pointed out in the pediatric guidelines although previous studies have shown that hypotension and hypoxia are potentially avoidable secondary insults that significantly increase the morbidity and mortality of severe pediatric traumatic brain injury patients, evidence suggesting that outcome from severe head injury is improved by preventing hypotension and hypoxia in the prehospital setting is lacking (3). Further studies are needed in pediatric patients with severe head injury to assess the role of prehospital hypotension and hypoxia on functional outcome, to ascertain treatment thresholds for hypotension and hypoxia, to evaluate the potential beneficial role of hypertension, and to assess prehospital management protocols, including brain-directed therapies, in order to optimize prehospital management and subsequent functional outcome of pediatric patients with severe head injury.

**EVIDENCE-BASED TREATMENT STRATEGIES—INTENSIVE MANAGEMENT**

The use of intensive management protocols has significantly reduced mortality and morbidity in pediatric patients with severe head injury. Such protocols include early intubation and rapid transport to an appropriate trauma care facility; prompt intravenous fluid resuscitation; CT scanning; surgical evacuation of intracranial mass lesions; and meticulous management in an intensive care unit setting, with continuous monitoring of physiologic parameters. Routine monitoring of pediatric patients with severe head injury includes continuous invasive arterial blood pressure monitoring,
pulse oximetry, and monitoring of ICP, central venous pressure, temperature, end-tidal carbon dioxide, and urine output. The primary goal of intensive management of severe pediatric head injury is to improve mortality rates and functional recovery by preventing secondary injury to the brain caused by systemic hypotension, hypoxia, elevated ICP, and/or reduced cerebral perfusion pressure (CPP). To avoid secondary brain injury, normal, age-appropriate physiologic parameters must be maintained or prompt intervention must occur when deviations in these parameters arise.

The CPP, defined as the mean arterial blood pressure (MAP) minus ICP, is the physiologic variable that represents the pressure gradient driving cerebral blood flow and metabolite/oxygen delivery and, therefore, is related to cerebral ischemia. The harmful consequences of elevated ICP stem from its effect on regional and global cerebral blood flow. Pediatric patients with severe traumatic brain injury, especially those with subdural hematomas, large multifocal contusions, hypoxic injury, and/or gunshot wounds to the head, frequently develop significant brain swelling and/or diffuse cerebral edema, which, in turn, cause intracranial hypertension (i.e., pathologically elevated ICP) and a reduction in cerebral blood flow (i.e., cerebral ischemia). Because intracranial hypertension is associated with decreased survival and poor functional outcome, pediatric patients with severe head injury require aggressive monitoring in the pediatric intensive care unit, including ICP monitoring, to enable rapid detection and correction of neurologic deterioration through medical and/or surgical treatment.

Intracranial Pressure Monitoring

Although to date no randomized controlled clinical trial exists that examines the role of ICP monitoring on the functional outcome of pediatric patients with severe traumatic brain injury, ICP monitoring and the medical and/or surgical treatment of intracranial hypertension are mainstays in the management of severe pediatric head injury and have become widely accepted practice. Maintenance of physiologic ICP is necessary to ensure adequate cerebral perfusion, which, in turn, is required for the delivery of oxygen and metabolic substrates to neurons and supporting cells. In addition, physiologic ICP must be maintained to prevent cerebral herniations (caused by the mechanical displacement of brain, cerebrospinal fluid, and blood vessels from one cranial compartment to another) and subsequent cerebral infarction.

Several class III studies provide evidence to support an association between intracranial hypertension and poor neurologic outcome (22,30–32). Moreover, other class III studies provide strong evidence that accurate continuous monitoring of ICP with effective treatment of elevated ICP in severely head-injured pediatric patients results in improved functional outcomes (33–36). Therefore, in pediatric patients with severe head injury (i.e., GCS score ≤8 including infants), an ICP monitor should be placed for continuous ICP monitoring and treatment of elevated ICP in an intensive care unit setting, especially in the face of diffuse brain swelling, cisternal effacement, midline shift, and/or multiple contusions on the admitting head CT scan. In addition, the pediatric guidelines recommend at the option level that an ICP monitor may be placed in patients with a GCS >8 if a mass lesion is present or if serial neurologic examinations cannot be performed because of sedation, neuromuscular blockade, or anesthesia for management of extracranial injuries (3).

The goal of ICP management is to reduce the ICP enough to ensure an adequate supply of well-oxygenated blood to the brain. With regard to the recommended ICP level for which treatment should be initiated in pediatric patients with
severe head injury, no absolute treatment thresholds have been established (3). In the past, practitioners have used 15, 20, or 25 mmHg as the arbitrary upper limit, beyond which treatment is initiated. All available evidence related to ICP thresholds comes from class III studies (e.g., see Refs. 31, 34), which suggest that the pathological effects of elevated ICP are related both to the absolute peak of ICP as well as to the length of time the ICP remains elevated. Based on the results of these and other similar class III studies, the pathological ICP level for which treatment should be initiated is 20 mmHg. Also, as suggested in the pediatric guidelines interpretation and treatment of ICP, regardless of the threshold chosen, should be validated by frequent clinical examination, cranial imaging, and monitoring of physiologic variables, such as CPP and MAP (3). Finally, to ensure the best possible outcome related to ICP management, one must pay strict attention to detail, repeatedly assessing changes in ICP and ongoing responses to therapy.

Accurate and reliable methods for monitoring ICP in pediatric patients with severe head injury include intraparenchymal fiberoptic catheter tip pressure transducer devices (e.g., Camino fiberoptic ICP monitor; Camino Laboratories, San Diego, California; Ref. 37), a ventricular catheter connected to an external strain gauge, and external strain gauge transducers. According to the adult guidelines a ventricular catheter connected to an external strain gauge transducer is the recommended method for ICP monitoring in adult patients with severe head injury (1). Although this method has the added therapeutic benefit of reducing elevated ICP with cerebrospinal fluid (CSF) drainage, continuous monitoring of ICP cannot be achieved with this method, since ICP cannot be measured while CSF is draining. To achieve accurate, reliable and continuous monitoring of ICP concomitant with therapeutic cerebrospinal fluid (CSF) drainage, one should place both an intraparenchymal catheter tip pressure transducer device for continuous monitoring of ICP and a ventriculostomy catheter for CSF drainage. In addition to enabling ICP monitoring and therapeutic CSF drainage at the same time, this technique also enables periodic measuring of ICP by the ventriculostomy catheter, which can then be compared to the ICP measured by the intraparenchymal catheter tip pressure transducer device to evaluate for measurement differences and drift. Moreover, in pediatric patients with severe head injury, fiberoptic ICP monitoring is safe and effective with a low mechanical failure rate, low risk of infection despite prolonged use of fiberoptic monitors, and low incidence of complications (e.g., hemorrhage) associated with placement of these monitors (38).

Cerebral Perfusion Pressure

There is increasing evidence that cerebral blood flow is reduced as a consequence of vasospasm following traumatic brain injury and that this may produce cerebral ischemia. As noted above, CPP, which is equal to the MAP minus ICP, is the physiologic parameter that represents the pressure gradient driving cerebral blood flow and metabolite/oxygen delivery. CPP correlates well with cerebral blood flow. A low CPP correlates with poor outcome in traumatic brain injury patients. Currently, there are no prospective randomized controlled trials (i.e., class I studies) that elucidate the optimal CPP levels in pediatric patients with severe traumatic brain injury. However, several class III studies and one class II study have shown that a CPP <40 mmHg is associated with decreased survival (32,39). Therefore, in pediatric patients with severe head injury, CPP should be maintained at least above 40 mmHg to prevent regional or global cerebral ischemia.
Treatment of Intracranial Hypertension

As noted above, ICP monitoring, with aggressive treatment of intracranial hypertension and maintenance of adequate CPP/cerebral blood flow (CBF), has led to improved survival and neurological outcomes after severe traumatic brain injury in pediatric patients. The goal of ICP management is to reduce the ICP enough to ensure an adequate supply of well-oxygenated blood to the brain and prevent ischemia. This requires brain-specific therapies to treat intracranial hypertension as well as the establishment and maintenance of normal systolic blood pressure and oxygenation in order to prevent cerebral ischemia and hypoxia during the treatment of intracranial hypertension.

As soon as vital signs are stable, the severely head-injured pediatric patient should undergo cranial CT imaging for accurate diagnosis of intracranial mass lesions. If a surgical mass lesion is observed on head CT, the patient should be taken to the operating room immediately for evacuation of the lesion. Also, while in the operating room, an ICP monitor and/or a ventricular drain should be placed if the patient’s GCS after resuscitation in the emergency department was ≤8 and/or the head CT showed diffuse brain swelling, cisternal effacement, shift, and/or multiple contusions. The ventricular drain may be left closed if the ICP is not elevated. The patient should also undergo placement of an arterial line for continuous blood pressure monitoring and serial arterial blood gas determinations. Moreover, the patient should undergo placement of a central venous line for monitoring central venous pressure and for frequent assessment of serum electrolytes, complete blood count including hemoglobin and hematocrit, serum osmolarity, and coagulation studies. Besides continuous monitoring of blood pressure, central venous pressure, and ICP, routine monitoring should include oxygen saturation by means of pulse oximetry as well as monitoring of temperature, respiratory rate, end-tidal carbon dioxide, and urine output. Monitoring of these parameters is essential to the medical management of pediatric head-injured patients because it allows for the establishment and maintenance of normal, age-appropriate physiologic parameters and enables prompt intervention when deviations occur.

At all times during the treatment of intracranial hypertension, the possibility that a surgical mass or an unexpected intracranial lesion may have developed should be reconsidered and the patient should undergo a repeat head CT. When intracranial hypertension (defined as ICP greater than 20 mmHg) occurs and there is no surgical mass lesion evident on head CT, there are several evidence-based treatment strategies that can be employed. First, physiologic parameters must be optimized. For example, PaO₂ should be maintained greater than 80 mmHg and PaCO₂ should be maintained around 35–38 mmHg since hypoxia and hypercarbia cause cerebral vasodilation, which results in increased cerebral blood volume and elevated ICP. In conjunction with this, blood transfusions should be administered as needed to keep the hemoglobin greater than 11 mg/dL. Fluid restriction should be avoided to prevent hypovolemia. Instead, intravenous isotonic or hypertonic crystalloid solutions should be administered in sufficient volumes to maintain a normal or slightly increased intravascular volume. With regard to temperature control, post-traumatic hyperthermia, defined as a core body temperature greater than 38.5°C, should be avoided in pediatric patients with severe head injury. This is based on data extrapolated from studies in animal models and in adult patients with severe head injury (1). In contrast, a role for therapeutic hypothermia in the treatment of intracranial hypertension in severe pediatric head injury has not been established. The patient’s
head should be maintained in a neutral position since rotation of the head or flexion of the neck can impede jugular venous outflow and increase ICP. The endotracheal tube tape and the cervical spine collar should be loosened sufficiently to avoid constricting jugular venous outflow. Finally, as long as the patient is euolemic and normotensive, the head of the bed can be elevated 15–30° to reduce venous outflow pressure, which is an effective way to reduce ICP without compromising CPP and cerebral blood flow.

Sedatives, Analgesics, and Neuromuscular Blocking Agents

Head-injured patients with intracranial hypertension who have a secure airway and are on mechanical ventilatory support can be treated with sedatives (e.g., benzodiazepines and barbiturates), analgesics (e.g., narcotics), and neuromuscular blocking agents. These medications aid in the management of intracranial hypertension by ameliorating agitation, reducing pain and stress, preventing coughing, straining, and shivering, minimizing movement and facilitating assisted ventilation. Also, as noted in the pediatric guidelines sedatives and analgesics can facilitate general care of the patient in the intensive care unit by helping to maintain the airway, vascular catheters, and other monitors and can facilitate patient transport to the operating room and for diagnostic procedures (3). However, care must be taken when treating patients with sedatives and analgesics because they can cause hypotension. Neuromuscular blocking agents can reduce ICP by inhibiting posturing, shivering, and breathing against the ventilator as well as by reducing airway and intrathoracic pressures and thereby improving jugular venous outflow (40). To prevent increased stress from immobilization, which can increase ICP, neuromuscular blocking agents should be given in association with adequate sedation and analgesia. Although sedatives, analgesics, and neuromuscular blocking agents are commonly used in the treatment of pediatric patients with severe head injury, classes I–III pediatric studies are currently lacking. Therefore, the pediatric guidelines recommend at the option level that the treating physician determine the choice and dosing of these agents (3). However, the continuous infusion of propofol for the purpose of sedation or management of elevated ICP is not recommended in pediatric patients with severe traumatic brain injury because it can cause lethal metabolic acidosis (41–43). Moreover, although lidocaine is commonly given in pediatric patients with severe head injury during suctioning of the endotracheal tube to blunt the reaction to airway stimulation and thereby prevent an increase in ICP, there are no studies in the literature that evaluate the use of lidocaine for this purpose in pediatric patients.

CSF Drainage

If ICP remains elevated despite the aforementioned maneuvers, the ventricular drain may be opened at 10–15 cm above the external auditory canal for CSF drainage. Ventricular CSF drainage lowers ICP by reducing intracranial fluid volume and has been shown in a class III study to improve mortality rate in pediatric patients with severe traumatic brain injury (44). Controlled lumbar drainage of CSF can also be employed to treat refractory intracranial hypertension in addition to ventricular drainage when the ventricular drain is functioning adequately and a recent head CT reveals that the basal cisterns are patent and that there are no major intracranial mass lesions or shift (45,46). However, lumbar drainage should be reserved for treatment of intracranial hypertension that is refractory to the aforementioned
Hyperosmolar Therapy

If intracranial hypertension continues to be elevated after ventricular CSF drainage, one should consider hyperosmolar therapy with intravenous boluses of mannitol and/or continuous infusion of hypertonic saline both of which are effective in the management of intracranial hypertension in pediatric patients with severe head injury (3). Mannitol, which is most effective in controlling ICP when administered intravenously as intermittent boluses, with doses ranging from 0.25 to 1.0 g/kg of body weight, can reduce ICP by at least two mechanisms of action. First, as an immediate but transient effect, mannitol changes the rheologic characteristics of the blood resulting in decreased viscosity, increased plasma volume, and decreased hematocrit (47–49). As long as the viscosity autoregulation of cerebral blood flow is intact, cerebral blood vessels respond to the decrease in blood viscosity by vasoconstricting, which decreases cerebral blood volume and thereby reduces ICP. Second, as long as the blood–brain barrier is intact, mannitol has a dehydrating effect, which results in movement of water from the brain parenchyma into the circulation and reduces brain volume (50,51). The osmotic effect of mannitol begins 15–30 minutes after mannitol is given and lasts up to six hours. Despite the long-standing and widely accepted use of mannitol in pediatric patients with severe head injury, there currently are no randomized controlled studies that evaluate the efficacy of mannitol with regard to treatment of intracranial hypertension and long-term neurologic outcome in pediatric patients compared with other brain-directed therapies (including other hyperosmolar therapies such as hypertonic saline).

Hypertonic saline is also effective in the management of intracranial hypertension in pediatric patients with severe head injury. The mechanism of action of hypertonic saline in reducing ICP is likely similar, at least in part, to that of mannitol, with both rheologic and osmotic effects playing a role. Unlike mannitol, however, hypertonic saline is most effective in reducing ICP when it is administered as a continuous intravenous infusion of 3% saline at a rate of 0.1–1.0 mL/kg of body weight per hour. Three class II studies for ICP and one class III study provide evidence supporting the use of 3% saline in the treatment of elevated ICP in pediatric patients with severe head injury (52–55). These studies demonstrated a reduction in ICP in pediatric patients with severe head injury treated with hypertonic saline. Two of these studies also demonstrated a reduced need for additional interventions to control ICP in patients treated with hypertonic saline compared to patients treated with 0.9% saline or lactated Ringer’s (54,55). Based on the results of these studies, there is guideline-level support for the use of hypertonic saline in treating intracranial hypertension. However, as pointed out in the pediatric guidelines clinical experience using hypertonic saline to treat elevated ICP in pediatric patients with severe head injury is limited and the available class II and III studies fail to address the effect of hypertonic saline on long-term neurologic outcome in severe pediatric head injury (3). Clearly, further studies are needed to address these issues.

When treating elevated ICP with hyperosmolar therapy, such as mannitol and/or 3% saline, it is necessary to maintain the patient in a euvoletic or slightly hypervolemic status. It is also essential to assess frequently the serum electrolytes as well as the serum osmolarity. In order to prevent acute renal failure, the serum osmolarity should not exceed 320 mOsm/L when treating only with mannitol or
360 mOsm/L when treating with 3% saline with or without mannitol. Moreover, prophylactic mannitol administration is not recommended unless the patient shows signs of cerebral herniation.

**High-Dose Barbiturates**

If intracranial hypertension remains refractory despite implementation of the aforementioned management strategies and there is no identifiable cause for ICP intractability noted on repeat head CT, one should consider therapy with high-dose barbiturates such as pentobarbital or thiopental. Treatment of refractory intracranial hypertension with high-dose barbiturates reduces ICP by suppressing brain metabolism and reducing cerebral blood flow and cerebral blood volume (56–58). Based on available data, high-dose barbiturate therapy is supported at the option level for the treatment of medically intractable intracranial hypertension in pediatric patients with salvageable severe head injury who are stable hemodynamically (3). In contrast, prophylactic use of barbiturates in pediatric patients early after severe head injury in an attempt to prevent the development of intracranial hypertension is not supported currently. Moreover, as with many of the other ICP-lowering therapies already mentioned, studies demonstrating an improved neurologic outcome in pediatric patients requiring high-dose barbiturate therapy are lacking.

Because serum levels of barbiturates do not correlate well with electrical activity, patients on high-dose barbiturate therapy should undergo continuous electroencephalographic monitoring for burst suppression (“barbiturate coma”), since this reflects a near-maximum reduction in brain metabolism and cerebral blood flow and, therefore, a maximum therapeutic effect (56,58). Protocols for treating patients with high-dose pentobarbital and thiopental have been reported. For pentobarbital, a loading dose of 10 mg/kg of body weight is given over a period of 30 minutes, which is followed by a 5 mg/kg bolus of pentobarbital every hour for three doses, followed by a maintenance pentobarbital dose of 1 mg/kg/hr (59). For thiopental, the recommended therapeutic regimen consists of a loading dose of 10–20 mg/kg followed by a maintenance dose of 3–5 mg/kg/hr (60). The maintenance dose is continued as long as the ICP remains elevated, with the goal of maintaining burst suppression on the electroencephalogram. The barbiturate infusion is continued in this fashion until the ICP has been well controlled for at least 24 hours. When the ICP is stable, the barbiturate infusion is weaned off gradually. Because barbiturates can cause severe myocardial depression, patients on high-dose barbiturates must be monitored carefully for hemodynamic instability. If hypotension is observed, intravenous fluids and pressors must be administered immediately to provide blood pressure support, with the goal of maintaining it within a normal, age-appropriate range.

**Hyperventilation**

If ICP is still elevated after employing the aforementioned management strategies for reducing ICP, hyperventilation can be considered. Hyperventilation, a previously widely practiced and long-standing therapy for the treatment of intracranial hypertension in both adult and pediatric head-injured patients (e.g., see Ref. 61), reduces ICP presumably by causing cerebral vasoconstriction and a concomitant reduction in cerebral blood flow and cerebral blood volume. Because of the concern that this induced vasoconstriction could cause global or regional ischemia, and thereby contribute to the brain injury and worsen neurologic outcome, the adult guidelines recommended at the level of treatment standard against the routine use of prolonged
hyperventilation (PaCO₂ less than or equal to 25 mmHg) in the management of head-injured adult patients (1). It was also recommended at the level of treatment guideline that prophylactic hyperventilation (PaCO₂ less than or equal to 35 mmHg) be avoided during the first 24 hours after head injury (1). To date, no pediatric studies have been conducted that compare the effect of hyperventilation with that of other ICP-reducing therapies on the outcome of pediatric patients with severe brain injury. In the past, aggressive hyperventilation therapy (PaCO₂ < 25 mmHg) was routinely employed in the management of intracranial hypertension in pediatric patients with severe head injury because it was thought that diffuse brain swelling and associated increased ICP were the result of post-traumatic cerebral hyperemia in these patients (62,63). However, more recent studies have revealed that increased post-traumatic cerebral blood flow (i.e., hyperemia) is not a common finding after severe pediatric head injury and have raised concerns similar to those in the adult head-injury literature regarding ischemia from hyperventilation-induced vasoconstriction as a cause of secondary brain injury and worsened neurologic outcome (64,65). As a consequence, the pediatric guidelines make the following recommendations, at the level of treatment options, regarding the use of hyperventilation in the management of severe pediatric head injury (3):

1. prophylactic hyperventilation (i.e., PaCO₂ less than 35 mmHg) should be avoided,
2. mild hyperventilation (i.e., PaCO₂ 30–35 mmHg) may be employed to treat intracranial hypertension that fails to respond to other ICP-reducing therapies such as sedation, analgesia, neuromuscular blockade, CSF drainage, and hyperosmolar therapy,
3. aggressive hyperventilation therapy (i.e., PaCO₂ less than 30 mmHg) may be used for brief periods to treat cerebral herniation or acute neurologic deterioration as well as to treat medically and surgically intractable intracranial hypertension.

Decompressive Craniectomy

Another option for treating elevated ICP due to diffuse cerebral swelling that is refractory to medical management is decompressive craniectomy. In pediatric patients with severe head injury and associated medically intractable intracranial hypertension, decompressive craniectomy has been shown to lower ICP significantly and have a beneficial effect on neurologic outcome (33,34,66). Commonly employed operative techniques include unilateral frontal-temporal-parietal-occipital craniectomy with expansion duraplasty for cerebral swelling localized to one side of the brain on head CT and bilateral frontal craniectomy with expansion duraplasty for diffuse bilateral cerebral swelling. In terms of achieving the best possible outcome from this procedure, decompressive craniectomy should be performed on salvageable patients with diffuse cerebral swelling on head CT with secondary clinical deterioration or evolving cerebral herniation syndrome who are within 48 hours of their injury, have a GCS score greater than three, and have not had any prolonged episodes of ICP elevation greater than 40 mmHg (3,33,34,66).

Anticonvulsants

In pediatric patients with severe head injury, the prophylactic use of anticonvulsants has not been shown to be beneficial in preventing late post-traumatic seizures or
improving outcome. Consequently, the prophylactic use of anticonvulsants in pediatric patients with severe head injury is not recommended. In contrast, seizures documented by clinical examination and/or electroencephalogram should be treated with anticonvulsants in pediatric patients with severe head injury because seizure activity can result in significant ICP elevation.

**Corticosteroids**

Randomized clinical trials evaluating the efficacy of corticosteroids in the management of severe head injury in adults have shown no significant improvement in the survival or functional outcome in head-injured adult patients treated with steroids (67). The evidence-based guidelines for the management of adult patients with severe head injury recommend against the routine use of steroids for improving outcome or reducing ICP in the management of adult patients with severe traumatic brain injury (1). Likewise, there is no role for corticosteroids in the treatment of pediatric patients with severe traumatic brain injury, even in the face of severe refractory intracranial hypertension. In support of this, two class II studies and several class III studies (e.g., see Ref. 70) have shown that steroids do not reduce ICP and do not improve neurologic outcome in pediatric patients with severe head injury (68,69). Moreover, exogenous steroid administration can suppress the production of endogenous cortisol and significantly increase the risk of complications such as infection and gastrointestinal hemorrhage (68).

**Nutrition**

Adult patients with severe head injury commonly become hypermetabolic, with increased energy expenditure, and are prone to catabolism and nitrogen wasting (71–73). As a consequence, their body energy requirements increase markedly. Based on the significant amount of nitrogen wasting that occurs and the nitrogen sparing effect of feeding that has been observed in studies on adult patients, the adult guidelines recommend at the guideline level that nutritional supplementation be instituted within 72 hours after the head injury and that full nutritional replacement be in effect by day seven (1). With regard to energy expenditure and need for nutrition in pediatric patients with severe head injury, only two previous studies (class II, see Ref. 74; class III, see Ref. 75) have investigated the need for nutritional support in the treatment of pediatric patients with severe head injury. These studies revealed a significant increase in the metabolic rate in pediatric patients with severe head injury but failed to address the effect of nutritional support on neurologic outcome in these patients. Nevertheless, based on the data from these two studies, the pediatric guidelines recommended at the option level that head-injured pediatric patients should begin feedings, either by parenteral or enteral formulas, by 72 hours and should be at full replacement (i.e., 130–160% of resting energy expenditure) by seven days (3). Despite the recommendation for early feeding of pediatric patients with severe head injury, the exact role of nutritional supplementation, including the effects of timing and type, on functional outcome in these patients has not yet been adequately investigated. Consequently, further studies are needed to address these issues. Moreover, if nutritional supplementation is instituted early in pediatric head injury patients, blood glucose levels should be monitored frequently and tightly controlled to prevent hyperglycemia, since previous studies have shown that hyperglycemia can worsen outcome from head injury by exacerbating secondary brain injury (76–78).
CONCLUSION

To reduce mortality and optimize functional outcome in pediatric patients with severe head injury, it is necessary to minimize the progression or the effects of secondary injury and thereby maximize the potential for recovery. Successful management of severe pediatric head injury requires complete and rapid physiologic resuscitation, which begins with aggressive and organized resuscitation in the field; avoidance of hypotension and hypoxia; prompt diagnosis and removal of intracranial mass lesions; aggressive treatment of intracranial hypertension; and maintenance of normal physiologic parameters, such as cerebral perfusion, in order to facilitate adequate delivery of oxygen and metabolic substrates to the brain. At present, many questions remain unanswered, especially at the class I level, regarding the optimal medical and surgical management of severe traumatic brain injury in the pediatric population. Thus, large, well-designed, prospective, randomized, controlled multicenter trials are needed to investigate further the effects of different treatment modalities on neurologic outcome in order to provide standards of care for the management of severe pediatric head injury.

REFERENCES


INTRODUCTION

Pediatric facial trauma patients differ from adults with similar injuries in several ways. First, the pediatric patient has the advantage of an accelerated ability to heal with a minimum of complications, especially in the well-vascularized tissues of the face. Second, through growth and the inherent ability of the child to adapt, recovery of damaged orofacial tissues can be maximized and loss of function can be minimized. Despite these advantages, certain characteristics of the pediatric facial trauma patient must be kept in mind. These include the anatomy of the immature face, the facial injury patterns from mechanisms typical of the pediatric patient, and the potential effect of trauma on growth, which makes long-term follow-up of these patients mandatory. Because of these factors, children with facial trauma cannot be managed in the same way as adults.

EPIDEMIOLOGY

The etiology of facial injuries varies with age. Overall, motor vehicles are the most common cause of severe facial injuries whether the child is a passenger or a pedestrian (1,2). Facial injuries are steadily increasing with the increasing use of wheeled and non-wheeled recreational devices (e.g., bicycles, scooters, skateboards, snowboards, and skis) (3–8). Falls are more common in the younger age groups and sporting injuries increase dramatically after the age of 12. Not surprisingly, the incidence of facial injuries increases over the summer months in northern climates.

Dog bites make up a unique category of pediatric facial trauma. Children are especially vulnerable to this type of injury because of their size, inquisitive nature, and lack of fear of apparently playful animals. Over 60% of all dog bite victims are children. About half of all children in the United States are bitten by a dog by the time they reach the 12th grade. Children younger than 15 years of age have the greatest risk for dog bites, which are frequently to the face, neck, and head. Dog bite wounds can be quite severe as the animal’s teeth engage the facial tissues while the child is pulling back, creating tangential flaps of tissue and frank avulsions.
Such severe dog bites, which unfortunately are not rare, almost always leave significant scars and deformities with lifelong cosmetic and functional implications (9).

Trauma to the head and face occurs in a large number of physically abused children. The possibility that a child's facial injury could be non-accidental must always be considered, particularly if the injury pattern and its explanation seem implausible (10).

ANATOMY AND PATHOPHYSIOLOGY

The child’s face is proportioned quite differently from that of the mature adult. The cranium is large and the facial structures are comparatively small. The size of the human newborn’s head is a fine balance between the diameters of the birth canal, the disproportionately large brain, and the face that must be sufficiently developed to allow for respiration and eating. The craniofacial ratio at birth is 8:1 and the face is recessed under the relatively large skull. Initially, the cranium grows faster than the face, reaching 80% of its mature size by the age of two years. Brain and ocular growth are near completion by age seven. However, facial growth continues into the second decade of life, so that by maturity the craniofacial ratio is 2:1. For these reasons, the cranium is more likely to be exposed to trauma before the age of seven than the face (11).

The architectural changes of facial development stem primarily from the pneumatization of the paranasal sinuses. After age seven, the development and expansion of the ethmoid air cells, frontal and maxillary sinuses, and permanent tooth eruption account for the continued growth of the maxilla (midface) and mandible, unfolding the face from the protective overhanging cranium. This pattern results in the exposure of the face to an increased risk of trauma as the child matures (12).

DIAGNOSTIC TESTS

Although pediatric facial injuries may be obvious, their diagnosis can be problematic. Soft tissue injuries, lacerations, and bruises may be obvious but injuries to deeper structure such as the facial bones and nerves may not. External examination alone will miss most maxillofacial skeletal injuries. As children frequently do not cooperate or communicate well with strangers, a detailed history and physical examination may be impossible. The history of the injury must rely on the parent’s or other observer’s account of the incident and their impression of whether the child’s appearance has changed as a result of the injury. In deep or extensive soft tissue injuries, repair of the facial wounds should be done promptly in the operating room where a thorough investigation of the depth of damage and involvement of associated structures is possible. In maxillofacial bone injuries, the cornerstone of diagnosis is the computerized tomography scan (13). Even in an apparently trivial facial injury, routine CT scanning may pick up unsuspected fractures. In the best of circumstances, imaging a child’s face can be difficult, so sedation or general anesthesia is often necessary. As most facial injuries are not life-threatening, delaying the CT examination for several days until the child is stabilized does not jeopardize the long-term facial outcome.
EMERGENCY MANAGEMENT

The provision of an adequate airway, prevention of aspiration, control of bleeding, and stabilization of the cervical spine are the major considerations in the emergency management of the pediatric patient with significant facial injuries (14). The edema from maxillofacial injuries, mandibular fractures in particular, can easily compromise the upper airway of an injured child. Even minor edema can produce sudden obstruction. Endotracheal intubation should be used liberally. Emergency tracheostomy is rarely, if ever, necessary. In fractures of the maxilla and mandible, aspiration of loose or broken teeth and blood is not uncommon. The mouth and pharynx should be cleared of any debris and the trachea intubated if necessary. Excessive bleeding, usually from the scalp, lateral face, neck, or mouth should be controlled by pressure and packing. There are too many important facial structures for random clamping at bleeding sites. As there is a significant incidence of cervical spine injuries with high-velocity facial trauma, particularly when mandible fractures are present, the neck should be stabilized until it is formally cleared.

DEFINITIVE TREATMENT

Facial Fractures

General Principles

Facial fractures are not as common in children and teenagers compared to adults and are often less severe because they result from lower impact forces (e.g., motor vehicle accident in an adult versus a sporting injury in a child). Due to their thinner and more pliable bone structure, children have a higher rate of non-displaced or minimally displaced facial fractures, which do not require surgical repair. Developing facial bones also have a rapid and extensive ability to remodel, so they tolerate more anatomic disruption without long-term functional sequelae. Furthermore, surgical scars and foreign bodies (e.g., metal plates and screws) may cause greater long-term problems than the initial injury. This leads to two important treatment principles:

1. the indications for open reduction of facial fractures are more restrictive (e.g., significant displacement with functional implications must be present).
2. the surgical procedure should be designed to prevent the adverse effects of scarring on subsequent skeletal growth and to minimize visible facial scarring.

When open reduction and internal fixation of pediatric facial fractures are indicated, the goals of treatment are to achieve bony union with anatomic reduction, restore form and function, normalize dental occlusion and prevent subsequent growth disturbances. Long-term follow-up in these patients is required to monitor for secondary deformities, which may occur as a result of growth disturbances or scar formation.

Nasal Fractures

Nasal fractures are common in children but the diagnosis can be difficult due to immaturity of the nasal bony pyramid (15). Plain radiographs are usually not helpful. The physical exam (after the swelling has gone down) and CT scans are most
diagnostic (Fig. 1). Depressed fractures require operative reduction and alignment as subsequent cartilaginous growth of the nose may result in widening or irregularities. Should primary treatment not be rendered, formal septorhinoplastic reconstruction will be required once growth is complete.

One often-undiagnosed nasal injury that may accompany bone fractures is a septal injury. The most common presenting symptom is nasal airway obstruction that accompanies a nasal fracture. Primary septal reconstruction in cases with severe septal fracture dislocation will minimize the occurrence of secondary nasal deformities (16). Severe septal fractures are often accompanied by a subperichondrial hematoma. These hematomas need drainage to prevent septal necrosis from the separation of the perichondrium from the cartilage. The long-term consequence of necrosis of nasal septal cartilage is the development of a saddle-nose deformity (17).

Naso-orbital-ethmoid (NOE) Fractures
The extension of a fracture beyond the nose, which requires greater impact energy, is an uncommon injury whose incidence coincides with the development of the paranasal sinuses. This is rare in children under five to seven years of age. The nose is impacted posteriorly with these fractures, causing displacement of the medial orbital walls outward and resultant telecanthus (widening of the interorbital distance). A CT scan accurately shows this fracture pattern. Intraoperative repair requires a wide coronal (scalp) exposure, bone reduction, medial mobilization of the laterally displaced orbital walls and canthal tendons, and cranial bone grafting of the nasal dorsum (18).
Orbital Fractures

Fractures of the bony orbit are relatively uncommon in children but increase after age seven when growth of the globe is complete. The diagnosis of orbital fractures is very unreliable by physical exam in the early post-injury period due to the usually significant amount of periorbital swelling. Axial and coronal CT scan assessment of the bony orbital box (walls, floor, and roof) is necessary to determine fracture location and the amount of displacement. Ophthalmologic assessment is mandatory and should be done as soon as possible before the periorbital edema makes eyelid separation difficult. Significant expansion (blow-out) of the medial or lateral walls or floor will likely lead to eventual enophthalmos (inward and downward displacement of the globe) and/or globe motility problems due to scar entrapment. Operative repair with defect grafting is indicated in these cases and can be done once the edema is decreased sufficiently to fully assess visual function (19).

Once pneumatization of the sinuses is complete, orbital fracture patterns resemble those of adults with floor blowouts being the most common. In younger children, orbital roof fractures (which are rare in adults) may be seen in association with anterior cranial base injury from direct blunt trauma to the brow (Fig. 2) (20).

Zygomatic Fractures

Zygomatic bony injuries almost never occur in the developing face until globe development and pneumatization of the maxillary sinus are complete. Once this occurs, around the age of seven, the zygomatic facial prominence increases and becomes more prone to injury. Fractures of the zygoma involve the orbital floor and lateral orbital wall (superiorly), the posterior maxillary buttress (inferiorly), and the arch attachment to the temporal bone (laterally). When fractured, the zygoma always rotates downward and inward (toward and into the maxillary sinus), producing clinical signs of a flat cheekbone (malar) area, downward positioning of the globe, dysesthesia of the infraorbital sensory nerve (cheek and upper lip numbness) and blood in the maxillary sinus. Facial edema may obscure these signs for a week or more. Axial and coronal CT scans demonstrate the deranged anatomy well and provide the most definitive early indication for open surgical reduction (Fig. 3) (21).

Maxillary/Midfacial Fractures

Fractures of the maxilla (midface) are not likely to occur unless there is a maxillary sinus, which provides an air space between the eyes and the teeth. This, along with the other protective features of the juvenile face, including its flatter profile and more abundant fat for padding, make midface fractures the least common of all pediatric facial fractures (22). However, once adolescence is reached, the incidence of midface fractures reaches adult levels.

The hallmark of a maxillary fracture is malocclusion as the teeth shift from mandibular alignment as its basal bone moves. Individual maxillary segments or the entire maxilla and palate may be fractured producing differential occlusal changes. This must be distinguished from a more limited fracture at the dentoalveolar level where individual or multiple teeth may be loose but the overlying bone is stable. Since children from 6 to 12 years of age present a mixture of primary and secondary teeth (transitional dentition), accurate assessment of occlusal alignment can be difficult. Because the midface is filled with permanent teeth until their final eruption in
adolescence, management of maxillary fractures is usually by closed, conservative means through alignment of the upper and lower dentition (23).

Mandible Fractures
Fractures of the mandible are the second most common type of facial fracture after those of the nose. Malocclusion, difficulty with opening the mouth, and pain are the most common clinical findings. Since multiple areas of the mandible requiring
different management can be fractured, accurate and thorough radiographic evaluation is important. Excellent imaging can be obtained with panoramic radiographs but most radiology departments do not have this equipment and patient cooperation may be difficult. Axial CT scans are the modality of choice with the addition of coronal images for better views of the condylar regions (24).

Conceptually, mandibular fractures involve either tooth-bearing bone (body, parasymphysis, and symphysis) or bone without teeth (ramus and condyle). While fractures in all areas result in displacement and malocclusion, fractures in

Figure 3  Zygomatic fractures present as malar deficiencies with infraorbital (V2) paresthesias. (A) After initial swelling has subsided, the malar impaction can be appreciated. (B) Postsurgical repair with intraoral reduction and plate fixation.
tooth-bearing bone are compounded into the oral cavity, which often results in loose teeth and fracture exposure. Such fractures require prophylactic antibiotics; closed fractures of the ramus and condylar regions do not. The anatomy and behavior of children predispose them to certain types of mandibular fracture. These include symphyseal (anterior mandible) and condylar fractures from direct contact on the chin from a fall (Fig. 4) (25). Older children and teenagers present fracture patterns similar to adults.

The mandible and the maxilla often require a different surgical approach than other facial bones. No other facial fracture can be treated as successfully with closed

Figure 4  Mandible fractures commonly involve disruption of the occlusion with the exception of those fractures involving the posterior ramus and condyle where an open bite, as opposed to disruption of the dental arch, may be seen. (A) Parasymphysis mandible fracture with separation between the canine and premolar teeth. (B) Intraoral reduction and resorbable plate fixation.
reduction. Restoring occlusion of the maxillary and mandibular teeth reduces the fracture anatomically and provides external stabilization [maxillomandibular fixation (MMF)]. In many minimally displaced mandible fractures, particularly of the condylar region, this is the treatment of choice. The number and type of teeth present, however, can limit the application of MMF techniques. Fractures of the condylar region of the mandible in children are of particular concern due to the long-term effects of injury to this important growth center (26).

**Craniofacial Fractures**

The prominence of the forehead and thinness of the bone predispose children to fractures of the frontal bone, supraorbital rim, and orbital roof. Associated intracranial injuries (pneumocephalus, epidural and subdural hematoma, and cerebral contusion) are not uncommon. CT scans are paramount in defining potential injury to the brain and globe. Neurosurgical and ophthalmologic input are essential. Posterior displacement of the frontal and supraorbital rim or inferior displacement of the orbital roof requires open surgical reduction. Wide exposure through a coronal incision is needed to dismantle and reassemble the fracture sites of the upper cranio-orbital skeleton properly (27).

**Soft Tissue Facial Injuries**

**General Principles**

The very specialized and compact soft tissue structures of the face, in conjunction with their psychological and esthetic importance, demand that special attention be paid to injuries of specific facial regions.

The management of soft tissue wounds of the face in children differs from that of adults in numerous ways. First, most facial lacerations, unless very minor, should be repaired in the operating room under general anesthesia. The anxiety of children and the need for very accurate anatomic alignment of delicate structures requires good lighting and instruments as well as a still patient. Too often, poor or inadequate facial repairs result from the limitations of surgery in the awake child in the emergency room. With sufficient sedation, however, some simple facial lacerations can be effectively repaired. Children understandably are apprehensive of needles for local anesthesia. Numerous topical anesthesia agents have been used either as a substitute for or as a premedication prior to the injection of the local anesthetic (28). In the facial region, however, their use is impractical (29). Second, the suture technique used should consider how they are to be removed. Skin closures with 6–0 and 7–0 monofilament non-absorbable sutures are excellent but will require postoperative removal. In children under six to eight years of age, some form of anesthesia is frequently necessary to remove facial sutures. In young children, the use of 6–0 plain gut sutures for the skin is an excellent alternative that eliminates this problem without creating suture track marks. With good dermal/subcutaneous closure, the use of topical cyanoacrylate glue can also be very effective (30,31). Third, the ability to provide complex postoperative wound care on the face is very limited in most pediatric patients. Antibiotic ointment without a dressing is most common. However, the use of fine, absorbable sutures with cyanoacrylate glue as a postoperative wound dressing eliminates the need for any post-injury facial wound care (Fig. 5). Lastly, it is important to remind parents and patient alike that scar revision of traumatic facial wounds is the rule rather than the exception.
Scalp

Scalp lacerations frequently produce large avulsions and tissue flaps in the subgaleal fascial plane, which is loosely adherent to the underlying periosteum and easily raised. Such injuries often bleed profusely, rapidly produce hemorrhagic shock, and require fluid and blood replacement. Bleeding can usually be controlled by pressure and the quick application of staples between the skin edges. Due to its robust blood supply, scalp can survive even on very small bridges of skin. The vigorous

Figure 5  During laceration repair in children the surgeon must be conscious of the difficulty of postoperative suture removal. In children under 10, fine plain (6–0) sutures with a cyanoacrylate glue covering work well. (A) Right periorbital laceration secondary to a dog bite. (B) Repair with 5–0 vicryl dermis, 6–0 plain skin, glue dressing.

(A)

(B)
blood supply also serves to make scalp infections uncommon, even in contaminated wounds. Such resistance to infection makes it unnecessary to clip or shave hair from the wound edges, even during intraoperative repair.

Most extensive scalp wounds can be closed primarily, despite their appearance, as retraction of the galea makes the apparent scalp loss more significant than it really is. When scalp wounds cannot be closed, the placement of a split-thickness skin graft (provided the pericranium is present) will serve as the method of obtaining a healed scalp wound until secondary reconstructive techniques can be undertaken.

**Forehead**
The eyebrow is the most valuable esthetic structure of the forehead. Preservation of hair-bearing skin and accurate alignment of the eyebrow unit are essential. It is important never to shave the eyebrow hairs because they may not fully regrow or they may produce eyebrow deformities if they do.

**Eyelid**
A primary consideration in treating injuries to the eyelids is to rule out injury to the underlying globe. A common error is to miss a foreign body. Therefore, lifting the lids away and carefully inspecting the depth of the fornices is a simple but important maneuver that may be difficult in young children. Corneal abrasions are common in facial trauma with pain and irritation of the injured eye. Definitive diagnosis requires ophthalmologic assessment with fluorescein dye. Healing is usually rapid and uncomplicated with patching and antibiotic ointment.

Any injury to the medial aspect of the eyelids, particularly the lower eyelid, may violate the lacrimal system. Inspection and cannulation of the punctum with probes will confirm the injury but one must have a high index of suspicion to do so. Repair is done by loop intubation through the punctum, lacrimal sac, and into the nose with silicone rubber stents.

**Nose**
Lacerations of the nose are usually uncomplicated but may involve the underlying cartilage or bone, which can be missed as the tissue recoils on itself, closing the depth of the wound. Deep lacerations need to be closed in three layers: mucosa, cartilage, and skin. The extremely rich vascular supply of the nose, which comes through the septum and overlying skin, makes survival of any hanging skin segment likely even with the smallest attachment.

Avulsion injuries to the nose are common as its prominence assures frequent exposure to abrasive tangential forces. Partial-thickness avulsions will heal on their own owing to the thickness of the dermis. Full thickness avulsions will likely require secondary grafting. Amputation injuries are dramatic and small nasal segments (2.5 cm or less in size) can be successfully replaced as free composite grafts.

**Lips**
Lip lacerations are extremely common, especially in children, as the lip is often pushed back against the teeth. Their repair is fairly simple but detailed attention
must be given to the proper alignment of the orbicularis muscle and, in particular, the skin-vermilion junction.

**Oral Cavity**

Lacerations of the intraoral mucosa of the cheek, floor of mouth, tongue, and palate commonly occur in many facial trauma patients. They usually result from compression or shearing of the mucosa against the teeth or penetration by fractured bone or external objects. Wounds to the palate and floor of the mouth are usually best left alone to heal secondarily. Cheek and tongue lacerations should be more carefully evaluated as they may require closure to control bleeding, may communicate with external facial wounds, and to prevent notching or secondary deformity of the tongue.

**Ear**

Blunt trauma to the ear can result in profound swelling and bruising which may be indicative of a hematoma. In the growing child, the accumulation of blood underneath the extensive perichondrium of the ear is likely to result in post-injury cartilaginous distortion (cauliflower ear). An ear hematoma necessitates immediate incision and drainage with suture coaptation of the expanded tissue space.

Due to the exclusive makeup by cartilage and skin, laceration repair will often require cartilage approximation prior to skin closure to prevent notching and contour irregularities. The ear is also prone to avulsion injuries as its prominence from the side of the head exposes it to being torn or crushed. With only a small skin attachment, a segment of ear may survive although less likely than in the nose. Most ear avulsions are closed primarily to await secondary reconstruction.

**Facial Nerve**

In any laceration to the lateral face, branches of the facial nerve are at risk. This is particularly relevant in slashing, avulsive facial injuries such as those from dog bites. Before skin repair, facial nerve function must be assessed. Injuries to the facial nerve anterior to a vertical line from the lateral canthus do not require repair as the superficial muscles in this part of the face are innervated in their posterior portions. Posterior to this vertical line, severed branches of the facial nerve should be repaired under microscopic control within the first 24 hours after the injury if possible. In this early period, the distal nerve ends may still be stimulated and found. The most severe functional deficits from facial nerve transection are in the peripheral nerve branches, the frontal and marginal mandibular nerves. They have no cross-innervation with other facial nerve branches and are unforgiving of inadequate or poor repair.

**Oral Commissure Burns**

This unique infant injury is common and easily treated. It occurs in toddlers under five years of age when the child places an electrical cord in his/her mouth. Chewing violates the cord’s plastic cover, the saliva creates an electrical short circuit and an arc is created. This arc produces high heat, up to 3000°C, and chars the portion of the mouth it contacts. This causes extensive local tissue destruction with a zone of full-thickness burn at the commissure of the mouth.
Despite the electrical nature of the injury, there is no need for cardiac work up or post-injury cardiac monitoring as has been done in the past. Nor is urgent treatment or debridement of the burned tissues required. The application of antibiotic ointment is all that is needed until the eschar separates several weeks later. The parents must be warned of bleeding from the labial artery after the sloughing of the eschar, but this is easily controlled with pressure. An oral splint is fabricated after commissure healing is complete. With compliance, this splinting usually avoids post-injury scar contracture or microstomia (32,33).

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INTRODUCTION

Of the 25,301 patients entered into the National Pediatric Trauma Registry (NPTR) between 1985 and 1991, 1553 (6%) had thoracic injuries. Of these, 228 (15%) died (1). One thousand two hundred and eighty-eight had blunt trauma, 230 had penetrating injuries and 35 had other injury mechanisms. Most of the children entered into the NPTR were managed at large trauma centers so these data do not include children with lesser injuries managed at smaller centers. Males are more likely to have thoracic trauma than females, with most series reporting a 3:1 ratio (2–4). Despite its low incidence, thoracic trauma in childhood is second only to severe head injury in lethal potential. Since the cause of death in children with chest trauma is usually not the thoracic injury itself, these injuries are really a marker for the presence of life-threatening multi-system trauma (5–7). This is in keeping with the findings of Holmes’ group that 12% of children with low systolic blood pressure, elevated respiratory rate, abnormal results on chest examination, femur fracture, and a Glasgow Coma Score (GCS) of less than 15 had a thoracic injury, while <1% of children had a thoracic injury when all these features were absent (8).

Anatomically and physiologically children are different from adults. For example, the rib cage in infants is very flexible, and significant compression can occur without a rib fracture. This greater compliance and recoil effect mean that pulmonary contusion and pneumatocele formation are more common than in adults and can often occur without bony injury. Greater flexibility of the mediastinum allows further shift due to tension pneumothorax or hemothorax. Similarly, the increased metabolic rate of children combined with a lower functional lung capacity means that deoxygenation occurs more rapidly than in adults (9).

Most children with chest injuries require no more than observation or tube thoracostomy following their initial evaluation (2,4,9,10). However, if operative intervention is required, this needs to be timely to be effective.
BLUNT INJURIES

The deceleration created in falls and motor vehicle accidents (MVA) accounts for most blunt injuries. The worst chest injuries that may result from such forces are myocardial disruption, aortic disruption, sternal fracture, flail chest, and tracheobronchial disruption. In those that die at the scene, more than one of these injuries may be present. In the emergency room, these injuries are usually isolated (96.5% of patients). If two such injuries are found, there is a reported 67% mortality, and if three are found, the mortality rate is 100% (11). This selection bias needs to be kept in mind when considering the incidence rates quoted below, which are based on patients who survive in the field to reach the hospital alive.

Automobiles caused 74% of the chest injury cases in the NPTR. Overall, 15% of those with blunt thoracic injuries died, although only 14% of these were actually as a result of the thoracic injury. Most of the remainder died as a result of a severe closed-head injury (1,7).

In most series, the majority of injuries (more than 90%) require no active intervention, or at most an intercostal catheter (12,13). The presence of more than one thoracic injury doubles mortality. Likewise, injuries to other body regions are also associated with increased mortality—from 5% with isolated chest injuries to 29% when another body region is involved. If a blunt chest injury and a closed-head injury are combined, the mortality is between 40% and 70% (6).

PENETRATING INJURIES

The prevalence of penetrating trauma in the pediatric population [especially gunshot wounds (GSW) in those over 12 years of age] steadily increased during the 1990s (14). In the NPTR between 1985 and 1991, penetrating injuries accounted for 15% of thoracic injuries in children; 60% of these were GSW (1). As is true for blunt trauma, 14% of those with penetrating thoracic injuries died. However, in contrast to blunt trauma, the thoracic injury itself caused 97% of these deaths. In one cohort of 110 Turkish children suffering GSW, 76% required a tube thoracostomy alone as definitive management, 9% required immediate thoracotomy, 4% delayed thoracotomy, and 9% observation alone. Mortality was 4.5%. Most patients in this series came from rural areas, and presumably the most severely injured children did not survive long enough for transfer to the tertiary center (15). In contrast, Nance’s series drew on an urban experience of 51 patients, half of whom required surgery and 12% of the total died (16). In this series, 30% had observation alone, and 20% had tube thoracostomy alone. About 12% underwent emergency department (ED) thoracotomy. Earlier, it had been described that adolescents were more likely to require operative intervention than any other age group, and it was proposed that this may relate to the size of the patient or the underlying mechanism (17). It may also be that an adolescent that sustains a penetrating injury may have a better chance of arriving alive to the ED than other age groups because their physiological status is more robust.

Patients with hemodynamic instability require an emergency thoracotomy. Patients who are hemodynamically stable on presentation may benefit from helical CT as the initial screening modality (18).
TRAUMATIC ASPHYXIA

The syndrome of subconjunctival hemorrhage, facial edema, cyanosis, upper chest, and face petechial hemorrhages caused by compression of the chest is called traumatic asphyxia. The cause of compression can be a motor vehicle, a closing electric door, garbage compactor, falling furniture, or other object heavier than the child (19–22). Mortality is low, however, death may result from suffocation. Surviving children usually return to normal health with supportive therapy.

PRE-HOSPITAL MANAGEMENT

Accurate assessment of the injured child’s physiological parameters will allow for rapid and appropriate mobilization of hospital resources in anticipation of the child’s arrival at the trauma center (23). Endotracheal intubation in the field is difficult, more likely to be unsuccessful, and associated with a higher complication rate than intubation in a pediatric trauma center. Therefore, intubation in the field should be reserved for airways which cannot be managed by bag-mask ventilation (24). Sucking chest wounds may be dressed, and flail chest segments supported during transfer to minimize chest wall movement. Intravenous fluids should be given carefully, as fluid overload may complicate the management of lung contusion (25).

INITIAL EVALUATION

Accurate triage and mobilization of the trauma response team should be initiated (23). All injured children should be evaluated and managed according to the principles of the Advanced Trauma Life Support® (ATLS®) Course of the American College of Surgeons. The mechanism of injury and other on-scene information can help to predict the likelihood of serious injury (for example, high speed MVA, pedestrian hit by a car, fall from more than 15 feet, significant deformity to the vehicle, fatalities involved with the same accident, and whether appropriate restraints were used by the child). The primary survey includes establishing and maintaining a clear airway, and ensuring that the trachea is midline and breath sounds are normal. If the trachea is not midline, further evidence for a pneumothorax should be sought and, if clinically confirmed (reduced breath sounds, chest hyper-expansion, and chest hyper-resonance), managed expeditiously. Massive hemothorax (hypotension, chest dull to percussion, reduced breath sounds, and blood from the chest drain), flail chest (bony crepitus, paradoxical chest wall movement, cyanosis and increased work of breathing), cardiac tamponade [hypotension, raised jugular venous pressure, muffled heart sounds, and positive focused assessment with sonography for trauma (FAST) exam] and sucking chest wounds should all be diagnosed and treated during the primary survey.

An anteroposterior (AP) chest film is obtained as part of the trauma series and examined for evidence of injury to ribs, vertebral, scapulae, and clavicles. The diaphragmatic contours and lung fields are then assessed. Signs of hemothorax, pneumothorax, soft tissue gas, and pneumomediastinum should be sought. The aortic arch should be assessed, keeping in mind that small children will have a large thymus. If there is concern about the integrity of the aorta a helical CT scan should be obtained.
It has recently been suggested that a routine chest X-ray is not required in children suffering blunt trauma if there is no chest wall tenderness, no back abrasion, and if the respiratory rate is normal for age (26). While there may be cost savings and a reduction in radiation exposure to the child, I retain a low threshold for obtaining a chest radiograph. Ultrasound may in time supplant the plain chest X-ray as a rapid way of excluding a body cavity as the source of bleeding in a hypotensive patient (will exclude tamponade, detect hemothorax, and peritoneal blood) (27–29).

Chest drains are inserted during the primary and secondary survey if evidence for pneumothorax or hemothorax is found or if these diagnoses need to be definitively and rapidly excluded in a moribund child.

Advanced Trauma Life Support® (ATLS) criteria suggest that children losing more than 20–30% of their blood volume with the initial return from chest drains, or bleeding more than 2–3 mL/kg/hr thereafter, will need a thoracotomy. These arbitrary criteria have not been validated by clinical study in children (29).

**ADJUNCTIVE INVESTIGATIONS DURING THE RESUSCITATIVE AND DIAGNOSTIC PHASE**

The role of routine CT scanning in the evaluation of injured children is controversial. Following adult reports suggesting poor sensitivity of plain chest X-rays (30,31), a prospective series of 93 children showed that plain radiographs missed injuries in 13 out of 25 patients who had normal chest radiographs, including two aortic injuries. These authors advocate routine thoracic helical CT scanning in children following high-risk deceleration injuries [motor vehicle accident (MVA) >10 mph unrestrained, MVA >30 mph restrained, fall greater than 15 feet] as a way of improving the diagnosis of aortic injuries, pneumothorax, and hemothorax (32). A recent paper resulting from concern about the risk of cancer in children exposed to low-dose radiation noted a normal thoracic CT scan rate of 38%. These authors observed that, compared to head and abdominal CT scans, thoracic CT scans were less commonly obtained but more likely to be positive, and they felt this may be a result of the screening effect of routine plain chest radiographs (33). There is little doubt that helical CT scans provide more meaningful information than plain radiographs. How this translates into changes in management or outcome, and in which subsets of injured children, is yet to be proven (34–38). The use of helical CT scans as a tool to screen for aortic injury [rather than aortography or trans-esophageal echocardiography (TEE)] appears to be safe and effective (34,39–41). Further investigation via aortography or TEE may be required prior to repair (41). Others have reported the use of TEE as a first line investigation for aortic injuries (42).

**EMERGENCY ROOM RESUSCITATIVE THORACOTOMY**

The first pediatric series of resuscitative thoracotomies was published by Beaver et al. in 1987—none of the 17 children reported survived. Fifteen of 17 had blunt trauma and none had detectable vital signs or electrical cardiac activity on presentation. The authors recommended that ER thoracotomy should be reserved for those suffering penetrating injuries or those who actually deteriorate in the ED and cannot be safely transported to the operating room (34). In the discussion following the article, Ramenofsky questioned whether the authors were too nihilistic, observing that many of the children did have
reversible injuries. Ramenofsky co-authored a paper the following year examining this same topic (43). In his paper, the outcomes of 19 children were studied (none under 17 years of age survived). Five survived—four with penetrating injuries (at least two having signs of life at the scene), and one 17-year-old blunt trauma victim who had signs of life in the ED. Among those suffering blunt trauma with signs of life in the ED, one of two survived. For those suffering blunt trauma and having no signs of life in the ED, none of six children survived. These results essentially supported Beaver’s conclusions. The following year a series from Denver was published—only 1 of 47 children sustaining blunt trauma survived. The survivor was 1 of 17 children having had signs of life in the ED following blunt trauma. None of 30 patients with blunt trauma and no signs of life in the ED survived (44). Four years later this pattern was again reported in a pediatric cohort—no survivors from blunt trauma (45). None of six patients undergoing ED thoracotomy following GSW survived (five were pulseless but had cardiac electrical activity at time of presentation) (16).

When indicated, ED resuscitative thoracotomy should be performed swiftly via a left anterolateral approach in the fifth intercostal space. The pericardium is opened, taking care not to damage the phrenic nerve. If no tamponade is observed, the descending thoracic aorta is cross-clamped and internal cardiac massage commenced. Needle aspiration of the heart is performed if air embolus is suspected. Internal defibrillation is performed if indicated. If vital signs are restored, the child should be transferred to the operating room to complete the damage control surgery (29,46). If bleeding from the left lung is observed, a hilar clamp or lung twisting maneuver may also be considered in the ED (47).

RIB FRACTURES

The two main themes in the literature of pediatric rib fractures are their use as a marker of significant energy transfer in true accidental injury (hence the risk of significant multi-system injury), and as a manifestation of child abuse. The NPTR records rib fractures in 38% of children sustaining blunt thoracic injuries and 7% of those suffering penetrating trauma (1). In one study of 2080 injured children, 32% of children with evidence of thoracic trauma had rib fractures. The mortality in those 33 children with rib fractures was 42%, and those children with rib fractures and a head injury had a mortality of 71% (48). About 70% of rib fractures resulted from motor vehicle accidents, 21% from abuse, and 9% from falls. The etiology of rib fractures in children less than three years of age was abuse in 63% of children. Survivors had fewer fractured ribs than non-survivors (2 vs. 5) (48). Four children in Garcia’s series had first or second rib fractures and none had associated great vessel injuries, in contrast with Harris’ study that identified subclavian artery injuries in two of six children with first rib fractures (49). Harris recommends aortography in those children with both first rib fracture and clinical evidence of vascular injury, as no patients with a normal physical examination had a neurovascular injury (it is unclear whether all patients had angiography performed, however, so missed injury is theoretically possible) (49). Treatment of isolated rib fractures includes appropriate analgesia and chest physiotherapy to minimize the development of atelectasis or pneumonia. Plain films or helical CT scanning should exclude underlying pulmonary injury.

Flail chest is usually associated with significant pulmonary contusion, and the overall mortality of children with a flail chest in the NPTR is 38% (1). Management consists of analgesia (intravenous narcotics or epidural block) and positive pressure
ventilation. In the absence of other significant injury, rib fixation may hasten recovery and discharge from the hospital (50).

Although the data linking radiographic rib fractures to child abuse are of questionable quality (51), a rib fracture is highly predictive of non-accidental injury in children younger than three years (51–53). Other injuries should be sought and the child placed in a protected environment (54). In one series, rib fractures attributable to fragile bones were all diagnosed in the first six months of life (55). Specific fracture patterns involving the posterior aspects of the ribs have been investigated in abused children, and the pattern suggests anteroposterior compression as the usual mechanism causing fracture (56). Fractures in the rib head, and at or lateral to the costotransverse process articulation are described. Lytic lesions in these sites may also be a marker of non-accidental fracture (57).

PULMONARY CONTUSION

Pulmonary contusion (alveolar hemorrhage and parenchymal destruction) may result from rapid deceleration (MVA, falls) or by shock waves (blast injury, high velocity GSW). In children, most are caused by motor vehicle accidents (more than 80%) (58,59). Pulmonary contusion is the most common (49%) blunt chest injury in children (1,60). Nearly a quarter of children with lung contusion related to blunt injury do not have an associated pneumothorax or hemothorax (10). Clinical evidence of respiratory difficulty and plain radiographic changes may both develop insidiously over a 12- to 24-hour period (61). Contusions may be complicated by pneumonia (22%) or adult respiratory distress syndrome (2%) (59,62). The mortality from isolated pulmonary contusion alone was zero in a recent pediatric series, compared to 2% in adults (59).

Three pathophysiologic phenomena related to pulmonary contusion have been described. The spalling effect results from shock waves passing through a liquid–gas interface as is seen with surface eruptions from underwater explosions. Deceleration forces cause shearing injuries as tissues change velocities at different rates (alveoli from more stable bronchovascular structures). Finally, gas volume changes associated with the pressure changes of a shock wave as it passes through the lung cause a violent wave of gaseous expansion and contraction (62). The resulting lung damage causes defects in both gas exchange and perfusion at the alveolar level, resulting in a degree of respiratory distress (hypoxia, hypercarbia, and increased work of breathing) proportionate to the injury. Inflammatory mediators released in response to the injured tissue may then exacerbate the ventilation/perfusion mismatch as edema develops 36 to 48 hours post-injury. Subsequent infection may also cause a further deterioration in respiratory function (62).

Radiological changes may not develop on plain radiographs until four to six hours following the injury. However, up to 85% of contusions are evident on the admission radiograph (58,59). CT scanning will detect the contusion earlier. The volume estimate of affected lung may predict the need for mechanical ventilation, though the decision to initiate mechanical ventilation is usually made on arterial blood gas derangements, the existence of other injuries, and increased work of breathing (60,63). The radiographic appearance of uncomplicated pulmonary contusions will resolve over 7 to 10 days, mirroring the clinical response. Roux and Fisher have described the frequency with which pulmonary contusions are related to pneumothorax (33%), pleural effusion (62%), and radiologically evident rib fracture (62%) (61).
Initial management includes provision of supplemental inspired oxygen, making the injured lung more dependent via patient positioning, and preventing gastric distension with the use of a nasogastric tube (60). Close clinical monitoring, together with serial chest radiographs and blood gases, are essential, as the clinical effects of the contusion may progress slowly over 24 hours. Chest physiotherapy is obtained to assist with the evacuation of blood and sputum. Analgesia is essential in children with rib fractures or other injuries in which ventilatory movements result in pain. Analgesia may be administered orally, intravenously, or as regional nerve blocks (epidural or intercostal) depending on the child’s condition and available resources.

Mechanical ventilation is instituted when evidence for deteriorating respiratory function is evident (increased work of breathing, hypoxemia, hypercarbia, and fatigue). Eighteen of 100 children with blunt chest trauma related to motor vehicle accidents required mechanical ventilation in one series. All of these children had other chest injuries in addition to the pulmonary contusion (61). This was not consistent with an earlier series of 35 patients with pulmonary contusion, none of whom required ventilation for respiratory insufficiency (58). The goal of assisted ventilation is to maintain an adequate arterial oxygen tension and maintain adequate alveolar recruitment. The addition of positive end expiratory pressure (PEEP) assists with both goals by preventing atelectasis, although excessive PEEP may cause further damage to the contused lung. When standard ventilatory measures are not sufficient, alternatives such as inverse ratio ventilation, high frequency oscillating ventilation, permissive hypercapnia, and inhaled nitric oxide may be of use (60). The successful use of extracorporeal membrane oxygenation in children with adult respiratory distress syndrome (ARDS) has been reported (64). Three of five children received veno-venous (V-V) extracorporeal membrane oxygenation (ECMO), the other two had venoarterial (V-A) extracorporeal membrane oxygenation (ECMO). Four of the five patients survived, the mean duration of ECMO was 575 hours. Measures to reduce hypovolemia and to promote the use of colloids as opposed to crystalloid fluids may reduce pulmonary edema and improve tissue oxygenation. Measurement of CVP or pulmonary capillary wedge pressures may assist with fluid management of the severely injured child with pulmonary damage. The use of furosemide, corticosteroids, and adenosine A2a receptor agonists may be of benefit, but are not currently recommended for use in pulmonary contusion management (60,65). Most children have no long-term respiratory problems following pulmonary contusion when chest radiographs or lung function studies are performed (66).

PNEUMOTHORAX

The incidence of pneumothorax in children sustaining blunt thoracic trauma is 24%; 9% have a hemopneumothorax. In penetrating cases the incidence of pneumothorax is 23% and hemopneumothorax is 24% (1). In a series of 97 children with a pneumothorax (63 due to trauma), all were adequately treated by a single drain placed in the sixth intercostal space in the midaxillary line (67). The mean duration of tube thoracostomy in this series was four days. If a tension pneumothorax develops, urgent needle thoracostomy followed by tube thoracostomy should be performed. Dyspnea, hypotension, and increased respiratory rate may point to a developing tension pneumothorax. Ipsilateral hyper-resonance and reduced breath sounds, together with tracheal shift to the opposite side, indicate the presence of a tension pneumothorax. Given the mobility of the mediastinum in children, these features
can be quite impressive clinically and radiologically. In Nakayama’s series, 23% of all pneumothoraces were under tension (3).

In adults, approximately 400 mL of air in the pleural space is required to demonstrate a pneumothorax on a plain, supine AP chest radiograph (68). Not surprisingly, CT scanning has revealed many pneumothoraces that were “occult” on plain films. The incidence of occult pneumothoraces on abdominal CT scans performed for blunt trauma was 4% in one series. Close observation and supplemental inspired oxygen may be considered if the patient is asymptomatic and not ventilated, balancing the morbidity of a chest drain (21% complication rate) against the expected benefit (68,69). Ultrasound may eventually become the investigation of choice for the trauma patient not otherwise requiring a CT scan. Ultrasound is no worse than plain chest X-ray in diagnosing pneumothoraces (70). In one series using CT as the benchmark, US had a sensitivity of 100% and specificity of 94%, and plain chest X-ray had a sensitivity of 36% and specificity of 100% (71).

TRAUMATIC PLEURAL EFFUSION—HEMOTHORAX

Twenty-seven of 56 children with traumatic pleural effusions also had a pneumothorax (61). In the NPTR, children suffering a penetrating injury were more likely to have a hemopneumothorax compared to a simple pneumothorax (51% vs. 26%). Hemothorax without pneumothorax occurred in 5% of children with blunt thoracic injury, and in 18% of those with penetrating thoracic injury.

Ultrasound in the ED or operating room will detect a hemothorax with a sensitivity of 84–96% and 100% specificity (27,28). If it is the policy of the trauma service to drain all hemothoraces, US may provide a cost-effective way of detecting and treating this problem.

When detected by chest X-ray, most clinicians would elect to drain a hemothorax. This avoids problems related to lung entrapment when the hemothorax organizes, minimizes the risk of empyema, and allows for the clinical assessment of the significance of the bleeding (initial volume and continued rate). If the hemothorax is small on CT scan, and no pneumothorax is present, one might elect to avoid drainage. In this instance, the morbidity of the drain may outweigh the benefit. Thoracoscopic evacuation of retained hemothorax has been recommended for those patients with culture positive fluid from chest drains, or in whom a third of the hemithorax is occupied by material not able to be evacuated by intercostal catheters (72). Evacuation of debris in this instance may uncover an underlying lung laceration that may also be dealt with thoracoscopically.

TRAUMATIC PNEUMATOCELE

Traumatic pneumatocele (traumatic pulmonary pseudocyst) occurs more commonly in children than adults. This may relate to the elastic pediatric ribcage that allows a greater transfer of force to the underlying lung. First the lung is compressed, and the resulting rapid decompression results in a high negative intrathoracic pressure that disrupts the lung parenchyma (73,74).

Symptoms related to an isolated pneumatocele are short lived. They include chest pain, cough, dyspnea, and hemoptysis (74). Radiographic lesions may be single or multiple, unilocular, or multilocular, and are usually present in the mid and lower zones (75). CT scanning is more sensitive than plain X-ray, and may assist with
establishing the diagnosis (74). Other injuries such as pulmonary contusion, hemothorax, and rib fractures may be evident. The differential diagnosis to be considered includes diaphragmatic rupture, pneumothorax, and esophageal perforation. Pneumatoceles usually resolve spontaneously (resolution in 3–4 months), though rapid enlargement and death from a tension-like mechanism has been reported (66,73). Serial chest radiographs should be obtained at least until a reduction in size is documented. Lung abscess and diffuse intravascular coagulation (DIC) may rarely follow infection of a traumatic pneumatocele (74).

**LUNG PARENCHYMAL AND HILAR VESSEL LACERATION**

Most (85–90%) pulmonary injuries are managed expectantly or with a chest drain as a maximum intervention. When operative intervention is required the patient is often unstable, and the mortality associated with emergency pneumonectomy is as high as 70% (76). This dismal outcome has driven the development of a number of operative maneuvers to allow expeditious and safe control of hemorrhage. Anatomic segmental resection can be time consuming and is also associated with significant mortality (76–78). Simple stapled wedge excision of peripheral injuries has become routine. Deep parenchymal lacerations can be controlled by a non-anatomic exposure of the laceration track or path (“tractotomy”) using a hemostatic linear stapling device, and subsequent direct repair or ligation of exposed bleeding vessels. Some authors feel that infective complication rates with this technique do not justify its use (79). The pulmonary hilar twist has proved to be a useful damage control maneuver for hilar injuries, providing rapid occlusion of the hilar vessels (48).

Staged repair or pneumonectomy can be performed when the patient is resuscitated and rewarmed (76). The progressive adoption of these operative techniques has led to a continued improvement in outcomes (78). It should not be forgotten that temporary chest closure (abbreviated thoracotomy) has a role in damage control surgery, allowing earlier transfer to the surgical intensive care unit (SICU) for rewarming and correction of acidosis and coagulopathy (80).

**TRACHEOBRONCHIAL INJURIES**

These uncommon injuries are reported to occur in two peaks, the first in five- to six-year-old pedestrians, the second in 12- to 14-year-old boys in motorbike accidents (81). A review of the literature up to 1988 revealed that 60% of injuries occurred as a result of motor vehicle accidents and only 6% involved penetrating trauma (82). The overall mortality is 30%, with in-hospital mortality between 10% and 20%. Those that die in-hospital usually die within two hours of arrival (82). The clinical spectrum is broad and varies from the asymptomatic (10%) to those patients with obvious symptoms including stridor, dyspnea, hemoptysis, hypotension, hypoxia, and subcutaneous emphysema (82–84). Failure to tolerate the supine position has been described as an ominous sign (85). Some patients have mild symptoms that resolve quickly, only to recur when tracheal or bronchial stenosis develop. Patients are usually assessed and treated for pneumothorax (76% of cases), and an index of suspicion is required to secure the definitive diagnosis, usually via endoscopy. Deceleration injuries are usually located at points of fixation (cricoid and carina), and compression injuries may rupture the membranous trachea (82,86,87). Injury to bronchial vessels is found in a quarter of patients (88). Radiological signs suggestive of major airway injury include rib fractures, soft tissue air, pneumothorax,
cricoid elevation (indicating tracheal transection), air surrounding a bronchus, and obstruction of an air-filled bronchus. When a mainstem bronchus is transected, the affected lung (within a pneumothorax) may drop down onto the diaphragm, unlike the appearance of a pneumothorax with the hilum still intact (89). The right mainstem bronchus is injured more commonly than the left (88,90,91). Helical CT scanning may assist with the diagnosis of tracheal and bronchial injuries, and some argue that CT localization of the injury may obviate the use of direct endoscopic visualization (92–95). However, most experts recommend rigid bronchoscopy for all cases of suspected major airway injury. It allows for ventilation through the instrument and better evacuation of blood and other debris. The presence of an injury is suggested by the presence of heaped up mucosa and exposed cartilage. A fiber-optic bronchoscope may miss the injury if passed through an endotracheal tube that is itself traversing the injury. If a tracheal injury is identified, care should be taken to exclude a concomitant esophageal or vascular injury.

The clinical course follows three basic patterns. Those that die rapidly, those that can be partially stabilized and undergo repair in the first few days, and those that stabilize, are discharged, and then return with the effects of a narrowed trachea or bronchus (bronchiectasis, pneumonia, and stridor) (83,84,91,96). Around three-quarters of all injuries to the trachea and bronchi are within 2 cm of the carina (91). A right posterolateral thoracotomy will give access to the intrathoracic trachea, right mainstem bronchus and branches, and proximal left mainstem bronchus. Distal left mainstem bronchial injuries are best approached via a left posterolateral thoracotomy. Controversy exists as to the best way of managing the airway and ventilation during repair in adults. This may be even more problematic in small children in whom double lumen tubes or separate endobronchial tubes may be physically impossible to use (85). The use of high frequency ventilation has been described (97,98).

Primary repair should be attempted if possible, and soft tissue coverage (pleura or muscle flaps) should be considered (88,96). Up to half the trachea can be removed in elective adult resections, and primary anastomosis achieved successfully, in children. Grillo demonstrated uncomplicated resection of 29% of the pediatric trachea with primary repair (99). In an emergency setting all viable trachea should be preserved. Nursing the patient with a flexed neck postoperatively will decrease the tension across a tracheal anastomosis.

Non-operative approaches are recommended for short, posterior linear tears of the trachea and for bronchial injuries in which at least two-thirds of the circumference is intact and ventilation distal to the rupture possible without excessive air leak (81,85,100). Careful follow-up is required, as stenosis at the repair can occur due to scar tissue and granulation tissue. Re-resection or lobectomy may be required in some cases (82,101,102).

INJURIES OF THE THORACIC AORTA AND ITS BRANCHES

It has been estimated that 93% of children sustaining a blunt aortic injury in a motor vehicle accident will die at the scene or be dead on arrival to the hospital (103). This in part explains why injury to the great vessels is uncommon in children arriving alive to definitive care, affecting 7% of children admitted with blunt chest injury in one report, and as low as 0.1% in another (104–106). The mortality for children with traumatic rupture of the aorta is less than that reported in adults (107). In the NPTR, 39 such injuries were reported (3% of children with thoracic injuries),
22 due to penetrating injuries and 17 due to blunt trauma (1). The majority that result from blunt injury follow motor vehicle accidents. Unrestrained children are at particular risk (108,109). There were no restrained children identified in one study of aortic injuries (108). Anomalous anatomy or previous aortic surgery may predispose to these injuries (110,111). Information that may help predict the absence of an aortic injury includes a velocity change of less than 20 miles per hour, less than 15 inches of intrusion, and an impact away from the near side of the vehicle (112).

Adult guidelines can be adapted to the management of aortic injuries in children (113). Most are suspected either clinically or radiographically (widened mediastinum on initial chest radiograph). Helical CT scanning and transesophageal (TEE) appear to be as accurate as aortography in diagnosing these injuries, though aortography is still needed if endovascular stent repair is the considered treatment (108,113). Some authors recommend confirming CT findings with transesophageal echocardiogram prior to operative intervention in the hemodynamically stable patient. Similar reservations regarding operative repair based solely on CT findings were voiced by Hormuth et al. (106). Conversely, others recommend obtaining additional information from TEE after an aortogram has demonstrated an injury (114). For hemodynamically unstable patients, TEE on the operating table may provide timely information if readily available (43,108). Aortography appears to be associated with a longer time from presentation to operation [5 hours compared to less than 3 hours for CT and TEE (108)]. Interestingly, it has been reported that for adults diagnosed and treated in less than three hours there was a survival rate of 91% compared to only 70% for those who got to the operating room more than three hours after the injury (104). Stents should be considered especially in patients in whom cardiogenic shock, severe bilateral lung contusion, or in whom systemic anticoagulation (and therefore cardiopulmonary bypass) is contraindicated. In one series the average cross-clamp time was 52 minutes (range 49–55 min), and one patient had new paraparesis postoperatively (108). In a non-randomized series of 11 children receiving surgery (n = 6, cross clamp time 19–35 minutes), endovascular stents (n = 3), or non-operative management (n = 2), all receiving open surgery survived, one with partial paralysis. Two of the three patients receiving stents died of their head injury. Of the two children with non-operative management due to multiple serious injuries, one survived intact and one died from concomitant head injury (113). All of the children without evidence of raised intracranial pressure received beta blockade until definitive treatment.

Two main operative approaches are used. The first involves the use of distal perfusion modalities (shunt or cardiopulmonary bypass), and the other is the clamp and sew approach. Proponents of the first group aim to minimize spinal cord ischemic injury, proponents of the latter seek to avoid all unnecessary delay in order to repair this life-threatening injury. The size of the child and the presence of other injuries may preclude the use of cardiopulmonary bypass in some injured children. The American Association for the Surgery of Trauma Prospective Study of Blunt Aortic Injury concluded that distal perfusion techniques were associated with significantly lower paraplegia rates compared with clamp-and-sew (4.5% vs. 16.4%) without increasing mortality (14.9% vs. 15.1%). Aortic cross-clamp time longer than 30 minutes was also associated with an elevated risk of spinal cord injury (115). These results were confirmed by later studies (116–118). More recent studies advocate the use of a centrifugal pump (Biomedicus®) for partial left heart bypass and distal aortic perfusion as this obviates full systemic heparinization (119).

Primary suture of the aortic injury is best although seldom possible. This may be performed with or without the aid of pledgets. Interposition grafts may be
complicated by the development of a pseudo-coarctation if performed in the still growing child. Similar size and growth considerations pertain to the use of endoluminal grafts. Early Post-procedure problems with endoluminal grafts include limb ischemia if the “landing zone” of the stent occludes the takeoff of the left subclavian artery, occlusion of the left mainstem bronchus, erosion into adjacent structures, persistent leak, and rarely paralysis due to spinal cord ischemia (113,120). Patients receiving non-operative management require beta blockade to reduce the systemic blood pressure, and conversion to surgical options should occur if an expanding lesion is recognized on serial imaging.

CARDIAC INJURY

Injuries to the heart from blunt trauma include myocardial contusion, ventricular laceration and rupture, valvular disruption, and life-threatening arrhythmias (commotio cordis). Estimates of blunt cardiac injury in children with blunt chest trauma range from 0% to 43%, and it is likely that the previous absence of reliable markers for injury account for such a wide range (121).

The most common mechanism of injury is motor vehicle accidents (85.3%) and the most common diagnosis is myocardial contusion (94.5%). These injuries are usually sustained with other body system injuries, which is reflected in the mean Injury Severity Score (ISS) of 27 and 14% mortality in Dowd’s series (121). Myocardial contusion in children has resulted from deployment of air bags (122). Almost half of the patients present with chest pain, and between half and three-quarters will have external evidence of thoracic injury.

Commotio cordis describes the occurrence of life-threatening cardiac arrhythmias following a blunt, non-penetrating and often innocent looking blow to the chest. These occur in the absence of heart disease or morphological injury to the heart or chest wall. Two recent reviews have encapsulated the current understanding of this condition (123,124). This condition occurs most commonly in white males playing baseball or softball, though other activities have been implicated. Three factors combine to produce commotio cordis. First, the blow needs to be directly over the precordium. Second, the blow needs to occur 15–30 ms prior to the T wave peak to produce ventricular fibrillation (blows during depolarization/QRS frequently result in complete heart block). Finally, the risk for cardiac arrest appears to be inversely proportional to the energy of impact—it is usually a low-energy event. It may be that children are more at risk as their compliant chest wall transmits the blow to the heart more effectively (70% of cases are in patients less than 16 years of age). Most arrhythmias related to blunt chest trauma occur in the first few hours post-injury, with delayed (4–6 days) cardiac arrhythmias being rare (125). Monitoring the ECG of those with known cardiac injuries is recommended for at least 24 hours, with some authors recommending 48 hours (125).

Myocardial contusions manifest themselves as arrhythmias, hypotension secondary to myocardial dysfunction, and aneurysms from myocardial wall weakness (126). The diagnosis is made on the basis of ECG, cardiac enzyme or troponin assays, and echocardiography. Patients are managed in a unit where the ECG can be continuously monitored and any arrhythmias promptly and appropriately managed. In a post mortem review of blunt cardiac injuries, none of the 41 pediatric patients died from cardiac contusion alone—most deaths were due to either cardiac rupture or brain injury (127). Early studies demonstrated the unreliability of Creatine Kinase (CK), Creatine Kinase Bioenzyme MB (CKMB), and admission ECG in excluding a
cardiac contusion, and authors stressed the importance of clinical findings (significant mechanism of injury, pulsus paradoxus, and unexplained hypotension) (127–130). Early studies of troponin assays suggested that this may be a more useful serum marker for injury (131,132). A more recent study has suggested that troponin assays are more sensitive, especially when combined with the ECG. If both the ECG (admission and 8 hours postadmission) and troponin I levels (admission, 4 and 8 hours postadmission) are normal, the risk of having a significant injury (arrhythmia requiring treatment, unexplained hypotension requiring vasopressors or cardiogenic shock requiring inotropes) is minimal (133). If both tests are normal, and there are no other injuries requiring admission, then discharge is safe. If either test is abnormal, close monitoring for at least 24 hours is indicated. If both the ECG and troponin assays are abnormal, admission to an ICU environment is indicated. Of the 15 patients who had both a significant cardiac injury and a transthoracic echocardiograph, the echo showed an abnormality in only seven patients. TEE and MRI are currently being evaluated with respect to their ability to detect cardiac contusion/hematoma and define valvular injuries (43,134).

Myocardial rupture due to blunt cardiac injury has a mortality rate between 76% and 93% (135), and this is reflected by post-mortem reviews (127,136). Patients usually (but not always) present in extremis and with signs of cardiac tamponade (137). The diagnosis may be confirmed quickly by FAST examination. Emergency operative intervention is indicated. The right atrium is the most common site of rupture in survivors (135). There is a single case report of a hemopericardium in a child following blunt trauma that was related to injury to the coronary arteries diagnosed on hospital day three (138). Valvular disruption following blunt thoracic trauma is uncommon. The physical examination reveals a cardiac murmur, and arrhythmias may be present. The diagnosis is confirmed by echocardiography (139). Repair can be delayed in stable patients (140). Pericardial rupture has been detected and reported sporadically for over 60 years. Heart herniation/luxation as a complication of pericardial rupture has a mortality rate of 33% (141).

Penetrating cardiac injuries are usually identified when the patient develops signs of an acute cardiac tamponade that results from bleeding from a cardiac chamber. Delayed tamponade due to injury to a coronary vessel has been described (142).

**DIAPHRAGMATIC INJURIES**

Penetrating injuries accounted for the majority of diaphragmatic injuries in the NPTR. The incidence of blunt diaphragmatic injuries was only 2% (1). In a recent review of diaphragmatic injuries, the incidence of traumatic diaphragmatic hernias in all injured children was 0.07% (143). Apart from one all-terrain vehicle accident, all the blunt injuries in this series were as a result of motor vehicle accidents. Other reports include falls and crush injuries as causes (144).

Clinically, most children display dyspnea (86.6%), abdominal pain and vomiting (144). Diminished breath sounds were recorded in three-quarters of the patients in this series. Recent series show both hemidiaphragms were equally involved (143–145). Previous series demonstrated a left sided predominance. Missed injury may explain this discrepancy (146). Of interest, 46% of injuries were diagnosed before surgery, 30% during surgery, 7% after surgery, and 13% at autopsy. All patients had significant associated injuries, and a third of the patients died. Brandt et al. earlier reported similar findings (147).
Most traumatic diaphragmatic hernias can be diagnosed on an AP chest X-ray (143). Insertion of a nasogastric tube prior to taking the X-ray may assist with the diagnosis. Diagnostic features include the presence of the nasogastric tube tip in the chest, bowel loops in the chest, obliteration or elevation of the hemidiaphragm, arch-like soft tissue opacity in the lower chest forming a pseudo-diaphragm, plate-like atelectasis, mediastinal shift to the non-affected side, and pleural effusion. CT findings may include the “curled” diaphragm sign where a lobulated and irregular thickening of the diaphragm is noted, the presence of herniated omental fat or other abdominal viscera (often a “waisting” is seen where the margins of the defect compress the herniated structure) (145,148). A “dependent viscera” sign has also been described, in which abdominal viscera are seen to lie directly against the ribs in a dependent fashion (149). Coronal and sagittal reconstructions available with helical CT improve the diagnosis of diaphragmatic defects close to the body wall, especially on the left (100% sensitivity on the left, 70% sensitive on the right) (145,149,150). MRI may give superior differentiation of soft tissue structures in children in whom the diagnosis is suspected but not seen on plain radiography or CT scan. The time needed for acquisition together with the introduction of helical CT makes MRI less useful as an early investigation (145). Delayed diagnosis has been attributed to delayed rupture (contused diaphragm eventually rupturing), positive pressure ventilation preventing visceral herniation, and false negative diagnostic peritoneal lavages (143).

At operation both hemidiaphragms should be carefully examined. Primary repair is possible in most cases, chronic defects may require a patch (151). Case reports of laparoscopic and thoracoscopic repair have been reported (151–153). Thoracoscopic evaluation may be preferred in patients with a suspected but non-proven diaphragmatic injury. However, the ability to repair damaged abdominal viscera from the thoracic cavity is limited (154). The thoracoscopic approach allows for complete evacuation of intrapleural blood, and repair of damaged lung (155). Of interest, one series reported 2 of 15 patients having ileoileal intussusception following diaphragmatic repair (144).

**ESOPHAGEAL INJURY**

Injury to the esophagus from blunt trauma is very uncommon, and accounts for 0.2% of all blunt chest injuries. In the pediatric literature seven separate cases have been reported (156,157). The biggest single institution study of esophageal injuries listed only 1 of 24 cases resulted from blunt trauma (156). The intrathoracic esophagus is well shielded from direct injury due to blunt trauma. Perforations are postulated to occur when intraluminal pressure rises rapidly and the luminal material cannot be expelled orally, from vascular damage when deceleration or traction causes ischemia, or if blast effects are sustained (presumably the tracheal explosion impacts the esophagus) (158). Reported cases appear to involve chest impacts against the steering wheel in five MVA cases, and two crush injuries from heavy sporting equipment (157).

Recognition of the injury was significantly delayed in five of the seven children because the symptoms, chest pain, fever, and subcutaneous emphysema were non-specific and could also be explained by associated injuries. When suspected, injury is best excluded by combining contrast esophagram with endoscopic evaluation, as either test alone is not sufficiently sensitive (157). Definitive operative repair can be primary, or delayed with the use of diversion or exclusion of esophageal contents to the injured segment. Historically, uncontrolled mediastinal sepsis is rapidly fatal, and primary repair is only recently receiving renewed interest. Primary repairs buttressed with pleural or...
chest wall muscle flaps, together with vigorous antibiotic support, bowel rest, and total parenteral nutrition (TPN) appear to offer satisfactory results.

Penetrating esophageal injury accounts for the majority of reported esophageal injuries. The recent multi-center study reported by the American Association for the Surgery of Trauma, which included children, provides the clearest information for this injury (159). Approximately half of the patients studied received preoperative investigations and the other half were treated emergently in the operating room. One hundred seventy-one patients in the preoperative evaluation cohort underwent 124 esophagoscopys, 105 contrast studies and 74 CT scans (53% of cases were clinically suspected of having an injury prior to investigation). Mean time to operation for the whole group was 6.5 hours (13 hours for those undergoing evaluation, one hour for the group going directly to the OR). About 82% underwent primary repair, 4% had resection and diversion, 3% resection and anastomosis, and 11% drainage alone. Muscle flaps to buttress repairs were used in 16% of patients. Twenty-four of 405 patients died in the ED, 35 died in the operating room. There were 19 late deaths. Early operation was associated with significantly reduced rates of infection, and the SICU length of stay was also much lower (11 days vs. 22 days). While the authors do not clearly advocate early exploration for all patients, it is clear that delay to definitive treatment is undesirable.

REFERENCES


INTRODUCTION

The development of pediatric expertise in regional trauma systems has led to advances in triage and transport of seriously injured children to appropriate facilities prepared for the unique challenges of these patients (1). Several recent reviews of the National Pediatric Trauma Registry (NPTR) indicate that 8% to 12% of blunt injured children will have abdominal injury (2,3) (Discala, C. personal communication, March 2001). Fortunately, more than 90% of those with blunt abdominal injuries survive and only 22% of the deaths are related to the abdominal injury. Whereas abdominal injuries are 30% more common than thoracic injuries, they are 40% less likely to be associated with a fatal outcome.

The treatment of children with major abdominal injuries has changed significantly in the past two decades. Surgical restraint has been the theme, and increased awareness of anatomic patterns and physiologic responses has prompted successful nonoperative care of many abdominal solid organ injuries in children. Our colleagues in adult trauma care have acknowledged this success and applied many of the principles to their patients (3).

Historically, trauma surgeons who were unfamiliar with a nonoperative approach for solid organ injuries often raised questions about the consequences of such treatment. Their concerns included the potential for increased transfusion requirements, increased length of hospital stay, and missed associated injuries. Some even questioned the need for involvement of pediatric surgeons in nonoperative
treatment protocols. Experience that has settled these controversies is outlined below, although few consensus guidelines exist.

Few surgeons will have extensive experience with massive abdominal solid organ injury requiring immediate surgery due to the success of nonoperative treatment for the majority of children with solid visceral injury. It is imperative that surgeons familiarize themselves with current treatment algorithms for life-threatening abdominal trauma.

Important contributions have been made in the diagnosis and treatment of children with abdominal injury by radiologists with cross-sectional imaging, interventional procedures, and endoscopists. The resolution and speed of computed tomography (CT), screening capabilities of focused abdominal sonography for trauma (FAST), and the less invasive percutaneous, angiographic, and endoscopic interventions of non-surgeon members of the pediatric trauma teams have all enhanced patient care and improved outcomes. The specific sections of this chapter will focus on the more common blunt injuries and unique aspects of care in children. The readers are referred to standard trauma texts for detailed discussion of penetrating injuries and operative maneuvers (4).

**SOLID ORGAN INJURY**

**Spleen and Liver Injury**

The spleen and liver are the organs most commonly injured in blunt abdominal trauma with each representing one-third of the injuries. Abdominal CT is the most useful diagnostic test because it produces images that define the presence and extent of splenic and hepatic injury and associated changes. Abdominal CT is the standard diagnostic test for all hemodynamically stable patients with suspicion of abdominal injury. The American Association for the Surgery of Trauma (AAST) grading system for splenic and hepatic injury is the accepted standard for defining the anatomic severity of injury (Table 1, Fig. 1) (5). The decision to operate for spleen or liver injury, which should always be made by a surgeon, is best based on clinical signs of continued blood loss such as low blood pressure, elevated heart rate, decreased urine output, and falling hematocrit. Nonoperative treatment of isolated splenic and hepatic injuries in stable patients has been standard practice in pediatric surgery. The departure from splenectomy was a response to increasing evidence of the important role of the spleen in cellular and humoral immunity, and the frequent finding at celiotomy of injured spleens that were no longer bleeding. The rates of successful nonoperative treatment of isolated blunt splenic and hepatic injury now often exceed 90% in most pediatric trauma centers and adult trauma centers with strong pediatric commitment (6–9).

A recent study of over 100 patients from the National Pediatric Trauma Registry (NPTR) indicated that the nonoperative treatment of spleen or liver injury is indicated even in the presence of associated head injury if the patient is hemodynamically stable (10). Rates of operative intervention for blunt spleen or liver injury were similar with or without the presence of a closed head injury.

Surgeons unfamiliar with nonoperative treatment algorithms for blunt splenic injuries in children occasionally question the nonoperative approach to solid visceral injury. Significant numbers of seriously injured children are treated in adult trauma centers. While several adult services have reported survival statistics for pediatric trauma patients that are similar to their adult patients, analysis of specific treatment
for pediatric spleen and liver injuries reveals an alarmingly high rate of operative treatment (6,11–13). It is possible that trauma surgeons influenced by their experience with adult patients have less operative restraint than their pediatric surgical colleagues. Adult trauma surgeons caring for injured children must consider the hemodynamic and physiologic differences between pediatric and adult trauma patients and incorporate these into their treatment protocols. The major concerns are related to the potential risks of increased transfusion requirements, missed associated injuries, and increased length of hospital stay. Each of these concerns has been shown to be without merit.

**Transfusion Requirement**

The relative frequency and volume of transfusion in children treated by observation versus those undergoing celiotomy is a factor that could influence the choice of treatment. Reports on nonoperative treatment of pediatric solid organ injuries over the past two decades have shown decreasing rates of transfusion in the observed patients (14,15). It has been suggested that nonoperative management of blunt splenic injuries requires more blood transfusion than operative hemostasis. In fact, a study from

**Table 1** AAST Organ Injury Scaling: Spleen and Liver—1994 Revision

<table>
<thead>
<tr>
<th>Grade</th>
<th>Type</th>
<th>Description</th>
<th>AIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spleen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Hematoma</td>
<td>Subcapsular, &lt;10% surface area</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>&lt;1 cm parenchymal depth</td>
<td>2</td>
</tr>
<tr>
<td>II</td>
<td>Hematoma</td>
<td>Subcapsular, 10–50% surface area;</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intraparenchymal, &lt;5 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>1–3 cm parenchymal depth</td>
<td>2</td>
</tr>
<tr>
<td>III</td>
<td>Hematoma</td>
<td>Subcapsular, &gt;50% surface area;</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intraparenchymal, &gt;5 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>&gt;3 cm parenchymal depth</td>
<td>3</td>
</tr>
<tr>
<td>IV</td>
<td>Laceration</td>
<td>Segmental or hilar vessels;</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>devascularization &gt;25% spleen</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Laceration</td>
<td>Completely shattered spleen</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Vascular</td>
<td>Hilar injury which devascularizes spleen</td>
<td></td>
</tr>
<tr>
<td>Liver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Hematoma</td>
<td>Subcapsular, &lt;10% surface area</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>&lt;1 cm parenchymal depth</td>
<td>2</td>
</tr>
<tr>
<td>II</td>
<td>Hematoma</td>
<td>Subcapsular, 10–50% surface area;</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intraparenchymal, &lt;10 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>1–3 cm parenchymal depth</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;10 cm length</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Hematoma</td>
<td>Subcapsular, &gt;50% surface area;</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>intraparenchymal, &gt;10 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>&gt;3 cm parenchymal depth</td>
<td>3</td>
</tr>
<tr>
<td>IV</td>
<td>Laceration</td>
<td>Disruption of 25–75% of lobe</td>
<td>4</td>
</tr>
<tr>
<td>V</td>
<td>Laceration</td>
<td>Disruption of &gt;75% of lobe</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Vascular</td>
<td>Juxtahepatic venous injury</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>Vascular</td>
<td>Hepatic avulsion</td>
<td>6</td>
</tr>
</tbody>
</table>

*Abbreviations: AAST, American Association for the Surgery of Trauma; AIS, Abbreviated Injury Scale.*

*Source: Adapted from Ref. 6.*
the early 1990s showed that children treated without operation had a significantly lower rate of transfusion compared to a group of hemodynamically stable patients undergoing celiotomy for blunt splenic injury (16). Two recent studies of more than 1100 patients with isolated spleen or liver trauma showed a transfusion rate of less than 5% in children with grade I–III injuries (8,17). Current belief that hemodynamically stable patients have already stopped bleeding has allowed patients to be managed successfully by accepting lower hematocrits to avoid transfusion. Our current practice is to transfuse only if patients show signs of continuing blood loss; a low hematocrit alone is not an absolute indication for transfusion.

Missed Associated Abdominal Injuries

Advocates of surgical intervention for splenic trauma cite their concern about missing associated abdominal injuries if no operation is performed. Morse and Garcia reported successful nonoperative treatment in 110 of 120 children (91%) with blunt splenic trauma, of whom 22 (18%) had associated abdominal injuries (18). Only 3 of these 120 patients (2.5%) had gastrointestinal injuries, and each was found at early celiotomy done for a specific indication. There was no morbidity from missed injuries.

Figure 1 CT examples illustrating different severities of splenic and hepatic injuries. (A) Small splenic laceration less than 1 cm in depth along the lateral margin corresponding to grade I injury (arrow). (B) A slightly more extensive hepatic laceration within the posterior aspect of the right lobe: grade II injury. (C) A large branching laceration of the posterior lobe of the liver extending to the IVC compatible with grade III injury. (D) Shattered spleen with active extravasation and extensive hemoperitoneum, which is grade V injury. Abbreviation: IVC, inferior vena cava.
or delayed surgery. Similarly, a review of the NPTR from 1988 to 1998 revealed 2977 patients with solid abdominal visceral injury, including only 96 (3.2%) with associated hollow viscus injury (19). Higher rates of hollow viscus injury were associated in assaulted patients and those with multiple solid visceral injury or pancreatic injury.

Differences in the mechanism of injury may account for the much lower incidence of associated abdominal injuries in children compared to adults with splenic trauma. There is no justification for an exploratory celiotomy solely to avoid missing potential associated injuries in children.

Length of Stay
Historical treatment protocols for stable children with solid organ injury included days of observation in the intensive care unit (ICU), up to seven days of bed-rest, and a 10–14-day hospital stay. Recent reports have questioned the necessity of ICU admission and long hospital stay in stable children with either spleen or liver injury due to the lack of significant clinical events (15,20). These authors have recommended a shorter hospital stay without mandatory ICU admission in stable children with low CT grade and isolated high CT grade as these patients rarely need transfusion or operation. With these studies as background, the American Pediatric Surgical Association (APSA) Trauma Committee sought to define consensus guidelines for resource utilization in this cohort. The results of the APSA initiative are described in detail below.

Does Outcome Correlate with CT Grade?
The prognostic value of CT grading in children with blunt spleen or liver injury has been widely debated with seemingly contradictory results (7,20,21). Some studies indicate that the Injury Severity Score (ISS) and not CT grade correlate with the outcome. Obviously, resource utilization and outcome would be significantly influenced by a closed head injury or other significant associated injuries rather than by a stable liver or spleen injury. However, there is a strong correlation of CT grade and outcome when the cohort with isolated spleen or liver injury are analyzed (9). Many have outlined the correlation of spleen or liver injury CT grade to time of radiographic healing (defined as normal parenchyma or linear echogenic “scar”) using the follow-up CT or ultrasound in hundreds of patients (22–25). However, the appearance of the spleen or liver in imaging studies does not necessarily correlate with the integrity of the organ, and therefore offers little help to the clinician in advising the period of restricted physical activity after injury.

APSA Evidence-Based Consensus Guidelines
Evidence-based medicine involves integrating current best evidence (medical literature) with clinical expertise and patient preferences in making decisions about the care of individual patients. Evidence-based methodology is the emerging cornerstone of the clinical practice guideline process (26–29). Although nonoperative treatment of children with isolated blunt spleen or liver injury has been universally successful, there is great variation in the management algorithms used by pediatric surgeons. Review of the NPTR and recent surveys of the APSA membership confirms the wide disparity in care, acknowledging the limitations of trauma registry and survey reviews (30–32).
The evolution and refinement of nonoperative treatment in children with isolated spleen or liver injury has been well documented at individual centers (14). However, guidelines for ICU admission, number of hospital days, the need for pre-discharge or post-discharge imaging, or the appropriate interval of restricted physical activity remain undefined. The APSA Trauma Committee sought to define evidence-based guidelines for resource utilization in these patients (8). We performed a thorough review of the medical literature and found no randomized, controlled trials (class I evidence) regarding optimal resource utilization in children with isolated spleen or liver injury. Therefore, using evidence-based methodology, standards of care could not be proposed in the absence of class I data. Formal consensus development techniques utilizing expert opinion are required to develop practice guidelines whenever there is a lack of adequate evidence (Table 2). A contemporary, multi-institution database of 832 children with isolated liver or spleen injuries treated nonoperatively at 32 centers in North America from 1995 to 1997 was established and analyzed (Table 3). Consensus guidelines on ICU stay, duration of hospital stay, use of follow-up imaging, and physical activity restriction for clinically stable children with isolated spleen or liver injuries (grades I–IV) were defined by analysis of this database (Table 4). The guidelines were based upon severity of injury by CT scan. It is important to emphasize that no recommendation falls outside the 25th percentile of current practice at participating centers.

These guidelines were applied prospectively in 312 children treated nonoperatively at 16 centers from 1998 to 2000 (Table 5) (17). Patients with minor, remote

### Table 2  Evidence-Based Guideline Development

1. Topic selection (area of variability)
2. Selection of “expert” panel
3. Clarification of proposed guideline purpose and scope
4. Listing specific goals and questions
5. Grading scientific evidence
6. Establishing recommendations
7. Presentation
8. Dissemination and implementation
9. Evaluation and revision

### Table 3  Resource Utilization and Activity Restriction in 832 Children with Isolated Spleen or Liver Injury

<table>
<thead>
<tr>
<th>CT grade</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Admitted to ICU</td>
<td>55.0%</td>
<td>54.3%</td>
<td>72.3%</td>
<td>85.4%</td>
</tr>
<tr>
<td># Hosp. (mean)</td>
<td>4.3 days</td>
<td>5.3 days</td>
<td>7.1 days</td>
<td>7.6 days</td>
</tr>
<tr>
<td># Hosp. (range)</td>
<td>1–7 days</td>
<td>2–9 days</td>
<td>3–9 days</td>
<td>4–10 days</td>
</tr>
<tr>
<td>Transfused</td>
<td>1.8%</td>
<td>5.2%</td>
<td>10.1%</td>
<td>26.6%</td>
</tr>
<tr>
<td>Laparotomy</td>
<td>None</td>
<td>1.0%</td>
<td>2.7%</td>
<td>12.6%</td>
</tr>
<tr>
<td>Follow-up imaging</td>
<td>34.4%</td>
<td>46.3%</td>
<td>54.1%</td>
<td>51.8%</td>
</tr>
<tr>
<td>Activity restriction (mean)</td>
<td>5.1 weeks</td>
<td>6.2 weeks</td>
<td>7.5 weeks</td>
<td>9.2 weeks</td>
</tr>
<tr>
<td>Activity restriction (range)</td>
<td>2–6 weeks</td>
<td>2–8 weeks</td>
<td>4–12 weeks</td>
<td>6–12 weeks</td>
</tr>
</tbody>
</table>

*aGrade III vs. Grade IV, p < 0.014.

*bGrade III vs. Grade IV, p < 0.0001.
injuries such as nondisplaced, noncomminuted fractures, or soft tissue injuries were included as long as the associated injuries did not influence the variables in this study. The patients were grouped by the severity of injury as classified by CT grade. Compliance with the proposed guidelines was analyzed for age, organ injured, and CT grade. All patients were followed up for four months after injury. It is imperative to emphasize that these proposed guidelines assume hemodynamic stability. The extremely low rates of transfusion and operation document the stability in the study cohort of patients.

Specific guideline compliance was 81% for ICU stay, 82% for hospital stay, 87% for follow-up imaging, and 78% for interval of activity restriction. There was a significant improvement in compliance from year 1 to year 2 for ICU stay (77% vs. 88%, p < 0.02) and interval of activity restriction (73% vs. 87%, p < 0.01). There were no differences in compliance by age, gender, or organ injured. Deviation from guidelines was the surgeon’s choice in 90% and patient-related in 10%. Six (1.9%) patients were readmitted although none required operation.

Compared with the previously studied 832 patients, the 312 patients who had prospective application of the proposed guidelines had a significant reduction in ICU stay (p < 0.0001), hospital stay (p < 0.0006), follow-up imaging (p < 0.0001), and interval of physical activity restriction (p < 0.04) within each grade of injury (Table 6).

From these data, we concluded that the prospective application of specific treatment guidelines based on injury severity has resulted in a conformity in patient management, improved utilization of resources, and validation of guideline safety. Significant reduction in the duration of ICU stay, hospital stay, follow-up imaging,

### Table 4 Proposed Guidelines for Resource Utilization in Children with Isolated Spleen or Liver Injury

<table>
<thead>
<tr>
<th>CT grade</th>
<th>ICU days</th>
<th>Hospital stay</th>
<th>Pre-discharge imaging</th>
<th>Post-discharge imaging</th>
<th>Activity restrictiona</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>2 days</td>
<td>None</td>
<td>None</td>
<td>3 weeks</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>3 days</td>
<td>None</td>
<td>None</td>
<td>4 weeks</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>4 days</td>
<td>None</td>
<td>None</td>
<td>5 weeks</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>5 days</td>
<td>None</td>
<td>None</td>
<td>6 weeks</td>
</tr>
</tbody>
</table>

*aReturn to full-contact, competitive sports (i.e., football, wrestling, hockey, lacrosse, mountain climbing, etc.) should be at the discretion of the individual pediatric trauma surgeon. The proposed guidelines for return to unrestricted activity include “normal” age-appropriate activities.

### Table 5 Clinical Parameters in 316 Children with Isolated Spleen or Liver Injury

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Age</td>
<td></td>
</tr>
<tr>
<td>1–9 yr</td>
<td>51.1%</td>
</tr>
<tr>
<td>10–17 yr</td>
<td>48.9%</td>
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<tr>
<td>Gender</td>
<td>72.5% male</td>
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<tr>
<td>CT grade</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>13.1%</td>
</tr>
<tr>
<td>II</td>
<td>29.2%</td>
</tr>
<tr>
<td>III</td>
<td>38.1%</td>
</tr>
<tr>
<td>IV</td>
<td>19.6%</td>
</tr>
<tr>
<td>Operation</td>
<td>4/316 (1.3%)</td>
</tr>
<tr>
<td>Transfusion</td>
<td>16/316 (5.1%)</td>
</tr>
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</table>
and length of activity restriction has been achieved without adverse sequelae when compared to our retrospective database.

The APSA Office of Outcomes and Clinical Trials was established to expand on the efforts of the Trauma Committee with funding from the Department of Health and Human Services’ Maternal and Child Health Bureau. The impact of developing clinical guidelines on the quality of care and costs can be significant. Consensus guidelines will have direct economic relevance while enhancing both clinician and patient satisfaction. The evidence-based study design described above can bring order and conformity to patient management, resulting in optimal utilization of resources while maximizing patient safety. The rapidly changing health care environment has put new pressures of accountability on physicians. There is a great need and opportunity to apply evidence-based methodology in pediatric trauma care and pediatric surgery in general to enhance the care for our patients (33). Outcomes of research and evidence-based studies will allow pediatric surgeons to proactively define optimal care rather than to be reactively responding after the fact to the concerns of others with less expertise and differing motivations.

### Complications of Nonoperative Treatment

Nonoperative treatment protocols have been the standard for most children with blunt liver and spleen injury during the past two decades. This cumulative experience

<table>
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<tr>
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<tbody>
<tr>
<td></td>
<td>Mean ICU stay (days)</td>
<td>Mean hospital stay (days)</td>
<td>Mean activity restriction (weeks)</td>
</tr>
<tr>
<td>CT grade I</td>
<td>0.92</td>
<td>0.12</td>
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<tr>
<td>CT grade II</td>
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</tr>
<tr>
<td>CT grade III</td>
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</tr>
<tr>
<td>CT grade IV</td>
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<td>&lt;0.0001</td>
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<td>Mean ICU stay (days)</td>
<td>Mean hospital stay (days)</td>
<td>Mean activity restriction (weeks)</td>
</tr>
<tr>
<td>CT grade I</td>
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<td>2.15</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CT grade II</td>
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<td>2.73</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CT grade III</td>
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<td>&lt;0.0006</td>
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<td></td>
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<td>Mean hospital stay (days)</td>
<td>Mean activity restriction (weeks)</td>
</tr>
<tr>
<td>CT grade I</td>
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<td>3.77</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>CT grade II</td>
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<td>4.27</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CT grade III</td>
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<td>&lt;0.0001</td>
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<tr>
<td>CT grade IV</td>
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<td>6.98</td>
<td>&lt;0.004</td>
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<td>Mean hospital stay (days)</td>
<td>Mean activity restriction (weeks)</td>
</tr>
<tr>
<td>CT grade I</td>
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<td>7.3</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>CT grade II</td>
<td>46.3</td>
<td>8.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>CT grade III</td>
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<td>&lt;0.001</td>
</tr>
<tr>
<td>CT grade IV</td>
<td>51.8</td>
<td>23.3</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

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allows us to evaluate both the benefits and risks of the nonoperative approach. Fundamental to the success of the nonoperative strategies is the early cessation of hemorrhage. Transfusion rates for children with isolated spleen or liver injury have fallen below 10%, confirming the lack of continued blood loss in the majority of this cohort (7,8,17,34). Despite the favorable observations, isolated reports of significant delayed hemorrhage with adverse outcomes continue to be reported. Shilyansky et al. reported about two children with delayed hemorrhage 10 days after a blunt liver injury (35). Both children had persistent right upper quadrant (RUQ) and right shoulder pain despite normal vital signs and stable hematocrit (Fig. 2). The authors recommended continued in-house observation until symptoms resolved. Brown et al. described a patient with significant bleeding 38 days after sustaining a grade II spleen injury (36). These rare occurrences create anxiety in identifying the minimum safe interval prior to resuming unrestricted activities.

Splenic and hepatic pseudoaneurysms following trauma can be identified by imaging studies (37,118,119). Splenic pseudoaneurysms may be asymptomatic and may resolve with time spontaneously (38,118,119). The true incidence of self-limited, post-traumatic splenic pseudoaneurysms is unknown as routine follow-up imaging after successful nonoperative treatment has been largely abandoned. Other rare complications such as splenic pseudocyst, bile duct leaks, and hemobilia are amenable to percutaneous and endoscopic treatment plans in conjunction with interventional radiologists and endoscopists (Fig. 3) (38,39,118,119).

### Immediate Surgery for Blunt Abdominal Injuries: Damage Control Strategies

Surgeons treating children with abdominal injuries have refined nonoperative management over the past three decades. Review of the NPTR Registry from 1995
through 1999 shows that only 11% of 1177 children with spleen injury and only 6% of 1179 children with liver injury required operations (2). In a recent report from the APSA Trauma Committee only 28 (2.5%) of 1144 children with isolated spleen or liver injury had operations (9,18). These data indicate that few surgeons will have extensive experience with massive abdominal solid organ injury requiring immediate surgery. It is imperative that surgeons familiarize themselves with current treatment algorithms for life-threatening abdominal trauma.

The indications for immediate surgery following abdominal trauma in children include hemodynamic instability, evidence of persistent hemorrhage (Fig. 4), suspicion of hollow viscus perforation, and major pancreatic ductal disruption. Most liver injuries requiring operation are amenable to simple methods of hemostasis using some combination of manual compression, suture, and topical hemostatic agents. The early morbidity and mortality of severe hepatic injuries are related to the effects of massive blood loss and the replacement of large volumes of cold blood products. The consequences of prolonged operations with massive blood product replacement include hypothermia, coagulopathy, and acidosis. Although the surgical team may keep pace with blood loss, life-threatening physiologic and metabolic consequences are inevitable, and many of these critically ill patients are unlikely to survive once

![Figure 3](image3.png)

**Figure 3** Hepatic arterial pseudoaneurysm in a 7-year-old girl who sustained grade III injury to the liver following a motor vehicle accident. (A) Initial CT scan demonstrates extensive intraparenchymal hematoma adjacent to and surrounding the right hepatic vein. Retroperitoneal injury and hematoma were also present. (B) CT scan obtained two weeks later for persistent hemobilia demonstrates a low-intensity region in keeping with biloma formation with a rounded, high-density area present medially in keeping with hepatic arterial pseudoaneurysm (arrow). (C) Angiographic confirmation of hepatic arterial pseudoaneurysm. (D) Satisfactory treatment of pseudoaneurysm following angiographic embolization with coil placement.
their physiologic reserves have been exceeded. A multi-institutional review identified exsanguination as the cause of death in 82% of 537 intraoperative deaths at eight academic trauma centers (41). The mean pH was 7.18 and mean core temperature was 32°C prior to death.

Lethal abdominal hemorrhage in infants and children can result from a variety of causes. Moulton reported survival in only 5 of 12 (40%) consecutive operative cases of retrohepatic vascular or severe parenchymal liver injury in children (41). VanderKolk reported severe liver hemorrhage in 8 of 68 (12%) infants during laparotomy for necrotizing enterocolitis (NEC), with one of these eight infants surviving (43).

A recent report of 328 children with liver injury revealed that hemodynamic instability, as defined by the need for blood transfusion in excess of 25 mL/kg within the first two hours of presentation, was a strong indicator of the need for surgical intervention and hepatic vascular injury (prediction accuracy of 88% and 95%, respectively) (43). Pryor et al. (45) reported about 30 children with AAST grade V liver injuries and found that the survivors had lower ISS and higher Glasgow Coma Scale (GCS) score. Ten of 11 (91%) treated nonoperatively survived compared to 6 of 14 (43%) who underwent immediate surgery. These authors recommend aggressive resuscitation of major liver injury in children allowing 40 mL/kg packed red blood cells (PRBC) with the hope of avoiding the often lethal massive blood loss at surgery. Thresholds and indications for operation in these patients are not clear and should be guided by physiologic and metabolic criteria.

Maintenance of physiologic stability during the struggle for surgical control of severe bleeding is a formidable challenge even for the most experienced surgeon, particularly when hypothermia, coagulopathy, and acidosis occur. This triad creates a vicious cycle whereby each derangement augments and excacerbates the others and

Figure 4  Hepatic and inferior vena caval injury in a 14-year-old boy who fell from a height of 12 feet suffering hepatic and inferior vena caval injury. This child required immediate surgery following CT for hemodynamic instability. Note the active extravasation adjacent to the intrahepatic portion of the inferior vena cava (arrows).
the physiologic and metabolic consequences of the triad often preclude completion of the procedure. Lethal coagulopathy from dilution, hypothermia, and acidosis can rapidly occur. Thromboelastography is a simple and rapid test that can determine coagulation abnormalities. Watts et al. (46) used thromboelastography to determine platelet function, enzyme activity, and fibrinolysis in 72 hypothermic trauma patients. The decrease in platelet function and the slowing down of enzyme activity contributed to hypothermic coagulopathy with core temperatures below 34°C. Fibrinolysis was not affected.

Increased emphasis on physiologic and metabolic stability in emergency abdominal operations has led to the development of staged, multidisciplinary treatment plans, including abbreviated laparotomy, perihepatic packing, temporary abdominal closure, angiographic embolization, and endoscopic biliary stenting (46,47). Asensio et al. (49) reported about 22 patients with grade IV or V injuries treated between 1992 and 1997. Mean blood loss was estimated at 4.6 liters and mean packed red cell transfusion requirement was 15 units. Ten patients were packed at the first operation. Fifteen patients had postoperative angiographic embolization in an attempt to control hemorrhage. Survival was 92% in 13 grade IV patients and 78% in 9 grade V patients.

Abbreviated laparotomy with packing for hemostasis, allowing resuscitation prior to planned reoperation, is an alternative in unstable patients where further blood loss would be untenable. This “damage control” philosophy is a systematic, phased approach to the management of the exsanguinating trauma patient (49,50). The three phases of damage control are detailed in Table 7. Although controversial, a variety of resuscitative end points have been proposed that go beyond conventional “vital signs” and urine output parameters, including serum lactate, base deficit, mixed venous oxygen saturation, and gastric mucosal pH.

Once patients are rewarmed, coagulation factors replaced, and oxygen delivery optimized they can be returned to the operating room for pack removal and definitive repair of injuries. Review of nearly 700 adult patients with abdominal packing from several institutions demonstrated hemostasis in 80%, survival of 32% to 73%, and abdominal abscess rates of 10% to 40% (51,52). Although abdominal packing (PACKS) with planned reoperation has been utilized with increasing frequency in adults during the past two decades, there is little experience reported in children (46–59). We reported the treatment of a 3-year-old child who required abdominal packing for a severe liver injury, making closure of the abdomen impossible (54). A Silastic® “silo” was constructed to accommodate the bowel until the pack could be removed and the patient made a complete recovery. The combined technique of packs and a silo allowed time for correction of the hypothermia, acidosis, and coagulopathy without compromise of respiratory mechanics. A recent review reported

| Phase 1 | Abbreviated laparotomy for exploration, control of hemorrhage and contamination, packing and temporary abdominal wall closure. |
| Phase 2 | Aggressive ICU resuscitation; core rewarming, optimize volume and oxygen delivery, correction of coagulopathy. |
| Phase 3 | Planned reoperation for packing change, evacuation and definitive repair of injuries, abdominal wall closure. |
22 infants and children with refractory hemorrhage (ages: 6 days to 20 yrs) were treated with PACKS (55). The anatomic site of hemorrhage was the liver and/or hepatic veins in 14 patients, retroperitoneum and/or pelvis in seven patients, and the pancreatic bed in one patient. Fifteen patients (68%) had PACKS inserted during a primary operative procedure. Seven patients (32%) had PACKS inserted during a re-exploration for persistent hemorrhage after the start of the re-exploration. Twenty patients (91%) were coagulopathic (mean prothrombin time > 16 seconds), hypothermic (mean temperature < 35°C), and acidotic (mean pH < 7.2) at the time of packing. The mean volume of intraoperative blood product transfusion prior to PACKS was 190 mL/kg (50–600 mL/kg). Primary fascial closure was accomplished in 12 (55%) patients while temporary skin closure or prosthetic material was used in the other 10. PACKS controlled hemorrhage in 21 of 22 (95%) patients. Removal of PACKS was possible within 72 hours in 18 (82%) patients. No patient re-bled after PACKS removal; however, two patients died with PACKS in place. Seven patients (32%) developed an abdominal or pelvic abscess. All were successfully drained by laparotomy (six patients) or percutaneous (one patient) approach. Six of these seven patients with abdominal sepsis survived. Eighteen patients (82%) survived. Two deaths were due to multi-system organ failure, one succumbed to cardiac failure from complex cardiac anomalies, and one death was from exsanguination after blunt traumatic liver injury. There were no differences in volume of intraoperative blood product transfusion, time to initiate PACKS, physiologic status, or type of abdominal closure between survivors and non-survivors.

While the success of abdominal packing is encouraging, the sequelae of abdominal packing may contribute to significant morbidity such as intraabdominal sepsis, organ failure, and increased intraabdominal pressure. Adams et al. (61) evaluated fluid samples from 28 patients with abdominal packing and found peritoneal endotoxin and mediator accumulation even when cultures were sterile. The authors concluded that laparotomy pad fluid accumulating after damage control laparotomy clearly can contribute to neutrophil dysfunction by enhancing neutrophil respiratory burst, and at the same time inhibit neutrophil responses to specific chemotactic mediators needed to fight an infection. Thus, the known propensity of such patients to both intraabdominal and systemic infection may be related to changes in neutrophil receptor status and effector function related to accumulation of inflammatory mediators in the abdomen. Early washout, repetitive packing, and other efforts to minimize mediator accumulation deserve consideration.

It is essential to emphasize that the success of the abbreviated laparotomy and planned reoperation depends on an early decision to employ this strategy prior to irreversible shock. A staged operative strategy for unstable patients represents advanced surgical care and requires sound surgical judgement and expertise. Abdominal packing, when employed as a desperate, last-ditch resort after prolonged attempts at hemostasis have failed, has been uniformly unsuccessful. Physiologic and anatomic criteria have been identified as indications for abdominal packing. Most of these have focused on intraoperative parameters including pH (~7.2), core temperature (< 35°C), and coagulation values (prothrombin time > 16 seconds) in the patient with diffuse hemorrhage requiring large volumes of blood product transfusion.

The optimal time for reexploration is controversial because neither the physiologic end points of resuscitation nor the increased risk of infection with prolonged packing are well defined. The obvious benefits of hemostasis provided by packing are also balanced against the potential detrimental effects of increased intraabdominal pressure on ventilation, cardiac output, renal function, mesenteric circulation, and...
intracranial pressure. Timely alleviation of the secondary “abdominal compartment syndrome” may be a critical salvage maneuver for patients. Temporary abdominal wall closure at the time of packing can prevent the abdominal compartment syndrome. We recommend temporary abdominal wall expansion in all patients requiring packing until the hemostasis is obtained and visceral edema subsides.

A staged operative strategy for unstable trauma patients represents advanced surgical care and requires sound judgement and technical expertise. Intraabdominal packing for control of exsanguinating hemorrhage is a life-saving maneuver in highly selected patients in whom coagulopathy, hypothermia, and acidosis render further surgical procedures unduly hazardous. Early identification of patients likely to benefit from abbreviated laparotomy techniques is crucial for success.

**Abdominal Compartment Syndrome**

Abdominal compartment syndrome is a term to describe the deleterious effects of increased intraabdominal pressure. The “syndrome” includes respiratory insufficiency from worsening ventilation/perfusion mismatch, hemodynamic compromise from pre-load reduction due to inferior vena cava (IVC) compression, impaired renal function from renal vein compression, as well as decreased cardiac output, intracranial hypertension from increased ventilator pressures, splanchnic hypoperfusion, and abdominal wall overdistention (61). The etiology of intraabdominal hypertension in trauma patients can include hemoperitoneum, retroperitoneal and/or bowel edema, and use of abdominal/pelvic packing. The combination of tissue injury and hemodynamic shock creates a cascade of events including a capillary leak, ischemia-reperfusion, and release of vasoactive mediators and free radicals, all of which combine to increase extracellular volume and tissue edema. Once the combined effects of tissue edema and intraabdominal fluid exceed a certain level, abdominal decompression must be considered.

The adverse effects of abdominal compartment syndrome have been acknowledged for decades; however, abdominal compartment syndrome has only recently been recognized as a life-threatening yet potentially treatable entity. The measurement of intraabdominal pressure is adjunctive information that can be useful in determining the contribution of abdominal compartment syndrome to altered physiologic and metabolic parameters (63,64). Intraabdominal pressure can be determined by measuring bladder pressure. This involves instilling 1 mL/kg of saline into the foley catheter and connecting the catheter to a pressure transducer or manometer via a three-way stopcock. The symphysis pubis is used as the zero reference point and the pressure measured as cmH2O or mmHg. Intraabdominal pressures in the range of 20–35 cmH2O or 15–25 mmHg have been identified as an indication to decompress the abdomen. Many prefer to intervene on alterations in physiologic and metabolic parameters rather than rely on a specific pressure measurement. Chang et al. (63) reported 11 adult trauma patients with abdominal compartment syndrome in whom abdominal decompression improved pre-load, pulmonary function, and visceral perfusion using pulmonary artery catheters and nasogastric tonometry.

Experience with abdominal decompression for abdominal compartment syndrome in children is limited (55,63,64). Neville et al. (65) reported use of patch abdominoplasty in 23 infants and children of which only three were trauma patients. These authors found that patch abdominoplasty for abdominal compartment syndrome effectively decreased airway pressures and oxygen requirements. Failure to respond with a decrease in airway pressures or FiO2 was an ominous sign in their
series. Similarly, DeCou and associates found that abdominal decompression resulted in decreased airway pressures, increased pO2, and increased urine output in three children with abdominal compartment syndrome.

Many materials have been suggested for use in temporary patch abdominoplasty, including Silastic sheeting, Gore-Tex®, intravenous bag, cystoscopy bag, ostomy appliance, and various mesh materials. The vacuum pack technique, recently used in adults, seems promising (50).

Summary

Recent advances in the delivery of trauma and critical care in children have resulted in improved outcome following major injuries. The data addressing specific concerns about the nonoperative treatment of children with solid organ injuries and recent radiologic and endoscopic contributions have made pediatric trauma care increasingly nonoperative. Although the trend is in this direction, the pediatric surgeon should remain the physician-of-record in multidisciplinary care of these critically injured children. The decision not to operate is always a surgical decision.

INJURIES TO THE DUODENUM AND PANCREAS

As differentiated from the solid organs previously described, injuries to the duodenum and pancreas are much less frequent with reported rates between 1% and 4% of intraabdominal injuries in children sustaining blunt trauma. Isolated duodenal and pancreatic injuries occur in approximately two-thirds of cases with combined injury to both organs in the remainder. The severity of the combined injury and other associated injuries determines the necessity for operative versus nonoperative management. The protected location (retroperitoneal) limits the chance of injury but increases the difficulty in early diagnosis. Added to this diagnostic dilemma is the frequency of associated intraabdominal and/or multisystem injuries, which can mask subtle physical and radiographic diagnostic signs found in injury to the duodenum and pancreas.

Duodenum

In a report on blunt duodenal rupture by Ballard and coauthors (66) a six-year statewide (Pennsylvania) experience is reviewed. Of 103,864 patients registered from 28 trauma centers, blunt injury to the duodenum occurred in 206 (0.2%), of whom only 30 (14.56%) had full-thickness rupture. The mechanism of injury was car crash in 70% with both adults and children included in this report. Of those without significant head injury (26 of 30), 92% either gave a history of abdominal pain or had tenderness or rebound found on physical examination. CT scanning was performed in 18 patients with retroperitoneal air or extravasation of contrast seen in only 26% and an equal number interpreted as normal. Mortality was 13% and was not affected by a delay in diagnosis or treatment. This study emphasizes the difficulty in analyzing this injury with individual centers (and surgeons) reporting such low numbers. Additionally, they review the range of repairs performed from duodenal closure to the Whipple procedure but comment that no definitive recommendations can be made due to the small numbers and many centers. In contrast to this report, the
group from Toronto reported a single-center experience in a series of 27 children sustaining blunt duodenal injury (mean age of 7 years) treated over a 10-year period (1989–1996) (66). Thirteen children had duodenal perforations (mean age = 9) and 14 sustained duodenal hematomas (mean age = 5). Associated injuries were seen in 19 [10 pancreas, 5 spleen, 4 hepatic, 2 long bone fracture, 1 central nervous system (CNS), 1 renal contusion, 1 jejunal perforation and 1 gastric rupture]. Seventeen patients were transferred from other facilities with the median time to transfer of four hours. The median interval from injury to surgery in those sustaining perforation was six hours. The clinical presentation, laboratory evaluation, and radiographic findings of those with duodenal hematoma versus perforation are summarized in Table 8. Most patients had abdominal CT scans performed with oral and IV contrast. A comparison of CT findings in these patient groups is depicted in Table 9.

As can be seen from this data the clinical presentation was strikingly similar in both groups with only age and ISS achieving significance statistically (but of little clinical relevance in individual patients). However, in comparing CT findings, extravasation of air or enteral contrast into the retroperitoneal, paraduodenal, or prerenal space was noted in every child with a duodenal perforation (9/9) and in none who had duodenal hematoma (0/10). The authors note that few previous reports in the literature describe these specific CT findings with duodenal injuries in general and no previous series of pediatric patients in particular with this data had previously been reported. The CT scans [or upper gastrointestinal (UGI) contrast studies in equivocal cases] showing duodenal narrowing, corkscrewing, or obstruction without extravasation was diagnostic in all. The CT and UGI findings in duodenal hematoma and duodenal perforation are illustrated in Figures 5 and 6.

The management of duodenal hematoma from this experience and a previous report from the same center in 1986 summarizes a total of 24 patients with this injury, all treated nonoperatively (67,68). In the current series of 14 patients treated nonoperatively, the duration of nasogastric decompression was 12 days (mean) and

<table>
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<tr>
<th>Patient characteristics</th>
<th>Duodenal hematoma</th>
<th>Duodenal perforation</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>5</td>
<td>9&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>ISS</td>
<td>10</td>
<td>25&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Seat belt worn:n (%)</td>
<td>6 (100)</td>
<td>5 (71)</td>
</tr>
<tr>
<td>Presentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pain or tenderness:n (%)</td>
<td>10 (71)</td>
<td>12 (92)</td>
</tr>
<tr>
<td>Bruising:n (%)</td>
<td>6 (43)</td>
<td>11 (85)</td>
</tr>
<tr>
<td>Glasgow Coma Scale score</td>
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<td>15</td>
</tr>
<tr>
<td>Associated injuries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pancreatic injury:n (%)</td>
<td>7 (50)</td>
<td>3 (23)</td>
</tr>
<tr>
<td>Lumbar spine injury:n (%)</td>
<td>1 (7)</td>
<td>4 (31)</td>
</tr>
<tr>
<td>Total:n (%)</td>
<td>11 (79)</td>
<td>8 (62)</td>
</tr>
<tr>
<td>Laboratory evaluation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hgb:(mg%)/Hct</td>
<td>12.3/0.36</td>
<td>12.1/0.37</td>
</tr>
<tr>
<td>Amylase:U (%)</td>
<td>678 (64)</td>
<td>332 (46)</td>
</tr>
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</table>

<sup>a</sup>Statistically significant difference. Source: Adapted from Ref. 67.
length of total parenteral nutrition administration was 18 days (mean). Symptoms resolved in 13 of 14 patients an average of 16 days after injury. The remaining child developed a chronic fibrous structure requiring operative duodenoplasty 49 days post-injury. This child also had a pancreatic contusion.

The patients sustaining duodenal perforation were all treated operatively in a variety of ways depending on the severity of the injury and surgeon’s preference. However, in this report certain operative recommendations were made after reviewing the results and complications. They recommended primary closure of the duodenal perforation (whenever possible) combined with duodenal drainage and either pyloric exclusion with gastrojejunostomy or gastric drainage with feeding jejunostomy. These surgical options decrease the incidence of duodenal fistula, reduce the time to GI tract alimentation, and shorten hospital stay. In my practice I have found the easiest and safest combination when faced with complicated duodenal trauma to be the “three tube technique”: duodenal closure (primary or anastomosis) with duodenal drainage tube for decompression (tube 1), pyloric exclusion with an absorbable suture via gastrostomy, gastric tube placement (tube 2), and feeding jejunostomy (tube 3). Added to this are several drains judiciously placed where leakage might be anticipated. When the duodenum is excluded (via an absorbable suture with temporary closure of the pylorus) when performing the “three tube technique,” complete healing of the injury routinely occurs prior to the spontaneous reopening of the pyloric channel. However, no matter what repair the surgeon selects, a summary of the literature demonstrates that protecting the duodenal closure (drain and exclusion) and a route for enteral feeds (gastrojejunostomy or feeding jejunostomy) reduces morbidity and length of stay (69,70).

It should be noted that rarely should a pancreaticoduodenectomy (Whipple procedure) be required. Although this is occasionally reported in literature, it should be reserved for the most severe injuries to the duodenum and pancreas when the common blood supply is destroyed and any possibility of reconstruction is impossible; excluding penetrating trauma, this will rarely occur.

Table 9  Comparison of CT Findings of Children Who Sustained Duodenal Hematoma and Duodenal Perforation

<table>
<thead>
<tr>
<th>CT findings</th>
<th>Duodenal hematoma</th>
<th>Duodenal perforation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N=10</td>
<td>N=9</td>
</tr>
<tr>
<td>Free air</td>
<td>1 (8)</td>
<td>2 (22)</td>
</tr>
<tr>
<td>Free fluid</td>
<td>8 (80)</td>
<td>9 (100)</td>
</tr>
<tr>
<td>Retroperitoneal fluid</td>
<td>9 (90)</td>
<td>9 (100)</td>
</tr>
<tr>
<td>Bowel wall and peritoneal enhancement</td>
<td>2 (20)</td>
<td>4 (44)</td>
</tr>
<tr>
<td>Duodenal caliber change</td>
<td>4 (40)</td>
<td>3 (33)</td>
</tr>
<tr>
<td>Thickened duodenum</td>
<td>10 (100)</td>
<td>8 (89)</td>
</tr>
<tr>
<td>Mural hematoma</td>
<td>10 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Retroperitoneal air</td>
<td>0</td>
<td>8 (89)</td>
</tr>
<tr>
<td>Retroperitoneal contrastb</td>
<td>0</td>
<td>4 (57)</td>
</tr>
<tr>
<td>Retroperitoneal air or contrast</td>
<td>0</td>
<td>9 (100)</td>
</tr>
</tbody>
</table>

aThe child had an associated jejunal perforation.
bEnteral contrast was not administered in two children.

Source: Adapted from Ref. 67.
Pancreas

Injuries to the pancreas are slightly more frequent than duodenal injuries with estimated ranges from 3% to 12% in children sustaining blunt abdominal trauma (71). As in duodenal injuries, individual centers frequently have small patient numbers and therefore are unable to evaluate their results critically. Recently, two centers (Toronto and San Diego) reported their experience with divergent methods of managing blunt traumatic pancreatic injuries in a series of reports (72–77). We will compare these papers and excerpt another author’s experience to make recommendations in management. Canty and coworkers (San Diego) reported about 18 patients with major pancreatic injuries over a 14-year period (74). The mechanism of injury was either car or bike crashes. Sixteen of the 18 patients had CT scan on admission. Of these, 11 suggested injury and in five the injury was missed. Distal pancreatectomy was performed on eight patients (44%). In five of six patients with either proximal duct injuries or injuries missed on initial CT scan, pseudocysts developed (3). In two other children who had minimal initial symptoms and no CT scan on admission, pseudocysts also occurred. Of these seven pseudocysts, two resolved.

Figure 5 Duodenal hematoma and pancreatic injury in a 15-year-old boy who presented with abdominal pain and vomiting four days following trauma. (A) Axial CT demonstrating large duodenal hematoma involving the second and third portions of the duodenum (arrows). There is fluid extending into the anterior perirenal space but no free air or extraluminal contrast. (B) UGI study at initial presentation confirms obstruction of the second portion of the duodenum without contrast leak. (C) UGI study performed two weeks later demonstrates relief of complete obstruction with residual narrowed lumen of the distal second and third portion of the duodenum in keeping with the known duodenal hematoma.
and five were treated by cystgastrostomy. The remaining two patients, treated more recently, received endoscopic retrograde cholangiopancreatography (ERCP) with duct stenting leading to a resolution of symptoms and complete healing. They concluded that distal injuries should be treated with distal pancreatectomy, proximal injury with observation, and pseudocysts with observation or cystgastrostomy, and acute ERCP management with stent placement was safe and effective. They also concluded that CT scanning is suggestive but not always diagnostic for the type and location of pancreatic injury (72–74).

The experience summarized in the three reports from Toronto is markedly different (75–77). In the first brief report two patients with documented duct disruption (by ERCP or cathetergram) had complete duct healing without operative intervention (75). This was followed by a summary report of 35 consecutive children treated over 10 years (1987–1996) (76). Twenty-three had early diagnosis (< 24 hours) while in 12 diagnosis was delayed (2–14 days). Twenty-eight children were treated non-operatively; the remaining seven had operations for other causes. In the 28 cases not surgically treated, CT scan was diagnostic, revealing five patterns of injury: contusion, stellate fragmentation, partial fracture, complete transection, and pseudocyst (Fig. 7). The patients were placed in three groups clinically. A summary of these

---

**Figure 6** Duodenal perforation and pancreatic transection with pseudocyst formation in a 14-year-old boy struck by a truck in the lower thoracic region. (A) Initial CT demonstrates a subtle transection of the pancreatic head with linear hypodensity present (arrow). Anterior perirenal fluid is present. (B) Lung windowing shows subtle pneumoperitoneum with a bubble of air anterolateral to the liver (arrow). (C) CT scan obtained the next day demonstrates subsequent extensive pseudocyst formation with marked increase in peripancreatic fluid (arrows). Note the better demonstration of the pancreatic transection. (D) Fistulogram performed four months following initial injury demonstrates filling of a small, residual pancreatic pseudocyst and contrast filling of the pancreatic duct.
clinical groups and the proposed CT classifications is shown in Table 10. In these 28 patients, pseudocysts occurred in 10 (2 of 14 in group I; 5 of 11 in group II; and 3, after delayed transfer, had pseudocysts on presentation in group III). No patients in group I required drainage, whereas four in group II, and two in group III were aspirated (n = 1) or drained (n = 5). These drainage procedures occurred 10–14 days post-injury. Average time for initiation of oral feeds was 15 days (11 days for group I, 15 days for group II, and 23 days for group III). Mean hospital stay for all patients treated nonoperatively was 21 days. A summary comparing the San Diego to the Toronto protocols is depicted in Table 11. The striking differences in these series are: the 100% diagnostic sensitivity of CT scanning in Toronto versus 69% in San Diego and the 44% operative rate in San Diego versus 0% in Toronto. A subsequent study from Toronto reviewed follow-up on 10 of the duct transections from the earlier report; complete follow-up was available in nine (76,77). In these children four (44%) developed pseudocysts with three percutaneously drained. Mean hospital stay was 24 days. All patients recovered. Follow-up CT scan in eight of nine patients revealed atrophy of the distal pancreas in six and completely normal glands in

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**Table 10** Proposed Classification of CT Findings with Pancreatic Injuries

<table>
<thead>
<tr>
<th>Group (clinical)</th>
<th>Type (CT)</th>
<th>Pancreatic injury</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>Contusion</td>
<td>Diffuse or focal swelling of the pancreas</td>
</tr>
<tr>
<td>II</td>
<td>2</td>
<td>Stellate fragmentation</td>
<td>Fluid or blood dissecting within pancreatic parenchyma</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Partial fracture</td>
<td>Incomplete separation of two portions of the pancreas</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Complete transection</td>
<td>Complete separation of two portions of the pancreas</td>
</tr>
<tr>
<td>III</td>
<td>5</td>
<td>Pseudocyst</td>
<td>Persistent peripancreatic fluid collection</td>
</tr>
</tbody>
</table>

*Source: Adapted from Ref. 76.*
two (Fig. 8). There was no exocrine or endocrine dysfunction in a mean of 47 months of follow-up. The authors concluded that following nonoperative management of pancreatic blunt trauma, atrophy (distal) or recanalization occurred in all cases with no long-term morbidity.

Other reports from Dallas and Seattle (79) favor early distal pancreatectomy for transection to the left of the spine to shorten the duration of hospital stay (78,79). However, long-term sequelae of adhesive intestinal obstruction and endocrine and exocrine dysfunction are not assessed. An important part of the Toronto series is the CT classification previously discussed (Table 10) and graphically presented in Figure 7, and the detailed evaluation of the extensive CT findings suggestive of pancreatic injury. This data is displayed in Table 12. Other reports document the efficacy of early ERCP intervention for diagnosis and treatment with ductal stenting, the use
of somatostatin to decrease pancreatic secretions and promote healing, and magnetic resonance cholangiopancreatography (MRCP) as a diagnostic tool (80–84). However, further study of these modalities is clearly indicated.

It should be noted that a large single-center experience from Chiba, Japan, reported nonoperative management in 19 of 20 children with documented pancreatic injury (nine contusions, six lacerations, and five main duct disruptions) (85). In all cases recovery was complete without surgery. Their experience with pseudocyst formation and treatment and overall outcome virtually mirrors the Toronto report.

In summary, the surgical dictum “don’t mess with the pancreas” is probably wise. We favor:

1. early spiral CT with oral and IV contrast in all patients who, by history, physical, or mechanism of injury, may have blunt trauma to the pancreas;

<table>
<thead>
<tr>
<th>Table 12</th>
<th>Summary of Associated CT Findings in Children with Pancreatic Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Associated CT findings</td>
<td>Children</td>
</tr>
<tr>
<td>Intraperitoneal fluid</td>
<td>21</td>
</tr>
<tr>
<td>Lesser sac fluid</td>
<td>20</td>
</tr>
<tr>
<td>Focal peripancreatic fluid</td>
<td>20</td>
</tr>
<tr>
<td>Retroperitoneal fluid</td>
<td>20</td>
</tr>
<tr>
<td>Right anterior pararenal fluid</td>
<td>16</td>
</tr>
<tr>
<td>Left anterior pararenal fluid</td>
<td>15</td>
</tr>
<tr>
<td>Thickened gerota’s fascia (R and L)</td>
<td>16</td>
</tr>
<tr>
<td>Mesenteric fluid or hematoma</td>
<td>13</td>
</tr>
<tr>
<td>Left posterior pararenal fluid</td>
<td>9</td>
</tr>
<tr>
<td>Fluid separating SV and pancreas</td>
<td>7</td>
</tr>
<tr>
<td>Fluid surrounding SMV and PV</td>
<td>7</td>
</tr>
<tr>
<td>Fluid separating pancreas and duodenum</td>
<td>6</td>
</tr>
</tbody>
</table>

*Abbreviations:* SV, splenic vein; SMV, superior mesenteric vein; PV, portal vein. *Source:* Adapted from Ref. 67.
2. documentation of injuries and early ERCP to provide duct stenting in selected cases;
3. nonoperative management with NPO and total parenteral nutrition (TPN);
4. expectant management of pseudocyst formation;
5. percutaneous drainage for symptomatic, infected, or enlarging pseudocysts.

INJURIES TO THE STOMACH, SMALL INTESTINE, AND COLON

Injury to these organs is easier to diagnose and manage than those previously discussed (duodenum and pancreas). In blunt trauma there are three different mechanisms that cause distinct patterns of injury to these organs. First is a crush injury. This occurs as the stomach, jejunum, ileum, or transverse colon is compressed violently against the spine. Hematomas, lacerations, or partial or complete transections can occur with instantaneous or delayed perforation and/or obstruction. Second, burst injury occurs when rapid compressive forces are applied to a filled and distended hollow viscus without direct mechanical compression. Shoulder and seat belt injuries to the GI tract can occur in this fashion. Last is sheer injury, caused by rapid acceleration/deceleration of an organ that is tethered at one end, e.g., ligament of Treitz, ileocecal region, rectosigmoid junction, etc. As the deceleration occurs the injury is caused by tearing of tissue at the point of fixation. Regardless of the mechanism of injury, a perforated viscus causes rapid contamination of the abdominal cavity. On initial trauma assessment virtually all neurologically intact patients have some degree of symptoms (pain) and physical findings (tenderness, guarding, rebound, etc.). In fact, many reports have documented that the initial and serial physical examinations have a higher degree of diagnostic specificity than ultrasound (US) or CT for these injuries (86–88). In a series from New Mexico reporting 48 patients with small bowel injury, all conscious patients had abnormal physical findings either on presentation or after serial physical examinations (86). Other diagnostic tests were of less value comparatively [US, CT, diagnostic peritoneal lavage (DPL), lab tests]. Their findings were confirmed by a similar series from North Carolina where, of 32 children with intestinal injury confirmed at laparotomy, 94% had physical findings suggestive of intestinal injury on admission with 84% having diffuse abdominal tenderness (peritoneal signs) (87). The lack of subtlety in diagnosing these injuries is due to the often massive air and GI tract contents expelled into the abdominal cavity at the time of the initial injury. However, when partial thickness lacerations, hematomas or avulsed blood vessels are the initial injury, progression to full thickness defects with perforation can take hours to several days. Therefore, frequent physical exams and vigilance is required (88). A subset of these injuries is caused by children with shoulder and lap belt restraints while passengers in high-speed automobile crashes. These children present with visible “seat belt signs” on physical exam of the abdomen and chest. Multiple studies have documented increased abdominal injuries to both solid and hollow organs with this finding (89–91). An interesting triad of injuries has been noted with duodenal/pancreatic contusions, “Chance” fractures of the lumbar spine, and isolated jejunal/ileal perforations. One report reviewed 95 patients, all of whom had been wearing seat belts, who were admitted with abdominal trauma (90). In 60 of 95 there was a “seat belt sign.” The proportion of patients with intestinal injuries with and without the seat belt sign were 9/60 and 0/35, respectively. When evaluating patients with the lap belt
sign, increased vigilance, hospital admission, physical examination, and supplementary diagnostic imaging (to include abdominal CT scans and lumbar X rays) and laboratory testing is mandated (Fig. 9).

Imaging of the GI tract has evolved over the past decade, with spiral CT and/or a FAST exam done by surgeons in the emergency room (ER), directly impacting our diagnostic accuracy and decision making. Some of the strengths and weaknesses of CT diagnosis have been discussed. However, our ability to diagnose and treat blunt abdominal trauma in children has been clearly enhanced by this modality (Fig. 10). Two studies from Toronto discussed these issues. The first, in 1992, reviewed 12 patients with blunt abdominal trauma evaluated by CT (92). They found bowel wall enhancement (BWE) as a sign of either global GI tract ischemia associated with fatal CNS injury (Fig. 11), or when seen with bowel wall thickening and free peritoneal fluid as a sign of bowel-perforation (Fig. 12). A follow-up study in 1996 reviewed 43 patients evaluated over 10 years with surgically confirmed GI tract perforation (93). Extraluminal air was seen in 47% with one false positive. Five CT scan findings were found to be suggestive but not diagnostic of GI tract perforations. These were: extraluminal air, free intraperitoneal fluid, bowel wall thickening,
BWE, and bowel dilatation. In every patient who had all five of these findings, bowel perforation was confirmed. This occurred in only 18% of the study population. However, all patients had at least one or more of these five specific CT findings. There were no false-negative studies. As mentioned previously, although CT scanning

![Figure 10](image1.png)

**Figure 10** Jejunal perforation CT of the abdomen of a 7-year-old boy involved in a motor vehicle accident with a moderate amount of free intraperitoneal fluid. There was no evidence of solid organ injury. A small intraperitoneal air bubble is present in Morrison’s pouch (*arrow*). At surgery, jejunal perforation was disclosed.

![Figure 11](image2.png)

**Figure 11** Hypoperfusion complex CT of a 3-year-old girl who was involved in a high-speed motor vehicle accident. Diffuse intestinal dilatation, abnormal increased enhancement of bowel wall, and small aortic and inferior vena cava caliber are all consistent with hypoperfusion perfusion complex. Resuscitation efforts failed and the patient subsequently died.
is a reliable modality for assessing GI tract perforations, it does not replace or improve on diligent and repeated clinical evaluations. A similar study from Calgary reviewed 145 children with blunt abdominal trauma (94). CT scans were interpreted as positive for GI tract injury in 20 and negative in 152 (several children had more than one study). The sensitivity of abdominal CT scan was determined to be 0.93 for mesenteric or intestinal injuries requiring surgery with a negative predictive value of 0.99 in this study population. Therefore, CT was evaluated as rarely missing significant mesenteric or intestinal injuries.

The significance of isolated free intraperitoneal fluid in the absence of solid organ injury has frequently been heralded as a sign of intestinal trauma. In work done in Oregon they reported a series of 259 CT scans (all with oral and IV contrast) and found only 24 patients (9%) with isolated free intraperitoneal fluid (95). In 16 of these patients with a “small amount” of isolated fluid, only two required laparotomy. However, in four of eight patients (50%) with fluid found in more than one location, there was bowel injury requiring exploration. They also noted that enteral contrast is rarely present to aid in the diagnosis of bowel injury. Similar findings were also reported from University of California Davis with small quantities of intraperitoneal fluid having little clinical significance (96). In this report only 8% of abdominal CT scans were positive for isolated intraperitoneal fluid, and in only 17% of these was there an identifiable injury. This represented only seven patients out of the 542 children studied. Finally, in a report from Tampa, Florida, FAST was found to be useful as a screening tool with high specificity (95%), but, unfortunately, low sensitivity (33%) in evaluating intestinal injury (97). In this study, of 89 FAST-negative children only 20 went on to have CT scans performed, all at the surgeons’ request. Perhaps, without this finding, all would have had abdominal CT scans. Clearly, as a screening tool, FAST can perhaps decrease the number of CT scans performed, but it will not allow for the diagnosis of specific abdominal organs injured. FAST, therefore, will be of limited value in assessing these injuries. Finally, to come full circle, in a large study from Pittsburgh 350 children with abdominal trauma were reviewed, with 30 requiring laparotomy (8.5%) (98). There were five false-negative CT scans (26%) in 19 patients who underwent delayed laparotomy (3.5 hours or

Figure 12  Jejunal perforation A child following a motor vehicle accident with jejunal perforation demonstrating markedly thickened, enhancing bowel loops.
more post-injury). They concluded that serial physical examination and not CT scanning was the “gold standard” for diagnosing GI tract perforations in children. We concur!

Injuries to the stomach and small intestine are straightforward to repair. A full stomach usually ruptures at the greater curvature with a blowout or stellate configuration. Debridement with direct repair is virtually always sufficient. Small intestinal injuries run the gamut from simple lacerations to transections to complete avulsion with larger segments of compromised bowel. However, unless the contamination is massive (and/or other injuries require extensive repair), debridement and/or resection with anastomosis is all that is usually required. In large bowel injuries, particularly if there is a delay in diagnosis and significant fecal contamination, colostomy with defunctionalized distal mucous fistula or Hartman’s pouch is performed. If isolated large intestinal injuries occur and are repaired early, on-table bowel irrigation, bowel anastomosis, and perioperative antibiotic coverage is safe, effective, and avoids the complications caused by stomas and reoperation. The critical issue with injuries to the intraperitoneal GI tract organs is early recognition of the injury, prompt resuscitation, expeditious surgery with complete removal of contamination and devitalized tissue, reconstruction or diversion of the GI tract as clinically indicated, and broad spectrum antibiotics with the duration of therapy dependant on the degree of contamination and postoperative clinical course (e.g., normalization of white blood cell count, absence of fever, and return of GI tract function).

Diaphragmatic Injury. Traumatic injury to the diaphragm is infrequently observed even at the largest pediatric trauma centers. At Children’s Hospital of Illinois, from 1998 to 2002, with over 800 admissions requiring Level I pediatric trauma evaluation, only two traumatic diaphragmatic injuries have been treated. At the Hospital for Sick Children, Toronto, from 1977 to 1998, only 15 children with this injury were seen (99). The injury is caused by massive compressive forces to the abdominal cavity, creating acceleration of abdominal content cephalad rupturing the diaphragmatic muscle. Occasionally, penetrating trauma will cause this injury; however, in these cases the injury is often found incidentally at exploration for other injuries. In the series reported from Toronto, 13 of 15 patients had diaphragmatic rupture from blunt trauma; the mean age was 7.5 years with the right and left diaphragm equally involved. The diagnosis was made frequently with only a chest X ray (53%), with other studies infrequently required. CT or mechanical resonance (MR) imaging may be helpful (Fig. 13). Three injuries were missed at the initial evaluation. Due to the force required to cause this injury, multiple associated injuries were observed (and should be expected). In this report 81% of patients had multiple injuries. These included: liver lacerations (47%), pelvic fractures (47%), major vascular injury (40%), bowel perforations (33%), long bone fractures (20%), renal lacerations (20%), splenic lacerations (13%), and closed head injuries (13%). As would be expected there were many complications, five deaths, and a mean length of stay of 20 days. Emergent surgery with minimal diagnostic testing often occurs in patients with the mechanism of injury causing this degree of violence to the abdominal cavity. Therefore, when operating on children with this constellation of associated injuries, observation and palpation of both diaphragms must be a routine part of the abdominal exploration. Direct suture repair is usually possible after debridement of any devitalized tissue. In my practice I have always used felt plgeted sutures to buttress the repair, prevent tearing of the muscle, and make the closure more secure. If sufficient diaphragm tissue is destroyed, a tension-free closure with a 2 mm Gore-Tex patch can be utilized in the manner of repairing congenital diaphragmatic hernias.
in newborns. In reports with either laparoscopic or thoracoscopic repair of this injury, they were either delayed repairs (by 10 years) or very stable patients without associated injuries (101,102). Delayed diagnosis of this injury in infants has been reported, as has renal avulsion into the chest through a traumatically ruptured diaphragm (103–105). Due to the infrequent presentation of this injury, a high index of suspicion must occur when the mechanism of injury and degree and location of other injured body systems would support the possibility of this injury occurring.

INJURIES TO THE PERINEUM, ANUS, AND GENITALIA

Children present with injuries to the perineum, anus, and external genitalia from two mechanisms: accidental falls and sexual abuse. The accidental injuries are sustained by falling onto blunt or sharp objects in a straddled fashion. These injuries are characterized by bruising, contusion, laceration, or penetration, depending on the object struck and the height of the fall (force). Accidental injuries frequently involve the external genitalia, urethra, perineal body, and anus, but rarely involve the rectum (Fig. 14). Conversely, injuries sustained by pediatric sexual abuse are universally rectal or vaginal penetrations from violent, nonconsensual sexual acts or the purposeful insertion of objects into these orifices causing injury. Therefore, when examining a child with injuries to the perineum, isolated rectal or vaginal trauma should always be considered child abuse until proven different, whereas poly-trauma to the perineum with genital, perineal, and anal involvement is almost universally accidental (Fig. 15) (106,107).

The diagnosis of the extent of the injury in this setting frequently requires an exam under anesthesia to include: proctoscopy, sigmoidoscopy, and retrograde urethrogram. After assessing the degree of injury, repair entails, at a minimum, anatomical reconstruction of the perineum, anus, and external genitalia. Then, depending on the extent of the injury, repair of urethral injuries (directly or via stenting), urinary diversion with a suprapubic cystostomy, repair of rectal tears, rectal irrigation, placement of drains when required, and, in the more complex injuries, fecal diversion by colostomy and laparotomy. After recovery, detailed radiological confirmation of
complete healing [e.g., intravenous pyelogram (IVP), cystogram, urethrogram, contrast enemas, etc] must be performed prior to reconstruction of fecal continuity or removal of urinary stents and/or urinary undiversion.

Although rare, pediatric fatalities have been reported with anal intercourse; or by “fisting,” “handballing,” or rectal impalement (108). Neonatal rectovaginal injuries have also been reported as an infrequent but life-threatening complication of traumatic delivery (109). However, more commonly, rectal insertion of thermometers, Hagar dilators, or enema tubes can cause significant rectal injuries in the newborn requiring surgical repair. We recently treated a 3-day-old infant with perforation of the rectosigmoid junction from frequent enemas required for treatment of obstipation from cystic fibrosis; laparotomy and colostomy were required. Therefore, in newborns, apparently innocuous rectal manipulation can cause severe injuries requiring surgical evaluation and intervention.

DIAGNOSTIC PERITONEAL LAVAGE AND LAPAROSCOPY

DPL has been a mainstay in trauma evaluation for over two decades. However, in pediatric trauma its utility has been very limited. Since greater than 90% of solid organ injuries do not require surgical intervention, the presence of significant amounts of blood assessed by DPL loses its clinical relevance. As mentioned previously, solid organ injury instability and the requirement for ongoing blood replacement is the determination for operation, not the presence of blood in the abdominal cavity. Additionally, the speed and accuracy of CT scanning for the traumatized patient has further decreased the need for DPL in pediatric trauma. We have previously reviewed in detail the sensitivity of CT in diagnosing not only solid organ injuries but more subtle injuries to the duodenum, pancreas, and small and large bowel. This has relegated DPL utilization to evaluating the stable patient with equivocal physical exam findings and no definitive diagnosis on CT scan of the abdomen. In this setting the presence of bile, food particles, or other evidence of GI tract
perforation is diagnostic (but not therapeutic). Recent literature has further suggested that in this setting laparoscopy can both diagnose and in some cases allow for definitive surgical management without laparotomy. In a study from Dundee, Scotland, comparing DPL to minimal laparoscopy, both tests were highly sensitive (100%) but minimal laparoscopy had a higher specificity (94% vs. 83%) compared to DPL (110).

Large prospective trials in adults have demonstrated an increased diagnostic accuracy, decreased non-therapeutic laparotomy rates, and significant decrease in length of stay with attendant reduction in costs. For example, in a report from the University of Tennessee, 55% of patients with abdominal trauma avoided laparotomy after laparoscopic evaluation (111). Similar work from Jacobi Medical Center in New York City revealed a direct relationship with a decrease in negative laparotomies from an increase in the utilization of laparoscopy for diagnosis and management (112). Multiple studies from centers around the world have shown (principally in adults) the utility of laparoscopy not only in trauma evaluation but in definitive management of related injuries. Repairs of intestinal perforations,

Figure 15  Pelvic disruption and urethral injury in a 15-year-old boy crushed by a falling concrete wall. (A) Pelvic radiograph demonstrating disruption of the symphysis pubis, pelvic fractures of the superior and inferior left pubic rami, and marked diastasis of the right sacroiliac joint. A suprapubic catheter has been placed. (B) Axial CT scan through the pelvis shows the suprapubic catheter entering into the bladder and extravasation of contrast material along the right side of the pelvis and crossing to the left posteriorly behind the rectum. (C) Coronal CT reformation showing extensive extravasation of contrast material with preservation of the bladder outline. Some contrast is present within the proximal urethra. (D) A retrograde urethrogram demonstrates venous filling with complete obstruction at the level of the proximal portion of the penile urethra.
bladder ruptures, liver lacerations, diaphragmatic injuries, gastrostomy repair, splenic injuries, etc., have all been reported (113–115). The extent of operations feasible is directly related to the skill of the surgeon at advanced laparoscopic technique and the overall stability of the patient. As with elective abdominal surgery, the role of laparoscopic surgery in trauma will increase substantially as training programs and trauma centers redirect their training of residents to this modality and more pediatric centers report outcome studies for laparoscopic trauma management in children (116–118).

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INTRODUCTION

Trauma is the leading cause of death between the ages of 1 and 44 years, and accounts for almost 50% of deaths in children aged 1 to 14 in the United States (1). Injury to the urinary tract occurs in 3–10% of patients suffering from blunt or penetrating trauma and is second only to the central nervous system in frequency of childhood injury (2,3). However, death due to genitourinary trauma is uncommon. Although the pediatric urologist is rarely involved in the initial resuscitation of the trauma patient, the trauma surgeon relies heavily upon him to deal with complex injuries to the urological system. The team approach to management provides the highest level of expertise in reducing morbidity and preventing mortality.

The majority of clinical practice in pediatric urologic trauma is derived from adult standards. However, the anatomy and physiology of the pediatric patient differ in numerous ways. Management of the pediatric patient should be tailored to reflect these differences. There are several aspects in the evaluation of trauma patients that are unique to the pediatric population, and caution must be exercised in the application of adult treatment algorithms. Despite these distinct differences, there is a paucity of literature available that outlines clinical guidelines for children. In this review, we attempt to highlight the pertinent issues in genitourinary trauma in children that allow for a more focused diagnostic approach and appropriate management plan.

RENAL TRAUMA

The kidney is the most commonly injured organ in the urogenital system as well as the most commonly injured abdominal organ (4,5). Children appear to be more susceptible to major renal trauma than adults (6). Several unique anatomic aspects contribute to this observation including: less cushioning from perirenal fat, weaker abdominal musculature, and a less well-ossified thoracic cage. The child’s kidney
also occupies a proportionally larger space in the retroperitoneum than does an adult kidney (7). In addition, the pediatric kidney may retain fetal lobulations, permitting easier parenchymal disruption (6).

Renal trauma is broadly classified as being blunt or penetrating. Blunt trauma is more common, accounting for greater than 90% of injuries in some series (8). In the pediatric population 14% of blunt abdominal trauma patients have a renal injury (9). Blunt renal injuries are most commonly associated with rapid deceleration forces, automobile accidents, pedestrian–vehicle accidents, falls, contact sports, and personal violence. The kidney, which is relatively mobile within Gerota’s fascia, can be crushed against the ribs or vertebral column, resulting in parenchymal lacerations or contusions. Kidney tissue may also be lacerated directly by fractured ribs.

Penetrating trauma accounts for 10–20% of renal injuries, yet is responsible for the majority of major renal injuries that require surgery (10). Penetrating trauma from stabwounds or gunshot wounds are much less common in children than adults (11). Reviews of firearm injuries show a significant rise in fatalities by firearms in children: homicides rose by 21% and suicides by 30% among those under 16 years between 1968 and 1991 (12). Gunshot wounds produce a radiating wave of injury and cavitation known as “blast effect,” which damages tissues beyond the tract of the projectile. Blast effect may cause delayed tissue necrosis leading to bleeding, urine leak, or abscess from areas that appear viable at the time of surgical exploration. Penetrating injuries to the chest, abdomen, flank, and lumbar regions should be assumed to have inflicted renal injury until proven otherwise (13).

Pre-existing or congenital renal abnormalities, such as hydronephrosis, tumors, or abnormal position, may predispose the kidney to injury from relatively mild traumatic forces. Historically, congenital abnormalities in injured kidneys have been reported to vary from 1% to 21%. More accurate recent reviews have shown that incidence rates are 1–5% (5,7,14,15). Renal abnormalities, particularly hydronephrotic kidneys, may be first diagnosed after minor blunt abdominal trauma (3,16). Most often, these patients present with hematuria following blunt trauma. Others may present with an acute abdomen secondary to intraperitoneal rupture of the hydronephrotic kidney (17).

Major deceleration and flexion injuries can lead to renal artery or vein injuries due to stretching forces on a normally fixed vascular pedicle. This type of injury may be more common in children because of their increased flexibility and renal mobility (18,19). Post-traumatic thrombosis of the renal artery occurs secondary to an intimal tear. The intimal layer tears from the wall of the vessel because the media and adventitia of the renal artery are more elastic than the intima (20). The intimal tear produces turbulence, thrombosis, and eventual occlusion that then results in renal ischemia. A high index of suspicion must be maintained in order to identify these injuries (21).

**Diagnosis**

**Blunt Trauma**

Once the patient has been resuscitated and life-threatening injuries have been addressed, evaluation of the genitourinary system can be undertaken. Following any blunt injury, the presence of hematuria (microscopic or gross), palpable flank mass, or flank hematomas are obvious indications for urologic evaluations. Most major blunt renal injuries occur in association with other major injuries of the head, chest, and abdomen. Urologic investigations should be undertaken when trauma to the lower chest is associated with rib, thoracic, or lumbar spine fractures. It should
also be undertaken in all crush injuries to the abdomen or pelvis when the patient has sustained a severe deceleration injury. Since a renal pedicle injury or ureteropelvic junction disruption may not be associated with one of the classic signs of renal injury, such as hematuria, radiological evaluation of the urinary tract should always be considered in patients with a mechanism of injury that could potentially injure the upper urinary tract.

Gross hematuria, the most reliable indicator for serious urological injury, mandates radiographic evaluation (22,23). The need for imaging in the patient with microscopic hematuria is not as clear cut. One must remember that the degree of hematuria does not always correlate with the degree of injury (24). Renal vascular pedicle avulsion or acute thrombosis of segmental arteries can occur in the absence of hematuria while mild renal contusions can present with gross hematuria (25). It is well documented in the adult literature that the vast majority of patients suffering from blunt trauma with microscopic hematuria and no evidence of shock (SBP < 90 mmHg) have minor renal injuries and do not need to be studied radiographically (25–28). Guidelines for evaluating the pediatric population are not as clearly defined. Due to the catecholamine response to trauma, children are able to maintain a normal blood pressure despite a significant loss of volume (24). Unlike adult patients, hypotension does not appear to be a reliable indicator of the severity of renal injury in children and diagnostic evaluation should not be reserved only for those in shock (23). Thus, all children with any degree of microscopic hematuria after blunt trauma have traditionally undergone renal imaging (15). Recently Morey et al. in a meta-analysis of all reported series of children with hematuria and suspected renal injury noted that only 2% (11 of 548) of patients with insignificant microscopic hematuria (<50 RBC/HPF) had a significant renal injury (29). However, it is important to note that all 11 of these patients were found to have multiple organ trauma so that renal imaging would have been performed in the course of evaluation despite the relatively minor amount of microscopic hematuria. Detection of significant renal injury was found to increase to 8% with significant microhematuria (> 50 RBC/HPF), and 32% in those with gross hematuria after blunt trauma. The presence of multi-system trauma significantly increases the risk for significant renal damage (23). They concluded that it is reasonable to consider observation with no renal imaging in children with microscopic hematuria of <50 RBC/HPF that are stable and without a mechanism of injury that is suspect for renal injury (29).

Historically, intravenous pyelography (IVP) has been the radiographic imaging study of choice in determining the presence and extent of renal injury. Sensitivity has been reported as high as 90% in diagnosing renal injury (13). Unfortunately, IVP misses other intra-abdominal injuries and has been shown to miss or understage renal injury in children by 50% in comparison to computed tomography (CT). Several studies now indicate that conventional IVP has an extremely low yield and rarely alters management in pediatric patients with blunt renal trauma, especially in patients with isolated microhematuria (5,30–32). However, intravenous pyelography still serves an important role in all penetrating renal and hemodynamically unstable blunt renal trauma patients who require immediate surgical exploration without preoperative imaging (25). A one-shot trauma IVP can be performed in the operative setting and consists of 2–3 mL/kg of non-ionic contrast injected intravenously, followed by a single abdominal radiograph 10 minutes later. The purpose of the IVP is to determine the presence of two functioning renal units, urinary extravastion, and renal parenchymal injury (13,33). With an intra-operative one-shot IVP the need for renal exploration has been obviated in 32% of patients (34).
CT scans are now used almost exclusively as the imaging study of choice for suspected renal trauma in hemodynamically stable adults and children (29,35). The CT imaging is both sensitive and specific for demonstrating parenchymal laceration, urinary extravasation, delineating segmental parenchymal infarcts, determining the size and location of the surrounding retroperitoneal hematoma, and/or associated intra-abdominal injury (36,37). The CT scans allow for accurate staging of the renal injury, which has important management implications which will be discussed later. With the advent of CT, evaluation of renal trauma has now become much more precise.

Several classification systems of renal trauma that are in part based on CT scan findings have been described. The most commonly used staging system is from the American Association for the Surgery of Trauma (Table 1) that divides renal trauma into five grades that have predictive value in the subsequent management strategy of these injuries: grade I renal contusion or nonexpanding subcapsular hematoma without a renal parenchymal laceration; grade II non-expanding perirenal hematoma or a renal cortex laceration ($<1.0$ cm) without urinary extravasation; grade III renal cortex laceration ($>1.0$ cm) and no urinary extravasation; grade IV renal cortical laceration extending into the collecting system (as noted by contrast extravasation), or a segmental renal artery or vein injury (noted by segmental parenchymal infarct), or main renal artery or vein injury with a contained hematoma; grade V shattered kidney, avulsion of the renal pedicle, or thrombosis of the main renal artery (Fig. 1) (38). The ultimate goal of complete staging is to provide sufficient information for management that results in the preservation of renal parenchyma and the salvage of injured kidneys (Fig. 2).

Ultrasonography also has been used to assess renal trauma. However, its sensitivity in demonstrating renal injury in comparison to CT is only 25–70%. It may also miss associated intra-abdominal injuries (5,39). Recently, focused abdominal sonography for trauma (FAST) has become increasingly popular as a screening test for patients with suspected intra-abdominal injury. Nevertheless, FAST has been shown to have a low sensitivity for solid organ injury in children. It also provides poor information concerning renal function or pedicle injuries. Thus, renal ultrasound, at present, is not currently recommended as a useful screening tool for urologic evaluation in the setting of blunt renal trauma (40).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Contusion</td>
<td>Microscopic or gross hematuria, urologic studies normal</td>
</tr>
<tr>
<td></td>
<td>Hematoma</td>
<td>Subcapsular, nonexpanding without parenchymal laceration</td>
</tr>
<tr>
<td>II</td>
<td>Hematoma</td>
<td>Nonexpanding perirenal hematoma confined by Gerota’s fascia</td>
</tr>
<tr>
<td></td>
<td>Laceration</td>
<td>$&lt;1.0$ cm parenchymal depth of renal cortex without urinary extravasation</td>
</tr>
<tr>
<td>III</td>
<td>Laceration</td>
<td>$&gt;1.0$ cm parenchymal depth of renal cortex without collecting system rupture</td>
</tr>
<tr>
<td></td>
<td>Vascular</td>
<td>or urinary extravasation</td>
</tr>
<tr>
<td>IV</td>
<td>Laceration</td>
<td>Parenchymal laceration extending through renal cortex, medulla, and collecting system</td>
</tr>
<tr>
<td>V</td>
<td>Laceration</td>
<td>Main renal artery or vein injury with contained hemorrhage</td>
</tr>
<tr>
<td></td>
<td>Vascular</td>
<td>Avulsion of renal hilum that devascularizes kidney</td>
</tr>
</tbody>
</table>

*Advance one grade for bilateral injuries up to grade III.
It is always important to remember that major renal injuries such as ureteropelvic junction (UPJ) disruption or segmental arterial thrombosis may occur without the presence of hematuria or hypotension. Therefore, a high index of suspicion is necessary to diagnose these injuries. Non-visualization of the injured kidney on IVP, or failure to uptake contrast with a large associated perirenal hematoma on CT are hallmark findings for renal artery thrombosis. UPJ disruption is classically seen as perihilar extravasation of contrast with nonvisualization of the distal ureter (20,23,29,41).

Penetrating Trauma
Renal injury due to penetrating trauma should be suspected with entrance wounds in the lower thorax, flank area, or upper abdomen. These injuries tend to be more severe and more unpredictable than injuries due to blunt trauma. Hematuria, usually gross, commonly accompanies major parenchymal lacerations. However, renal pedicle injuries may occur as an isolated laceration without producing hematuria. Renal imaging is therefore indicated in any patient with any degree of hematuria associated with penetrating trauma. As with blunt trauma, abdominal CT is the imaging study of choice for patients with suspected renal trauma from a penetrating injury. Selected patients, that are accurately staged, with minor renal injuries may be considered for non-operative management (42,43). In unstable patients requiring immediate resuscitation and laparotomy, an intra-operative single-shot
IVP should be performed and has been shown to accurately stage 68–72% of renal injuries in penetrating trauma (33,44).

Management

In general, attempts should be made to manage all renal injuries conservatively, with the exception of a grade V renovascular injury, where the risk of exsanguination mandates expedient operation (45–49). Minor renal injuries constitute the majority of blunt renal injuries and usually resolve without incident (9,18,48,50). The management of major renal parenchymal lacerations, although accounting for only 10–15% of all renal trauma patients, is currently controversial. Surgery is not always mandatory and many major renal injuries due to blunt trauma may be managed conservatively.

Figure 2  Grade IV renal laceration (A) with a large retroperitoneal hematoma and parahilar extravasation of contrast due to blunt trauma. The patient was managed conservatively and follow up CT at six weeks (B) depicts nearly complete resolution of the injury.
(18,23,45,51–53). When necessary, the goals of renal exploration are either to treat major renal injuries with preservation of renal parenchyma when possible, or to evaluate a suspected renal injury (54). The need for surgical exploration is much higher in patients with penetrating trauma as opposed to blunt trauma. McAninch has reported, in adults, that surgical exploration has been required in 77% of gunshot wounds, 45% of renal stab wounds, and 2% of blunt injuries.

Blunt Trauma

The indications for renal exploration vary greatly between individual trauma centers. Most centers expectantly manage grade I–III injuries with bed rest and observation. Controversies arise in the management of grade IV–V injuries. The majority of blunt renal injuries sustained are contusions and lacerations that are minor in nature. Even in the presence of gross hematuria, most blunt renal injuries will not require exploration and will have excellent long-term outcomes (Fig. 3) (53). Absolute indications for renal exploration include persistent life-threatening bleeding, an expanding, pulsatile, or uncontained retroperitoneal hematoma, or suspected renal pedicle avulsion. Relative indications for exploration include substantial devitalized renal parenchyma or urinary extravasation. Husmann and Morris have noted that injuries with significant (>25%) nonviable renal tissue associated with parenchymal laceration that are managed non-operatively have a high complication rate (82%) (55). Their findings demonstrate that when such renal injuries are associated with an intraperitoneal organ injury, the post-injury complication rate is much higher unless the kidney is surgically repaired. By surgically repairing such injuries, they reduced the overall morbidity from 85% to 23%. Urinary extravasation in itself does not demand surgical exploration. Matthews reported that, in patients with major renal injury and urinary extravasation who are managed conservatively,
urinary extravasation resolved spontaneously in 87%. Extravasation persisted in 13% and was successfully managed endoscopically (46). Incomplete staging of the renal injury demands either further imaging or renal exploration and reconstruction. Most commonly pediatric trauma patients undergo renal exploration because they are bleeding persistently, or because they have an associated injury that requires laparotomy.

When conservative management is chosen, supportive care with bed rest, hydration, antibiotics, and serial hemoglobin and blood pressure monitoring is required for uneventful healing. After the gross hematuria resolves, limited activity is allowed for two to four weeks until microscopic hematuria ceases (9). Early complications can occur within the first four weeks of injury including delayed bleeding, abscess, sepsis, urinary fistula, urinary extravasation and urinoma, and hypertension. The greatest risk of delayed retroperitoneal bleeding occurs within the first two weeks of injury and may be life threatening. Immediate surgical exploration or angiographic embolization is indicated in these instances. Angiographic embolization is an alternative to surgery in a hemodynamically stable patient in whom persistent gross hematuria signifies persistent low grade hemorrhage from the injured kidney. Persistent urinary extravasation has successfully been managed by percutaneous drainage. Hypertension in the early post-trauma period is uncommon. Hypertension may develop in the ensuing months and in most instances requires no further treatment other than medical management.

Penetrating Trauma
Nearly all penetrating renal injuries should be managed operatively. The exception is a stable patient with no missile penetration into the peritoneum, where the injury is well staged by CT. This is particularly true if the entrance wound is posterior to the anterior axillary line (43,56). Superficial and peripheral stab wounds universally respond well to nonoperative management. In sharp contrast, one out of every four grade III–IV injuries from penetrating trauma managed expectantly will be complicated by a delayed renal bleed (42). Abdominal or flank gunshot wounds producing hematuria suggest the possibility of major renal destruction due to potential blast effect. Most penetrating abdominal injuries will require laparotomy for associated injuries (61%). The presence of an unexpected retroperitoneal hematoma upon exploratory laparotomy where the renal injury has not been fully staged radiographically usually warrants renal exploration.

Renal Exploration and Reconstruction
A vertical midline incision from xiphoid to pubis is made for speed in opening and closing the wound and to afford maximum exposure. A complete inspection of the intraperitoneal contents is performed. Repair of major vascular, spleen, liver, and bowel injuries should generally be performed before renal exploration. Obviously, if renal hemorrhage is life threatening, the kidney must be explored first.

Early control of the vessels has been demonstrated to increase the rate of renal salvage (54–82%) (Fig. 4) (57). When proximal vascular control is initially achieved before all renal explorations, nephrectomy is required in less than 12% of cases (57). When primary vascular control is not achieved and massive bleeding is encountered, in the rush to control bleeding, a kidney that could have been salvaged may be unnecessarily sacrificed. The surgeon must carefully identify the relationships with
the posterior abdomen and the posterior parietal peritoneum. The colon is lifted from the abdomen in order to allow mobilization of the small bowel. The inferior mesenteric vein and the aorta are identified at this point, and the posterior peritoneum is incised medial to the inferior mesenteric vein. The aorta is dissected superiorly to the level of the ligament of Treitz, where the left renal vein is found crossing anterior to the aorta. Retraction of the left renal vein exposes both renal arteries beneath, which may now be isolated and controlled with vessel loops.

Once vessel isolation is complete, an incision is made in the peritoneum just lateral to the colon. The colon is reflected medially to expose the retroperitoneal hematoma in its entirety and the kidney may be exposed. If significant bleeding is encountered, the ipsilateral renal vessels may be occluded. Warm ischemia time should not surpass 30 minutes (58).

Traumatized parenchyma is debrided sharply and oversewn with 4-0 absorbable suture. Severe polar injuries are best treated with guillotine amputation to minimize

Figure 4  Technique of exposure of renal vessels. (A) Exposure of the root of the mesentery to visualize the aorta. (B) Relationship of the renal veins and arteries after incision of the posterior peritoneum over the aorta. Source: From Ref. 97.
delayed necrosis and fistula formation. Openings into the collecting system are closed with absorbable suture. Injured intraparenchymal vessels may be oversewn with the same suture. Additional hemostasis may be obtained with the use of the argon beam laser or gelatin bolsters. Once the bleeding has been controlled, the open margins of the kidney are reapproximated and the renal capsule is closed. Perinephric or omental fat or a free peritoneal free graft may be sutured to the capsular edges to ensure against any urinary leakage. A Penrose drain is left in the dependent portion of the wound.

Renal vascular injuries must be addressed promptly. Major lacerations to the renal vein are repaired directly by venorrhaphy. Repair of renal arterial injuries may require a variety of techniques, including resection and end-to-end anastomosis, bypass graft with autogenous vein or a synthetic graft, and arteriorrhaphy. Traumatic renal artery occlusion requires many of the same techniques for repair. However this must be performed in the first 12 hours from the time of injury, otherwise, the kidney is usually nonviable following this length of ischemia.

URETERAL INJURIES

The ureter is the least commonly injured portion of the genitourinary tract because of its small caliber and mobility and since it is well protected by the surrounding back muscles and retroperitoneal fat. Although blunt traumatic disruption of the ureter or ureteropelvic junction is rare, this injury is more common in children than adults (3:1) (19). Ureteral injuries are seen three times more often in the right kidney than the left (59). The injury is believed to result from compression of the renal pelvis and upper ureter against the 12th rib or lumbar transverse processes, or by stretching the ureter by sudden extreme flexion of the trunk. This is thought to be more common in children since the child’s spine and trunk are considerably more mobile and elastic than the adult’s (60).

Diagnosis

A high index of suspicion is required for evaluation of all traumatic ureteral injuries. It is not uncommon for UPJ disruption to go unrecognized initially. Delayed diagnosis is often made after complications such as abscess or ileus have resulted from massive extravasation of urine (41,61). Hematuria is a universally inconsistent indicator of ureteral injury and has only been found in 45–63% of ureteral injuries (61,62). If there is any suspicion of potential ureteral damage because of a history of a penetrating injury to the abdomen, retroperitoneum, or pelvis; fracture of the 11th or 12th rib; transverse lumbar process; bony pelvis; or significant abdominal or pelvic trauma, excretory urography or a CT scan must be obtained. IVPs remain nondiagnostic in anywhere from 66% to 75% of studies (61–63). Delayed IVP or CT films are usually necessary to establish the diagnosis. Hallmark radiographic findings include medial and periureteral extravasation as well as non-visualization of the ipsilateral distal ureter (64). Retrograde urography and direct surgical exploration remain the most sensitive tools with accuracy ranging from 85% to 100%. However, this is rarely performed in the acute trauma setting (63,65).

Management

Surgical exploration and direct intravenous injection of methylene blue or indigo carmine is the best course of action whenever acute ureteral injury is suspected.
Surgical intervention is dependent on the location and degree of the injury. The goal of primary repair should be a tension-free, spatulated, and water-tight anastamosis. For distal injuries below the iliac vessels, ureteral reimplantation into the bladder is the best option. Extra length for reimplantation may be obtained by tacking the bladder to the psoas musculature (a psoas hitch) or raising a flap of bladder to the injured ureter (boari flap). The kidney may also be mobilized to create a tension-free anastamosis. Mid and proximal ureteral injuries are best manged by an uretero–ureterostomy with an interrupted anastomosis over an indwelling ureteral stent. When ureteral damage is too extensive, temporizing measures may be performed such as bringing the cut end of the ureter out to the skin (ureterostomy), or by placing a nephrostomy tube with definitive therapy at a later time when the patient is more stable. Delayed reconstruction may include ileal or appendiceal interposition, transureteroureterostomy, or autotransplantaion of the kidney to the hypogastric vessels. The retroperitoneum should always be drained following reconstructive ureteral surgery in the setting of trauma.

Penetrating ureteral injuries are exceptionally rare in children. However, the principles of management are the same as above. Adequate debridement and direct repair with a ureteral stent is the preferred approach for most cases with a short defect. In severe life-threatening cases, a nephrectomy may be performed if the patient is known to have a normal contralateral kidney. Nevertheless, nephrectomy should be avoided if possible.

BLADDER INJURIES

Compared to adults, the bladder in children occupies a more abdominal position, especially when full. This abdominal position makes a child’s bladder more vulnerable to external trauma. As the bony pelvis grows, the bladder becomes more protected from injury. The dome of the child’s bladder is mobile and distensible and is therefore more susceptible to rupture from external forces. Despite this, the incidence of bladder injuries in association with pelvic fractures appears to be less in children than in adults. In the adult population, the association between pelvic fractures and lower urinary tract injury has a reported incidence of 10–25% (66). However, a much lower incidence (1%) has recently been reported in pediatric patients with pelvic fractures (67). The decreased incidence may be due to the elastic nature of a child’s pelvis and its associated attachments (68).

Presentation

Intraperitoneal rupture of the bladder occurs when there is a sudden rise in intravesicular pressure secondary to a blow to the pelvis or lower abdomen. This increased pressure results in a rupture of the dome, the weakest and most mobile part of the bladder. As stated earlier, this type of bladder injury is more common in children than adults because of the intraperitoneal position of the bladder. Intraperitoneal bladder ruptures account for one-third of all bladder injuries in children. Extraperitoneal ruptures are almost exclusively seen with pelvic fractures. In these cases, the bladder can be sheared on the anterior lateral wall near the bladder base by the distortion of the pelvic ring disruption (69). Occasionally the bladder will also be lacerated by a sharp bony spicule.
Bladder injury should be suspected when physical exam reveals suprapubic and vague, diffuse lower abdominal tenderness or bruises over the suprapubic and pelvic region. The patient may report that he was unable to void. Hematuria is a hallmark finding and is present in almost 95% of patients. A Parkland review of six years’ experience found gross hematuria in 98% and microscopic hematuria in 2% (70). In cases of penetrating trauma, bladder perforation should be suspected with any degree of hematuria and trauma to the lower abdomen, pelvis, or buttocks.

**Diagnosis**

Imaging is indicated in all patients with gross hematuria. Significant pubic arch involvement, and hemodynamic instability make a bladder injury very likely (69). Cystography is the definitive study for diagnosis of bladder rupture. The bladder must be completely filled for optimal detection of extravasation. In the child, bladder capacity is variable and must be estimated \([\text{age} + 2 \times 30 \text{ cc}]\) in order to ensure adequate distention (71). The water soluble iodinated contrast solution is instilled by gravity through a Foley catheter placed in the bladder. Films should include anteroposterior, lateral or oblique, and postdrain views. Cystography may fail to demonstrate extravasation if a clot occludes the perforation. If a urethral injury is suspected because of a pelvic fracture, high riding prostate on rectal examination, blood at the meatus, or marked ecchymosis and edema of the perineum, scrotum, and/or penis, a retrograde urethrogram must be done before attempted urethral catheterization (see section on urethral injuries).

Although spiral CT alone is not adequate to evaluate for bladder rupture, CT cystography is a highly sensitive and specific test (72). CT cystogram has been shown to be equally diagnostic to conventional cystography, with an overall sensitivity and specificity of 95% and 100%, respectively, for bladder rupture (73,74). A CT cystogram involves actual retrograde filling of the bladder with subsequent scanning after a conventional CT scan has been performed to evaluate for other bladder and pelvis injuries.

Characteristic radiographic findings for extraperitoneal ruptures include flame shaped areas of the extravasation that are usually confined to the perivesical soft tissue. If there is a large pelvic hematoma, the bladder will often be compressed into the “teardrop deformity.” Intraperitoneal laceration is identified by the presence of contrast material in the cul-de-sac, outlining loops of bowel, and eventually extending into the paracolic gutter (Fig. 5).

Metabolic evidence of urinary extravasation may also be helpful in differentiating intraperitoneal from extraperitoneal rupture or, in the absence of clinical findings, suggest bladder perforation in children. Children with intraperitoneal ruptures develop hyperkalemia, hyponatremia, increased serum urea, and creatinine due to peritoneal absorption of urine solutes into the bloodstream. In contrast, no differences in the serum chemistries are detected for extraperitoneal rupture (75).

**Management**

The treatment of pediatric bladder ruptures depends greatly on whether the injury is intraperitoneal or extraperitoneal. Isolated extraperitoneal ruptures can be managed in most cases with 10 days of Foley catheter drainage. However, the degree of extravasation seen on cystography may not necessarily correlate with the size of the perforation of the bladder wall. Given this, a policy of repairing cases of extraperitoneal
rupture with large amounts of extravasation is prudent. If the patient is to be explored for other injuries or if a large extraperitoneal rupture is suspected, it is best to open the dome of the bladder, not disturb the pelvic hematoma, repair the rupture intravesically, close the bladder, and insert a suprapubic tube (Fig. 6).

Intraperitoneal ruptures should be treated with prompt surgical repair. The peritoneal cavity should be opened, all urine and blood evacuated, the viscera and vasculature inspected for injury, and the appropriate therapy instituted. The bladder should be opened and thoroughly inspected. The bladder is closed in two layers from

Figure 5  (A) Intraperitoneal bladder rupture with visualization of contrast along both paracolic gutters and surrounding the loops of bowel. (B) Extraperitoneal rupture demonstrating extravasation of contrast into the perivesical space and extending into the scrotum.
the inside and a suprapubic cystostomy tube is placed through a separate stab incision. The pelvic space should be drained.

All patients with penetrating injuries from external violence to the lower abdomen and/or that have radiographic and/or clinical evidence of a bladder injury should undergo exploration of the abdomen and the missile tract should be followed from its entrance wound to its exit wound. The peritoneal cavity should be opened even if the injury is thought to be entirely extraperitoneal and the abdominal viscera and major vasculature examined for damage. If the ureteral orifices are involved or there is concern about the integrity of the ureters, 5 mL of indigo carmine should be injected intravenously. A search for extravasation should be made and a five French catheter should be placed in the ureter. The pelvic hematoma should be evacuated in order to identify any other pelvic injuries. The bladder should be opened and fully examined from the inside to determine the full extent of injury. Lacerations should be closed in two layers with absorbable suture. A suprapubic cystostomy tube should be placed along with a drain in the pelvis.

**URETHRAL INJURIES**

The urethra in the male is divided into four areas: (1) prostatic, (2) membranous, (3) bulbous, and (4) penile. The anatomic relationships are important because injuries in different areas require different treatment and have distinct, different outcomes. For treatment purposes, male urethral injuries are classified into two groups: (1) posterior (prostatic or membranous) injuries above or including the urogenital diaphragm and (2) anterior injuries to the bulbous and penile urethra. In children, it is postulated that the prepubertal puboprostatic ligament and bladder do not
constitute a structurally stable unit as they do in the adult. Clinically this is supported by the fact that most traumatic urethral injuries in children occur below the prostate at the membranous urethra. They can also occur through the prostate or at the junction of the prostate and bladder neck (76–78).

Urethral trauma in the female is much less common than in the male. However, female urethral disruption is more common in children than in adults (79). Severe pelvic fracture and bony displacement along with lacerations through the bladder neck and vagina are often present in cases of urethral trauma in the female.

**Posterior Urethra**

Posterior urethral disruption is the most severe injury of the lower urinary tract in children and usually results from violent external force. Strong shearing forces in high-speed blunt and crush injuries or high velocity penetrating trauma shear the attachment of the prostate and puboprostatic ligaments from the pelvic floor, while the membranous urethra, attached to the urogenital diaphragm, is pulled in another direction. As a result, the prostatic urethra is torn. Pelvic fracture is present in >90% of patients with posterior urethral injuries.

**Diagnosis**

Patients with posterior urethral injury may have attempted to void unsuccessfully before arrival at the hospital. If the patient voids, gross hematuria is present in almost all cases. On examination, blood is present at the urethral meatus in the majority of patients with urethral trauma. After laceration of the posterior urethra, the bladder and prostate ascend above the normal anatomic position and the defect fills with blood and urine. Digital rectal examination should be performed in all patients with pelvic trauma. On rectal examination, a boggy fluid collection is present in the normal location of the prostate. However, in children, this is not always a useful finding due to the immature development of the prostate.

Retrograde urethrography is indicated in all patients with suspected urethral trauma. The initial anteroposterior film of the pelvic series is utilized to identify pelvic fractures, bony displacement of the symphysis, or the presence of foreign objects. Next, the patient is placed in a 25–30° oblique position and water-soluble contrast material is injected into the urethral meatus. The best injection technique is with a small catheter inserted just past the fossa navicularis with the balloon inflated with 1 or 2 mL of water. If a urethral catheter already was inserted into the bladder, it should not be removed. In such cases, a retrograde urethrogram may be obtained by inserting an angiocatheter into the urethral meatus and injecting contrast alongside the urethral catheter.

The mildest form of posterior urethral injury (type I) is stretching and elongation of the urethra, owing to pelvic hematoma without rupture. Type II urethral injury is a partial or complete rupture of the prostatomembranous urethra. Extravasation on the retrograde urethrogram is confined below the urogenital diaphragm. Type III is a partial or complete rupture of the prostatomembranous urethra as well as rupture of the urogenital diaphragm and bulbous urethra. Extravasation of contrast material is seen in the pelvis and perineum. Type III urethral injury is the most severe and is twice as common as each of the other injuries.

Boone and coworkers reported on 24 boys with rupture of the posterior urethra who were followed through puberty (80). The level of rupture was prostatomembranous in 67%, supraprostatic in 17%, and transprostatic in 17% of
cases. In contrast, nearly all urethral ruptures above the urogenital diaphragm in adults occur at the prostatomembranous level. In children, the level of injury (i.e., prostatomembranous versus higher) correlated with specific complications as follows: impotence 31% versus 75% intractable structure 12% versus 75% and incontinence 0% versus 25%. Thus, all three complications have a higher incidence when the injury is above the prostatomembranous level. Given this, children are at a higher risk than adults for the development of impotence, structure, and incontinence following posterior urethral injury.

Management

Urethral catheterization for three to five days is recommended for patients with a type I injury since the hematoma distorting the urethra may produce incomplete voiding or urinary retention. These mild injuries usually heal without sequelae. In patients with a minor type II injury (partial tear) one can attempt to pass a catheter into the bladder. If successful, the catheter is maintained for 7–14 days, and a voiding cystourethrogram is obtained when the catheter is removed. Many of these injuries will heal without any structure or with a mild structure that is amenable to either periodic dilatation or endoscopic incision.

Management of patients with complete rupture of the posterior urethra is one of the most difficult and controversial areas of genitourinary trauma. The goal of therapy is adequate urinary drainage with the least negative impact on long term structure formation, incontinence, and impotence. Historical approaches to the patient with posterior urethral rupture emphasized primary exploration and direct urethral realignment. However, the rates of structure, incontinence, and impotence were unacceptably high. Therefore, avoidance of instrumentation at the time of injury and suprapubic cystostomy alone have been the preferred initial management of nearly all cases of posterior urethral rupture for approximately 25 years (81). Delayed definitive repair is undertaken three to six months after the initial injury when the pelvic hematoma has resolved. This has resulted in lessened rates of both incontinence and impotence.

However, in some select patients immediate open surgical realignment is the procedure of choice. These patients include those who (1) are going to have immediate pelvic exploration for a concomitant vascular or rectal injury, (2) have a severe prostatourethral dislocation with perhaps fixation of a “pie-in-the-sky” bladder and prostate due to a displaced comminuted bone fragment by the puboprostatic ligaments, (3) have major bladder neck lacerations or prostatic fragmentation (seen frequently in children), or (4) female patients (82–85). In such patients immediate exploration is preferable to delayed repair with respect to eventual continence at the level of the bladder neck.

Advances in endoscopic techniques with flexible cystoscopy and the use of guide wires and Seldinger technique are producing a reappraisal of both the initial management of posterior urethral rupture and the delayed repair of urethral structure. Immediate endoscopic realignment may have a role in adults (82,86–88). However, in children, the smaller instrumentation that is required and the associated technical difficulty may limit the use of primary endoscopic techniques. Thus, until further experience with immediate realignment is adequately evaluated in children, delayed repair continues to be the gold standard for the management of male children with posterior urethral disruption without concomitant bladder neck or rectal injuries (89,90).
Anterior Urethra

Injuries of the anterior urethra are more common than posterior injuries in children and result most often from blunt trauma, owing to urethral straddle injuries crushing the bulbous urethra against the pelvic arch. Anterior urethral injury may also occur as a result of penetrating wounds from gunshots, stabs, or iatrogenic instrumentation. Either blunt or penetrating trauma to the anterior urethra may produce partial or complete disruption of the integrity of the urethra and its fascial coverings. Buck’s fascia tightly surrounds the erectile bodies and the corpus spongiosum of the urethra from the suspensory ligament proximally to the coronal sulcus distally. Urethral rupture contained by Buck’s fascia leads to dissection of blood and urine along the penile shaft creating a hematoma that appears as a sleeve of the penis. Urethral rupture with extravasation of urine, blood, or pus into the scrotum and contained by Colles’ fascia produces a characteristic butterfly hematoma configuration in the perineum.

Diagnosis

Retrograde urethrography should be performed on all patients in whom the history or physical examination suggests possible injury to the anterior urethra. These findings include blood at the urethral meatus and evidence of penile, scrotal, or perineal contusion, hematoma, or fluid collection.

Management

Minor blunt contusions of the anterior urethra, without disruption, may be treated by a few days of catheter drainage. When the injury is more involved, or penetrating in nature, surgical exploration, debridement and direct repair are indicated. The incision is placed in the perineum for injuries of the distal bulb or proximal pendulous urethra. A circumcising incision with degloving of the penile shaft may be more suitable for injuries to the distal urethra. Partial urethral lacerations are debrided and closed over a urethral catheter, which is maintained for 7–10 days. Complete disruptions of the distal bulbous or pendulous urethra are repaired by direct end-to-end reanastomosis whenever possible. Meticulous care must be taken to debride all nonviable tissue to the healthy margins of the urethra.

Devastating blowout injuries may occur from shotgun blasts, power machine avulsions, or high-speed blunt contusion. Initial management consists of meticulous hemostasis, careful debridement and proximal urinary diversion by suprapubic cystostomy. The goal of the initial debridement of massive wounds of the perineum is to establish proximal urinary and fecal diversion and to approximate viable tissue in such a manner as to end up with a posterior urethral opening which may be repaired in a few months by staged urethroplasty (76).

TESTICULAR INJURIES

Rupture of the testis can be seen with either blunt or penetrating trauma (91). Physical exam reveals a variable amount of scrotal swelling, hematoma, and tenderness, making the testis and epididymis indistinct. Immediate exploration is indicated if the testicle is to be salvaged. Most simple scrotal hematomas in the absence of rupture can be observed if the injury appears stable (92). However, patients with large hematocoeles will generally recover faster with prompt incision and drainage (93). The best radiographic method to evaluate boys with a suspected testicular rupture is ultrasonography. Scrotal ultrasound is a rapid, non-invasive
and relatively accurate method to detect testicular abnormalities. The combined experience in 41 surgically explored cases revealed an overall accuracy for detection of traumatic testicular rupture by ultrasound as follows: specificity, 75%; sensitivity, 64%; positive predictive value, 60%. Thus, ultrasound can be useful in determining if a testicular rupture is present and whether surgical exploration is warranted. However, given the relatively low positive predictive value, surgery should still be considered in equivocal cases in which the ultrasound is not definitively diagnostic. Testicular torsion must always be considered in the diagnosis of all boys with scrotal pain following any type of trauma. Up to 5–8% of boys who are found to have testicular torsion have a history of recent scrotal trauma (94,95).

At the time of surgery, the injured testis should be irrigated with copious amounts of saline. Extruded necrotic seminiferous tubules are debrided, and the tunica albuginea is closed with an absorbable suture. Failure to close the tunica albuginea results in continued extrusion of seminiferous tubules and an increased risk for future infertility. A small drain is placed beneath the tunica vaginalis and brought out through a stab wound in the lower portion of the scrotum. Broad-spectrum antibiotic coverage is given for 7–10 days.

REFERENCES

INTRODUCTION

Skeletal injury in the child differs significantly from the adult both in the fracture patterns seen and in the methods of treatment. Most injuries are isolated fractures that respond well to straightforward management. Some, however, can be life-threatening or lead to significant long-term morbidity.

Over the last 20 years, there has been a major change in the treatment of orthopedic trauma in children. An altered philosophy, in combination with the development of fixation systems suitable for children, has led to an increase in the use of internal or external fixation to stabilize many fractures that in the past were managed with plaster casts or traction. This is particularly the case in femoral shaft, intra-articular, and growth plate (physeal) fractures. Rigid stabilization of these injuries allows early mobilization, and shorter hospital stays, and minimizes the risks of complications such as malunion and growth disturbance. It also simplifies the care of the multiply-injured patient.

INCIDENCE OF SKELETAL TRAUMA

Trauma is the leading cause of death in children over one year of age. It ranks second to infection as the greatest cause of morbidity (1). The highest proportion of childhood injuries are sprains (39%), followed by lacerations (35%), fractures excluding skull fractures (12%), intracranial injuries (5%), internal injuries (0.2%) and other injuries (9%) (2). As lacerations and sprains are usually not serious, fractures represent the most common significant injury in children.

The fracture is usually of a single bone, most commonly the distal radius, followed by the hand and distal humerus. In the lower limb, tibial fractures are more frequent than those of the femur. Physeal injuries account for between 15% and 30% of all fractures (1,3). These occur more often in the lower limb than the upper limb. The incidence of open fractures ranges between 1.5% and 2.6%. Multiple fractures are not common. The incidence averages 3% (1,3–5).
Thirty-seven percent of children’s fractures are caused by injuries sustained around the home, 20% are sport and recreation injuries, 5–20% occur at school and less than 5% are due to motor vehicle accidents (1,5). Not all fractures are due to accidents. In children under three years of age, child abuse is a frequent cause. In children under one year, more than 50% of cases of skeletal trauma are due to non-accidental injury.

At all ages, boys are more likely to suffer a fracture than girls. Forty-two percent of boys and 27% of girls sustain at least one fracture by age 16. The incidence increases throughout childhood peaking at age 12 in girls and 15 in boys (6).

Socioeconomic status, season of the year and time of day all influence the incidence of skeletal trauma. Most childhood fractures occur in the afternoon, after school. They are also more likely to occur in summer, when the days are longer, although this trend is not seen in children less than three years of age (4,5,7,8). Children in lower socioeconomic groups appear more likely to suffer fractures, as do those with behavioral difficulties (9,10).

**PATHOPHYSIOLOGY**

The anatomy, biomechanical properties, and the physiology of the immature skeleton differ profoundly from those of the adult. As a result, children have unique fracture patterns and the methods of treatment are altered to take the above factors into account.

A child’s bone is porous and can sustain more deformation than an adult’s before fracturing completely. This leads to typical fracture patterns such as buckle, or torus, fractures, greenstick fractures, and plastic bowing. Children are less likely to suffer comminuted fractures for the same reason.

The physis or growth plate provides longitudinal and circumferential growth to the bone. It is metabolically very active. It is also a zone vulnerable to injury. Joint dislocations and ligamentous disruptions are uncommon in children. The nearby physis usually fails first. Fractures through this region account for up to 30% of all skeletal injuries in children (1,3). They usually heal rapidly. Damage to the physis can, however, lead to growth arrest with subsequent deformity and shortening (11–14). The fracture patterns seen are described by the Salter–Harris classification (Figs. 1 and 2) (15). Type I injuries are more common in the very young. As the growth plate is radiolucent, they can be difficult to diagnose. This is especially the case if the adjacent epiphysis has not yet developed an ossific nucleus and is also radiolucent. Types III and IV extend across the epiphysis, into the adjacent joint. These carry a significant risk of growth disturbance and joint deformity (Figs. 3 and 4). Treatment relies on accurate reduction.
Type V fractures are rare and caused by an axial load crushing the physis. Complete cessation of growth follows. Type VI injuries (a category added by Rang) describe damage to the periphery of the physis (16). Deep, high-energy abrasions or lacerations can cause this type. Angular deformities may result.

Other fractures in long bones are classified by anatomic location. Diaphyseal fractures involve the shaft. The diaphysis can undergo plastic deformation or sustain

Figure 2  Salter–Harris type VI fracture (peripheral physeal injury of Rang).

Figure 3  Salter–Harris type III fracture of distal tibia.
complete fractures (Fig. 5). Complete fractures may be transverse, oblique, spiral, or comminuted, depending on the forces exerted by the injury. Metaphyseal fractures involve the expanding end of the bone where it is more porous and compression fractures are common.

The periosteum of children’s bones is thicker than that of adults. It is applied relatively loosely to the diaphyseal and metaphyseal regions but attached strongly to the periphery of the physis. The periosteum may be partially stripped off the shaft of a fractured bone, but, due to its physeal anchor, remain strong enough to confer significant stability to some fracture patterns (17). It also has greater osteogenic potential than in adults. This contributes to the faster rate of union of children’s fractures. In cases where there has been segmental loss of bone, if the periosteal sleeve remains relatively intact, there can be complete regeneration of the bone (18).

All fractures tend to remodel. In the child, because of growth, the potential to remodel is much higher. In many circumstances, anatomical reduction is not mandatory as the residual deformity is corrected by asymmetric growth of the physis and periosteum. Realignment will occur over months in response to the normal stresses of muscle action, weight bearing, joint movement and periosteal tension. Fractures that most reliably remodel are those close to a physis and angulated in the plane of movement of the nearest joint. The potential for remodeling is greatest in the young child. Valgus and varus deformities display little ability to correct, and rotational deformities almost no ability, except in infants and toddlers (Fig. 6).
Another consequence of growth on fractures is the tendency for overgrowth. The increased blood flow in response to bony injury can lead to higher rates of longitudinal growth. In the case of diaphyseal femoral fractures in young children, it may be desirable to accept 1 cm of overlap of the bone ends to compensate for this delayed effect (19–21). Proximal tibial fractures with an intact fibula can develop valgus angular deformity, the asymmetric growth possibly due to periosteal tearing or entrapment, growth plate injury, or soft tissue tethering (22).

**MULTIPLE TRAUMA**

In the urban setting, approximately 10% of pediatric trauma admissions involve multiple injuries (23). Motor vehicle accidents are the most common cause. Blunt trauma accounts for 65–90% of the injuries (24–26). The multiply-injured child presents difficulties in both diagnosis and treatment. The incidence of missed fractures varies from 1% to 40% (27–31). These findings stress the importance of meticulous examination of the injured patient and also the need for good quality radiographs in both the primary and secondary surveys. Bone scanning can play a role in the assessment of skeletal injury in the unconscious patient (32).

The early treatment of fractures by rigid fixation is becoming more common. The advantages include easier nursing care and reduced complication rates (33,34).
As a large proportion of residual morbidity in this patient group is secondary to orthopedic injuries, it is important to ensure that fractures are treated in a proper and timely fashion. In long bone fractures, good results have been reported with the use of external fixation, plating, flexible nails, and rigid, locked nails (35). If surgery for other injuries is required, the orthopedic procedures should be done at the same time, if the patient’s condition permits (33). In adults, there is evidence to show that in those with severe head injury or multiple blunt trauma, the risks of hypotension and hypoxia that can accompany the internal fixation of fractures may outweigh the benefits of early orthopedic surgery (36–38). The evidence for this in children is less clear (39,40). In this situation, reliance on clinical judgment and good communication between the pediatric surgeon, orthopedic surgeon and the anesthesiologist is necessary.

**OPEN FRACTURES**

Open fractures in children can be as life- and limb-threatening as those occurring in adults. The aims of treatment are also the same—to avoid infection, achieve soft tissue coverage and bony union and restore function. Early recognition and treatment of these injuries are essential in order to avoid major complications. The Gustilo and Anderson classification of open fractures is a useful descriptive tool.
It also aids in determining treatment and prognosis. The incidence of wound infection, delayed union and non-union, amputation and residual morbidity increases in proportion to the fracture grade (43). However, even pinhole wounds, if neglected, can lead to catastrophic infection, such as gas gangrene (44). Type I open fractures are usually relatively low-energy injuries, the wound often being caused by a spike of bone puncturing the skin. The fracture pattern is usually simple transverse or oblique and soft tissue damage minimal. In type II injuries, the fracture is more likely to be comminuted and the soft tissue injury to be more extensive. Type III open fractures are the result of high-energy injury. The bone is usually comminuted, with extensive periosteal stripping and soft tissue damage (Fig. 7). This class is subdivided into three subgroups. The type IIIA grading is given when the soft tissue coverage over the fracture is adequate. This includes all segmental or severely comminuted fractures caused by high-energy trauma, even if the overlying wound is small. In type IIIB injuries, the soft tissues are extensively damaged and contaminated and the bone exposed. Wound closure without reconstructive procedures is not possible. Type IIIC injuries are those where a limb-threatening arterial injury is also present.

When assessing fractures, it is important to establish that wounds that appear superficial are not, in fact, communicating with the bone. Even innocuous-looking small lacerations may represent a puncture wound from a bone end. Grades II and III injuries are more obvious. In the emergency room, the wound can be superficially irrigated to remove surface debris, and photographs taken. Swabs for microbiological culture should be performed. A dressing should then be applied and the limb immobilized. Careful neurovascular assessment is essential. Repeated inspections of the wound are to be discouraged. This aids in minimizing the risk of colonization with hospital acquired microorganisms. Tetanus prophylaxis and appropriate intravenous antibiotics should be given (45). For most grade I and II open fractures, a first generation cephalosporin given intravenously for at least 48 hours is sufficient. For grade III fractures, an aminoglycoside is added. If the wound has been contaminated with soil, penicillin should also be given as prophylaxis against anaerobic infection (Fig. 8) (46).

Thorough debridement in the operating theater should be done as soon as possible. Previously, it was recommended that this should be within six hours from the time of injury to lower the rate of infection. More recent studies suggest that there is no correlation between infection rates and the time to debridement. It seems that the early administration of antibiotics is more important (47–49).

At operation, all dead or devitalized tissue is removed. This should include a 1–2 mm perimeter of the skin edge. The wound is irrigated with large volumes of normal saline. Up to 20 L of irrigation is recommended—depending on the degree of contamination, pulsed lavage is more effective than simple rinsing (44). The bone ends need to be inspected to ensure that no foreign material has been impacted into them. In most instances, fragments of bone without soft tissue attachment should be removed. If the wound lies close to a joint, careful inspection is required to determine if the capsule has been breached. If the joint appears to be involved, then arthrotomy and joint lavage are needed.

The wound should only be closed if there is confidence that no foreign material or necrotic tissue remains. Repeated debridements are often necessary for grossly contaminated wounds. External fixation is preferable to internal methods if sterility of the wound after debridement is not certain.

In types IIIB and IIIC injuries, specialist plastic or vascular surgery is required. Free or pedicle flaps may be needed to achieve soft tissue coverage. Vacuum assisted closure (VAC vacuum pump, Kinetic Concepts Inc., San Antonio, Texas, U.S.A.) of
wounds has been successfully used to decrease the size of wounds and allow primary closure or application of split thickness skin grafts (50,51).

Open fractures of the pelvis are rare but are associated with a 50% mortality rate. Death is usually caused by either hemorrhage early or sepsis days or weeks after the initial injury (52).

AMPUTATIONS

Traumatic amputations in children are due to high-energy injury. The most common cause is a motor vehicle accident. Severe lower limb injuries due to riding lawn mowers are being reported with increasing frequency. The kinetic energy imparted by the spinning blade is three times that of a 0.357 Magnum bullet. The wounds are extensive, grossly contaminated and amputations are frequently complete on admission to hospital. Of 144 children with this type of injury, amputations occurred in 67 children. Sixty-three percent of amputations were through the toes. Thirty-one percent were through the hind foot, ankle, or tibia (53). In no case could the limb or digit be reattached (Fig. 9).

Reimplantation of a limb is most successful in cases of a clean “guillotine” type amputation. Because irreversible necrotic changes occur after six hours of ischemia,
reimplantation should begin inside this time. Cooling the limb to 4°C may extend the interval to 10 hours. As digits do not contain significant amounts of skeletal muscle, they can tolerate eight hours of warm ischemia time and up to 30 hours of cold ischemia (54).

Amputations due to crush or avulsion trauma are associated with extensive soft tissue and bone injury, often with nerves, blood vessels and musculotendinous units being torn well proximal to the level of the direct injury. For these reasons, it is less likely for the limb to be successfully reattached.

In IIIC fractures, the limb may be too badly damaged to reconstruct, making salvage impossible. In other circumstances, reconstruction may be technically feasible, but the functional outcome so poor as to not be justified. The mangled extremity severity score (MESS) gives objective criteria to predict amputation (55). Points are given for the energy of the trauma, hemodynamic status, presence of ischemia, and

Figure 8 Grade III open fracture of the forearm. Thorough and, if necessary, repeated debridement is essential.

Figure 9 Lawn mower injuries create grossly contaminated wounds and amputations are usually complete.
The principles of amputation surgery in children differ from adults in some important respects. As the child is growing, loss of a physis can have major effects on the ultimate length of the limb. Epiphyses should always be preserved if possible. For example, a knee disarticulation is generally preferable to an above knee amputation, especially in a young child. Growth is also responsible for the frequent incidence of late stump complications. Terminal stump overgrowth is the most common indication for amputation stump revision in juveniles (58–60). This is seen in both transmetaphyseal and transdiaphyseal amputations with almost equal frequency (60). Stump overgrowth is due to new bone formation by the periosteum, accompanied by endosteal remodeling. A sharp point forms which can progressively protrude through the soft tissues of the stump. Transarticular amputations do not develop this problem. However, the advantages of preserving a functional joint and maximizing stump length overcome the disadvantages of overgrowth, so a below knee amputation is almost always preferable to knee disarticulation.

As children have a superior ability to heal and greater plasticity in their soft tissues, the fairly rigid rules that apply to amputation levels and flap construction in adults do not apply. To maximize stump length, soft tissue cover need not be complete initially, as skin grafting and flaps can be performed later (58).

COMPARTMENT SYNDROME

Compartment syndrome occurs when the pressure within a myofascial compartment increases to the point where circulation is compromised, ischemia develops and ultimately, necrosis occurs. The usual cause in children is trauma, with or without fracture, but it has been described in other situations, such as septic arthritis and also after extravasation of intravenous fluid into a limb (61).

The pathogenesis of the syndrome begins with damage to soft tissue, which increases intracompartmental pressure, due either to edema or hematoma. This pressure may exceed the closing pressure of venules. Continued arterial inflow increases the pressure to a point where arterioles cease to flow and ischemia ensues (62,63). If the duration of the ischemia exceeds six hours, irreversible damage occurs. Volkmann’s ischemic contracture of muscle is one result; another is permanent nerve dysfunction. The limb may be rendered useless and late amputation a potential outcome. Prompt diagnosis followed by urgent fasciotomy avoids the devastating complications of compartment syndrome.

The key to treatment is early recognition of the symptoms associated with compartment syndrome. The most sensitive sign is pain out of proportion to the injury. This pain is severe and unrelieved by narcotic analgesia, elevation of the affected limb, loosening of dressings, or immobilization. The pain is worsened by passive stretching of the involved compartment. This is a sensitive early sign. The compartment will usually feel tense to palpation. Other classic symptoms and signs, such as pallor,
pulselessness, parasthesia, paralysis, and poikilothermia usually occur late and are less reliable guides.

The diagnosis may be aided by compartment pressure monitoring. Currently, a pressure greater than 30 mmHg or within 20–30 mmHg of the diastolic blood pressure is considered to be an indication for fasciotomy (62,63). However, controversy exists about the measurement techniques and the real significance of these threshold values. Pressures within a single compartment can vary along its length and also with limb position (63,65–67). Pressures over 30 mmHg can be tolerated without development of compartment syndrome (67,68). Therefore, reliance on an absolute pressure threshold in the absence of symptoms is not recommended. The diagnosis remains a clinical one. Pressure monitoring is a useful adjunct. In the situation of an unconscious patient, a greater reliance should be placed on the absolute values, given the absence of symptoms and some signs.

Treatment relies on decompressing the affected compartments before irreversible tissue damage has occurred. In the lower leg there are four compartments: anterior, peroneal, superficial posterior, and deep posterior. It is usual to release all four, via medial and lateral incisions, although a single lateral incision can be used. In the forearm, the deep flexor compartment is most commonly affected. The fasciotomy should extend, via a curvilinear skin incision, from the medial epicondyle to the distal edge of the carpal tunnel. Both the superficial and deep muscle groups need to be decompressed. The extensor compartment can be released through a separate dorsal incision if necessary, but usually flexor compartment decompression is sufficient to relieve it indirectly.

The skin wounds are left open and either delayed primary closure or split skin grafting performed when the swelling has decreased.

**SPINAL FRACTURES**

The pediatric spine is more flexible and more resilient to trauma than that of the adult. Its differing anatomy and biomechanics also create differing injury patterns. Clinical assessment can be difficult. When a spinal injury is suspected, the child should be immobilized on a pediatric spine board and in a hard collar or sand bag and tape to stabilize the head. The pediatric spine board allows for the child’s relatively large head by having a lowered section on which the head may rest without flexing the neck. Local tenderness or swelling, torticollis, or the presence of a palpable defect along the spinous processes should all arouse suspicion of spinal trauma. A significant head injury is a risk factor for an associated cervical spine injury. As the force required to cause spinal trauma is high, other regions may also be injured. Half of the children with spinal fractures will have concomitant injuries (69). Careful neurological examination at frequent intervals is mandatory. Between 20% and 30% of children with a spinal fracture will have a neurological injury, which may be delayed. Signs of a spinal cord injury include absence or asymmetry of deep tendon reflexes, paralysis, and clonus. Spinal shock may occur and presents as a 24–72-hour period of paralysis, areflexia, and hypotonia. This is followed by the return of reflexes and progressive spasticity. Corticosteroids have been recommended in adult spinal cord injury, as it may improve outcomes. To date, no study has evaluated their efficacy in pediatric spinal cord injury. Nevertheless, its prophylactic use in children would seem to be prudent. Methylprednisolone is given intravenously at a dose of
30 mg/kg as a bolus over 15 minutes, followed by a 45 minutes pause, and then an infusion of 5.4 mg/kg/hr for either 24 or 48 hours (70).

Fractures can occur through cartilaginous end plates, making radiographic assessment difficult. Normal variations such as pseudosubluxation of the upper cervical spine can appear pathological.

Approximately half of the children with a spinal fracture will have associated injuries. As up to 24% of spinal fractures are accompanied by fractures elsewhere in the vertebral column, careful clinical examination of the entire spine and radiographs of the same are recommended.

The incidence of spinal injuries has two peaks, one in children five years old or younger, the second in those older than 10 years (71). Cervical spine injuries are rare, accounting for less than 1% of all pediatric fractures. In children less than eight years, most fractures are of the upper cervical spine, 70% involving C1 or C2. In the older child, mid-cervical injuries are more common. Neurological deficits are infrequent and have a better prognosis than in adults. Most cervical fractures require immobilization in a collar or halo brace. Some require fusion.

Thoracic and lumbar injuries are also uncommon. Some series have reported them as occurring more frequently than cervical injuries, in others, less so (72,73). Similar fracture patterns are seen in both the thoracic and lumbar areas. These include compression, burst, flexion-compression, and fracture dislocation. Flexion-distraction injuries are typically seen in motor vehicle accidents where the child has been restrained in a lap seat belt (Figs. 10–12). This usually occurs in the upper lumbar spine and is known as a Chance fracture. The fracture line may pass entirely through bone, or through the disc/ligament complex, or involve a combination of both bone and soft tissue. Half of these fractures are associated with intra-abdominal injuries, usually to the small bowel or pancreas. Thoracic fractures tend to be relatively stable and may only need bracing. Unstable lumbar fractures may demand anterior and posterior fusion with instrumentation. More stable types can be braced.

Spinal cord injury without radiological abnormality (SCIWORA) can occur, usually in children under eight years old. The incidence ranges from 4% to 66% of all children with a spinal cord injury (74). The cause is unknown, but may be a result

Figure 10 Abdominal bruising from lap seat belt. Underlying injuries may include thoraco-lumbar fractures and duodenal rupture.
of an elastic spine and relatively inelastic cord, transient disc herniation or cord infarction. It most commonly occurs in the cervical or upper thoracic spine. Plain radiographs are normal but computed tomography or MRI will reveal signs of trauma—such signal change within the cord. Up to 50% can develop paraplegia up to four days after the injury (75).

**UPPER LIMB FRACTURES**

Upper limb fractures are usually isolated injuries that are well managed with closed reduction and application of plaster. Skeletal injury in the hand is also mainly treated by simple splinting with closed reduction if necessary, ensuring that any rotational malalignment has been corrected. Percutaneous pinning and occasionally open reduction and internal fixation are needed for unstable, intra-articular or irreducible injuries. Fractures of the scaphoid can occur in children as young as four years old, but they are rare. Diagnosis of this injury can be difficult, especially in children under 10 years, due to the incomplete ossification of the bone. Scintigraphy or computer tomography may be required when plain radiographs are normal but there is a clinical suspicion of fracture. Treatment of undisplaced carpal fractures is usually by cast immobilization. Open reduction and insertion of screws may be necessary if the fracture has separated more than 1 mm.

The most common upper limb injuries are forearm fractures. Again, the majority can be managed by closed treatment and casting for five to six weeks. However, for
shaft fractures treated in this way, 7–32% require remanipulation or other surgery due to loss of position (76,77). Shaft fractures remodel less well than those in the metaphysis and therefore, accurate alignment, especially of rotation, is important. Close follow-up is also needed to ensure that any loss of reduction is detected and treated before union has occurred. In some unstable fractures, the use of percutaneous Kirschner wires or elastic intramedullary nailing can maintain reduction without the need for exposing the fracture site (Figs. 13 and 14) (77–79). In adolescents, plating shaft fractures is more likely to be favored as adult patterns of injury predominate.

When one forearm bone has a displaced fracture, it is essential to ensure that there is not a dislocation of the other bone. The Monteggia fracture involves a fractured ulna and a dislocated radial head (Fig. 15). It is an injury that is still frequently missed. A Galeazzi fracture describes a fractured radius and dislocated distal radioulnar joint. All radiographs of the forearm should include the wrist and elbow to ensure that these injuries do not go undetected. Olecranon fractures are usually accompanied by other fractures about the elbow, such as a radial neck fracture. Most olecranon fractures are undisplaced and require only a sling (Fig. 16). Radial neck fractures may also be managed non-operatively if there is less than 30° of angulation at the fracture site. If the angulation is greater than this, closed or, rarely, open reduction is needed, as remodeling alone is unlikely to correct the deformity. Dislocations of the elbow without an associated fracture are rare. Careful examination of the radiographs is required, as an occult bony fragment, particularly from the medial epicondyle, may be trapped in the joint. Obtaining radiographs of the contralateral
elbow for comparison can assist in cases where a fracture is suspected but not apparent (Figs. 17 and 18). Fractures of the lateral condyle of the humerus can appear very innocuous on a radiograph as a sliver of metaphyseal bone. The majority of the displaced fragment is cartilaginous and the fracture extends into the joint. This is a Salter–Harris type IV fracture and requires open reduction and pinning if displaced, or if undisplaced, immobilization, and close follow-up to ensure that displacement does not develop (Fig. 19).

Supracondylar fractures of the humerus are common and, if significantly displaced, frequently associated with neurovascular complications, including compartment syndrome (80,81). Median nerve palsy is the most common nerve injury, followed by radial and then ulnar (80,81). Most palsies recover spontaneously.

The greatest concern is an associated brachial arterial injury. This may range from transient spasm, to an intimal tear, to complete transection. A weak radial pulse may still be present, as collateral circulation around the elbow in the child is extensive. A reduced or absent pulse, especially after reduction of the fracture, may indicate an

Figure 13  Unstable forearm fractures may require internal fixation using flexible intramedullary nails.

Figure 14  Unstable forearm fractures may require internal fixation using flexible intramedullary nails.
arterial injury. Exploration of the vessel is recommended in this circumstance (82). Arteriography may have a role as long as it does not delay treatment. Repair or grafting of the artery may be required. As compartment syndrome is a common complication of this injury, fasciotomies are usually performed prophylactically.

Once reduced, unstable supracondylar fractures usually require percutaneous pinning. Humeral shaft fractures and those of the proximal metaphysis are usually satisfactorily treated with a sling. Some may require a plaster slab in addition.

**Figure 15** A displaced ulna fracture will usually be associated with a fractured radius or, as in this case, a dislocation of the radial head—the Monteggia fracture dislocation.

**Figure 16** A valgus force applied to the elbow may be sufficient to avulse the medial epicondyle of the humerus. This fragment may become incarcerated within the elbow joint (arrow). This injury can be easily missed. A radiograph of the contralateral elbow can provide a useful comparison of the variable ossification centers around the child’s elbow. Alternatively, a CT scan will confirm the presence of the intra-articular fragment (arrow).
Figure 17  Alternatively, a CT scan will confirm the presence of the intraarticular fragment (arrow).

Figure 18  Displaced supracondylar fractures of the humerus are commonly associated with neurovascular injuries.
Occasionally, fractures of the proximal metaphysis may become irreducible as the deltoid interposes between the fragments. Open reduction may then be necessary.

Fractures of the clavicle account for up to 15% of all children’s fractures. The vast majority are managed with a sling or figure-eight bandage. Open fractures, those that threaten skin or have displaced sufficiently to compromise the neurovascular bundle or mediastinal structures, require open reduction, with or without internal fixation (83).

LOWER LIMB AND PELVIC FRACTURES

Fractures of the foot are rare and can usually be treated by closed methods. Displaced fractures of the calcaneus or neck of the talus may require open reduction and internal fixation. These hindfoot fractures can be easily missed, particularly if minimally displaced. Computer tomography or bone scan may be required if plain radiographs appear normal but clinical suspicion remains.

Ankle fractures are common and usually involve the growth plates of the tibia and fibula. Some may be difficult to discern on radiographs unless oblique views are obtained. Most can be managed with closed reduction. Intra-articular fractures require accurate reduction, usually by open techniques, and internal fixation. Tibial shaft fractures are often due to low-energy injury and can be quite stable, particularly if the fibula is intact. These are treated with closed reduction, if necessary, and application of a long leg cast.

Open or grossly unstable fractures, those with neurovascular trauma or compartment syndrome or the multiply-injured require open procedures, with or without rigid fixation. The presence of an ipsilateral femur fracture creates a “floating knee,” and this is also an indication for treating both fractures, by internal or external fixation (84).

Intra-articular fractures of the knee are usually due to ligamentous avulsions. The tibial spine can be displaced by traction from the anterior cruciate ligament. The patellar ligament (tendon) can avulse the tibial tubercle or the distal pole of the patella. These injuries are easily missed. Displaced fractures need to be reduced and internally fixed (Figs. 20 and 21). A patellar dislocation may be associated with a fracture of its articular surface. Computer tomography is often needed to demonstrate these intra-articular fractures. Fractures of the distal femoral or proximal tibial physes are always due to high energy. Associated vascular injuries are not
uncommon. The fracture is unstable and often requires pinning. The incidence of growth arrest after these physeal injuries is up to 40%. The fracture pattern is usually a Salter–Harris type II. Type II injuries in other bones have a low incidence of growth arrest. The high rates seen around the knee are due to the particular anatomy of those physes. Deep undulations confer stability to these growth plates. A large force is needed to rupture them and the subsequent fracture plane affects all layers of the physis, including the germinal cells. Complete or partial arrests result (Fig. 22).

Fractures of the shaft of the femur are now increasingly managed operatively. For children under six years, a closed reduction and application of a spica cast, with or without preliminary traction, is recommended (85). It is important to be aware that over 50% of femoral shaft fractures occurring in non-ambulatory children are due to abuse. Children between 6 and 10 years can be managed in the same way, but flexible nails also give good results without the difficulties of plaster (86). External fixation can be used for open or comminuted fractures and plating is still used in some situations (Figs. 23 and 24). As children approach skeletal maturity, rigid nails that are inserted through the greater trochanter can be used with low risk of clinically significant trochanteric growth arrest (87). There is a significant risk of avascular necrosis of the femoral head if the nail is inserted through the piriformis fossa of the skeletally immature. Even with a trochanteric entry point, avascular necrosis has been reported (88,89).

Femoral neck fractures are rare but associated with high complication rates due to avascular necrosis. To minimize this risk, urgent reduction and internal fixation are usually necessary. Hip dislocation without fracture can occur. In contrast to
Displaced intra-articular fractures require accurate open reduction and internal fixation to minimize the risk of growth abnormalities and osteoarthrosis.

Fractures through the physis of the proximal tibia or distal femur are high-energy injuries. There is a significant incidence of growth arrest.
older children, this injury in the young child can be due to low-energy trauma. Urgent closed reduction is required because, as for femoral neck fractures, the rate of avascular necrosis increases with the duration of the displacement (90). Open reduction is needed if the joint is irreducible or if a bony fragment remains incarcerated in the joint after reduction.

Pelvic fractures typically occur as a result of high-energy trauma. There is a high incidence of concomitant injuries. Death rates from pelvic fractures have been reported as 2–25% (91,92). Unlike adults, the fatalities are not usually from uncontrollable hemorrhage, but from associated injuries. The child’s pelvis is flexible and force is easily transmitted to the viscera within. The presence of a pelvic fracture should alert the clinician to the high likelihood of significant soft tissue injuries. Most pelvic fractures do not require surgical intervention (Fig. 25). Growth disturbances, including hip dysplasia, are common if the injury has involved the triradiate cartilage—the physis of the acetabulum (93).

NON-ACCIDENTAL INJURY

Child abuse is a serious and often unrecognized problem that is a major cause of morbidity and mortality. The incidence appears to be increasing, but better awareness and reporting may have influenced this trend. A report in 1995 determined that
Figure 24  Transverse midshaft fractures of the femur are well suited to internal fixation with flexible intramedullary nails.

Figure 25  Fractured body of the right pubic bone, secondary to non-accidental injury.
more than one million children in the United States are victims of abuse or neglect annually (94). Features in the initial assessment that should alert the clinician to the possibility of child abuse include a vague or inconsistent history from the parents or caregivers, delayed presentation after injury and abnormal interactions between the child and parents. Clinical signs such as poor general condition, developmental delay, and multiple bruises or other skin injuries add to the suspicion. A skeletal survey may identify multiple healing or healed fractures. Bone scan can also be a helpful adjunct in children under two years.

Differential diagnoses include osteogenesis imperfecta, congenital insensitivity to pain, scurvy, and infantile cortical hyperostosis. If there is suspicion of child abuse, then it is mandatory to notify the hospital-based child protection team or appropriate child welfare agency.

Fractures are the second most common presentation of non-accidental injury after skin lesions (95,96). The incidence of fracture ranges from 10% to 55%. They most commonly occur in children under three years of age. It is estimated that 50–69% of all fractures in children less than one-year old are due to abuse (97–99). The bones most commonly involved are skull, rib, humerus, femur, and tibia (97,98). In children under one year, up to 60% of femoral fractures are secondary to abuse (100). There is no typical pattern of femoral shaft fracture: spiral, oblique, and transverse can follow both accidental and non-accidental injury (98,100). The pathognomic fracture is the metaphyseal corner or bucket handle fracture, which may be seen in any long bone (Figs. 26 and 27) (101). A physeal separation

Figure 26  Non-accidental injury is the most common cause of femoral fractures in children under one year of age.
occurs due to severe shaking. A peripheral rim of metaphysis remains attached to the physeal fragment, creating a unique radiological appearance (Fig. 28). Other radiological signs of abuse include multiple fractures of varying age and posterior rib fractures.

The vertebral body, rather than the posterior elements, is the most common site of spinal injury in child abuse. Anterior compression fractures are the usual type. Fracture dislocations can occur and may not be appreciated in the initial assessment. Lateral as well as anteroposterior radiographs are needed. Spinal cord injuries can occur, with or without bony involvement.

**AN APPROACH TO ORTHOPEDIC TRAUMA**

For the “casual” orthopedist, there are some helpful principles to apply when managing bony trauma in children. A clear history will provide information about the likely energy of the trauma, anatomic site of injury, and presence of other injuries. This will direct the examination, which must be meticulous. The cardinal signs of a fracture are swelling, loss of function, and point tenderness over the site. Older children can identify the region of maximal tenderness accurately, making investigation and diagnosis easier. Children under the age of five years find it difficult to localize pain. A limb fracture usually presents as a pseudopalsy. The upper limb will be held limply by the side or flexed across the body. A fracture of the lower limb results in a refusal to bear weight. Careful palpation of the part, starting distally (or proximally) and working toward the suspected injury will usually yield the site of maximal tenderness—this may be as subtle as a change in pitch of the child’s cries.
Examination of the joints above and below the injury is necessary, as they can be involved in the fracture pattern. Similarly, neurovascular examination should always be performed. Some fractures, notably those of the supracondylar region of the humerus, have a high rate of nerve and vessel injury. Early identification is vital. If a fracture is suspected clinically and the radiograph is normal, trust your examination over the investigation and treat the child on that assumption. Undisplaced physeal fractures may be invisible on radiographs. A radiograph repeated one or two weeks later usually shows periosteal new bone, confirming the diagnosis. Further investigations, such as ultrasound or MRI scan, may be warranted, particularly with suspected fractures about the elbow, hip, or knee, where missed physeal injuries can have serious long term consequences.

In multiple trauma, the diagnosis of fractures becomes more challenging, especially if the child is unconscious. A careful secondary survey is needed. This entails undressing the child and looking carefully for bruises, abrasions, and deformities. The limbs and their joints, spine and pelvis are then palpated, with appropriate spinal precautions. The presence of pain, deformity, or crepitus should be considered to indicate a fracture until proven otherwise. Radiographs of the injured regions need to show two views, anteroposterior and lateral, as some fractures or dislocations will not be apparent in one plane. They must always include views of the joints proximal and distal to the fracture. The failure to diagnose a Monteggia fracture (fractured shaft of ulna with a dislocation of the radiohumeral joint) may lead to a permanent loss of forearm rotation and elbow flexion (Figs. 29 and 30). Femoral shaft fractures can also be associated with an ipsilateral hip dislocation. Good quality radiographs will lessen

**Figure 28** Subtle bucket handle-type fracture of the distal tibia, just proximal to the physis (arrow). This is a fracture typical of child abuse.
the chance of missing injuries such as these. Do not accept poorly penetrated or oriented films. Inadequate radiographs need to be repeated.

Once a fracture is diagnosed, it should be immobilized. This minimizes pain, reduces the risk of further injury and makes inter-department or inter-hospital transfer easier. For forearm fractures and fractures below the knee, plaster slabs provide excellent comfort. They should be wide enough to cover half the circumference of the limb and 8 to 10 layers thick. Rather than wrap the limb in padding, which is painful, it is better to lay the wetted slab onto a strip of padding and then lay both on the limb. The slab can be placed on the dorsal or ventral aspect of the limb—whichever can be accessed without unnecessary movement. The slab is then gently molded to the limb. Once hardened, the slab and limb can be lifted together, and wrapped with a bandage. Open fractures need to be photographed, superficially irrigated and then dressed, before immobilization.

An obviously deformed limb should be immobilized prior to arranging radiographs. This will minimize the movement, and therefore the pain, which occurs when positioning for radiographs. The image will not be significantly degraded by placing the limb in a plaster slab.

Prior to definitive management, displaced elbow fractures are best immobilized with a posterior or laterally placed plaster slab with the elbow in the position of maximum comfort—usually about 30° of flexion. Flexion of greater than 90°, in the presence of marked swelling, risks compression of the brachial artery and compartment syndrome. If the elbow is to be placed in a slab or sling and flexed, the

Figure 29  Monteggia fracture. In this view, the ulna has an obviously angulated midshaft fracture. The radius appears normal, but does not perfectly align with the capitellum.

Figure 30  In this slightly different view, the radial head is clearly dislocated. A line drawn down the shaft of the radius should intersect with the capitellum (circled) in all projections.
radial pulse should be palpated before and immediately after doing so, and then at regular intervals to ensure that no vascular compromise develops.

Displaced femoral shaft fractures should be placed in traction. In the emergency department, this can be achieved with a Thomas splint or other skin traction device. A femoral nerve block gives very effective analgesia and should be given prior to application of the splint if possible.

There are some conditions in orthopedic trauma, which if not diagnosed and managed promptly, will lead to significant complications or even death. Some of these potential disasters such as open fractures, non-accidental injury and spinal trauma are dealt with in detail in the text above. There are few true emergencies in orthopedic trauma, but they include compartment syndrome, fractures with vascular injury or progressive neurological deficit, amputations where replantation is feasible, fractures and dislocations of the hip, open dislocations, and gas gangrene. Any of these conditions necessitate urgent orthopedic review and treatment.

Most children who sustain orthopedic trauma recover completely from their injury. As in other conditions, the risk of mortality or long-term morbidity is minimized by careful initial assessment, judicious use of investigations, knowledge of the potential pitfalls, and appropriate treatment.

REFERENCES

Pediatric Hand Trauma

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INTRODUCTION

Pediatric hand trauma remains somewhat of a black box even to the most experienced traumatologist. In multisystem trauma, life-threatening injuries must be addressed first. However, for best long-term results hand injuries must be recognized early and the hand surgeon should be involved as soon as possible. This is especially true for open, vascular, or potential nerve injuries. It is also important to keep in mind that, due to the peripheral location of the hand, the hand surgeon can easily perform at least temporizing procedures while the trauma surgeon or neurosurgeon is operating on the trunk or head.

HISTORY

Publications depicting the study of the anatomy and function of the hand as a clinical entity first appeared in the 19th century with Sir Charles Bell’s treatise “The Hand—Its Mechanism and Vital Endowments as Envincing Design” in 1834 and Duchenne’s “Physiology of Motion” in 1867. However, it was not until the pre-World War II era that small groups of general surgeons in America recognized the consequences of hand disability and strove to elucidate the field of hand trauma. Through the efforts of surgeons such as Allen Kanavel and Sumner Koch of Chicago; Sterling Bunnell of San Francisco; Vilray Blair and James Barret Brown of St. Louis; and Jerome Webster, Hugh Auchincloss, and Condict Cutler, Jr. of New York, the specialty of hand surgery began to evolve. In 1942, “The Hand. Its Diseases and Disabilities” by Cutler and in 1944 “Surgery of the Hand” by Bunnell were published, firmly establishing surgery of the hand as a true and distinct surgical specialty (1).

RECENT LITERATURE

Much of the recent literature is either anecdotal or pertains to specific injuries. Excellent basic overviews can be found in both the emergency medicine and the pediatric
literature. Alove, Moy, and Peimer in “Pediatric Surgery for the Primary Care Pediatrician, Part II” in Pediatric Clinics of North America, December 1998 describe the basics of evaluation and treatment of a variety of hand injuries in children (2). They also make recommendations on what studies to perform and when to consult a specialist. Harrison and Hilliard in “Emergency Department Evaluation and Treatment of Hand Injuries” in Emergency Medicine Clinics of North America, November 1999 also cover the basics of evaluation and treatment, but are much more detailed in their appraisal of specific injuries (3). Although both of these papers are reviews rather than actual studies, they provide a quick reference of the generally accepted standard of care for most acute hand injuries.

Saies et al. from Duke discuss their replant experience over a 14-year period in “Results after Replantation and Revascularization in the Upper Extremity in Children” from The Journal of Bone and Joint Surgery, December 1994 (4). Seventy-three replants and 89 revascularizations of the upper extremity in 120 children were reviewed. The average follow-up was 36 months for replants and 30 months for revascularizations. They found the rate of survival of the affected part was significantly higher after revascularization than replantation (88% vs. 63%). There was no association between survival and the preoperative duration of ischemia, the level of injury, the particular digit injured, the number of arteries repaired, or the use of venous grafts. Survival of replants after complete amputation was higher for laceration injuries than for crush or avulsion injuries (72% vs. 53%). Survival of revascularizations after incomplete amputations was also higher for laceration injuries than for crush or avulsion injuries (100% vs. 75%). There was no relationship between patient age and survival after revascularization. However, there was a statistically significantly higher rate of replant survival in children less than nine years old than in those 9 to 16 years old (77% vs. 52%). Total active motion was better when the level of amputation had been distal to the insertion of the flexor digitorum superficialis tendon ($p < 0.0001$). For those digits, which were ischemic postoperatively, reoperation salvaged only 2 of 21 replants and 6 of 12 revascularizations.

**DIAGNOSIS OF HAND INJURIES**

**Clinical Assessment**

After initial stabilization of the patient following Advanced Trauma Life Support (ATLS®) guidelines, a complete history and physical focusing on the entire upper extremity must be performed.

History should include basic information such as the child’s age, dominant hand, and any prior injury to that extremity. Specific information relating to the accident, including when it happened, where it happened (clean vs. dirty environment), as well as the mechanism of injury is invaluable in formulating treatment plans. Knowing the position of the hand at the time of injury is also helpful as is information on treatment received so far. Of course, a general medical and surgical history including tetanus immunization, current medications, and allergies should be obtained as well.

A focused physical exam is next. Expose the entire upper extremity including the shoulder and neck. Note the color of the hand. Is there swelling or edema? If so, is it generalized or localized to certain areas? Check the position of the upper extremity and determine if it is held in an abnormal position. Both active and passive motion of the hand, fingers, and wrist should be checked and documented, as should sensation and vascularity.
To perform an accurate and detailed physical exam specific to the hand requires an exhaustive knowledge of hand anatomy and kinetics. A review of anatomy including muscles, tendons, nerves, and vascular supply is appropriate at this point (5).

**Extrinsic Muscle Flexors**

The bellies of the extrinsic muscles are located in the forearm. The flexors are on the volar surface. The flexor pollicis longus (FPL) attaches to the distal phalanx of the thumb and bends both the metacarpophalangeal (MP) and interphalangeal joints of the thumb. The flexor digitorum profundus (FDP) attaches to the distal phalanx of each finger and bends all joints. It has a common muscle belly for the small, ring, and long fingers and usually, an independent muscle for the index finger. The flexor digitorum superficialis or sublimus (FDS) attaches to the middle phalanx of the finger and bends the MP and the proximal interphalangeal (PIP) joints of the fingers. The FDS has independent muscle bellies for each finger. However, the muscle tendon unit to the little finger may be small or even absent. The FDP can be tested by asking the patient to bend the finger at the distal interphalangeal (DIP) joint, while the PIP joint is stabilized in extension by the examiner. Asking the patient to bend the finger at the PIP joint, while the other joints are stabilized in extension by the examiner can test the FDS.

In a young or unconscious child who will not cooperate with an examination, the flexors can be indirectly evaluated by observing the digital cascade and the tenodesis effect. When the hand is in a resting position, the digits have a cascade of progressively increasing flexion from the index through the little finger (Fig. 1). The tenodesis effect can be observed by passively flexing and extending the wrist. As the wrist moves from flexion to extension, intact flexors are placed under tension, causing the fingers to flex into their normal cascade (as described above). One may also squeeze the forearm, causing flexion of the digits with intact flexor tendons.

![Figure 1](image)

**Figure 1** A normal cascade with increasing flexion from the index through small fingers.
Injuries may occur anywhere along the course of the tendon, which has been divided into zones (Fig. 2) (6). Zone I extends from the fingertip to the middle of the middle phalanx (distal to the insertion of the FDS). Zone II extends from the middle of the middle phalanx, including the FDS insertion, to the distal palmar crease. This is the area of the tendon contained within the pulley system, which prevents the tendon from bowstringing with flexion. Injuries in this zone have the worst prognosis due to adhesion formation and failure of the tendon to glide within the pulley system. Zone III extends from the distal palmar crease to the proximal palmar crease. Zone IV extends from the proximal palmar crease to the distal wrist crease (the region of the carpal tunnel). Zone V extends proximal to the distal wrist crease.

Extrinsic Muscle Extensors
The extrinsic extensor tendons are arranged in six discrete compartments over the dorsum of the wrist (Fig. 3). The first dorsal compartment contains the abductor pollicis longus (APL) and the extensor pollicis brevis (EPB). Both result in some abduction of
the thumb. The second dorsal compartment contains the extensor carpi radialis longus (ECRL) and the extensor carpi radialis brevis (ECRB). Both extend the wrist while the ECRL also causes some radial deviation. The third dorsal compartment contains the extensor pollicis longus (EPL). The EPL lifts the thumb vertically with the palm flat down on a surface (Fig. 4).

The fourth dorsal compartment contains the extensor digitorum communis (EDC) and the extensor indicis proprius (EIP). The EDC is a common muscle belly, which extends (straightens) all four fingers, while the EIP extends only the index finger. The fifth dorsal compartment contains the extensor digiti minimi (EDM), which extends the little finger. The sixth dorsal compartment contains the extensor carpi ulnaris (ECU), which extends the wrist and deviates it ulnarly.

**Neurological Examination**

Neurological evaluation of the pediatric hand varies depending upon the age, willingness to cooperate, and state of consciousness of the child. In an ideal situation, both motor and sensory exams can be completed. Three major nerves innervate the hand: the median, the ulnar, and the radial.
The median nerve supplies sensation to the volar surface of the thumb, index, and middle fingers as well as the radial side of the ring finger, and the dorsal aspect of the index, middle, and radial half of the ring finger distal to the PIP joints (Fig. 5). The ulnar nerve innervates the dorsal and volar surfaces of the little finger and the ulnar half of the ring finger. The radial nerve supplies sensation to the radial three-quarters.
of the dorsum of the hand as well as the dorsum of the thumb. It also supplies the
dorsum of the index, middle, and radial half of the ring finger. Testing in the appro-
priate distribution is important with injuries proximal to the wrist where the main
trunks of these nerves may be transected. Additionally, with proximal nerve injuries,
the motor function of the hand may also be affected, and this should be tested.

The median nerve originates from the medial and lateral cords of the brachial
plexus. It enters the forearm through the pronator teres muscle and innervates the flexor
carpi radialis, palmaris longus, the FDS to all fingers, the FDP to the index and long
fingers, the FPL, and both forearm pronators. It enters the hand through the carpal tun-
nel and innervates the thenar muscles including the abductor pollicis brevis, the radial
half of flexor pollicis brevis (variable), the opponens pollicis, and the lumbricals to
the index and long fingers. The median nerve is tested by having the patient pinch
the thumb to the index finger and palpating the contraction of the thenar muscles at
the base of the thumb. Sensation is best tested on the radial side of the index fingertip.

The ulnar nerve originates from the medial cord of the brachial plexus and
enters the forearm just posterior to the medial epicondyle between the two heads
of flexor carpi ulnaris (FCU). It innervates the FCU and the FDP to the ring and
little fingers. The ulnar nerve enters the hand through Guyon’s canal and innervates
the abductor digitii minimi, the hypothenar muscles (flexor digiti minimi, opponens
digitii minimi, and abductor digiti minimi), the lumbricals to the ring and little fin-
gers, all of the interossei, and the adductor pollicis. It may also innervate all or
the ulnar half only of the flexor pollicis brevis. The ulnar nerve is tested by having
the patient spread the fingers out against resistance. The intrinsic muscles innervated
by the ulnar nerve control this function. It may also be beneficial to have the patient
demonstrate that he or she can cross two fingers—an action possible only with
intrinsic muscle function. This should be compared to the contralateral hand. Sensa-
tion is best tested on the ulnar side of the little fingertip.

The radial nerve originates from the posterior cord of the brachial plexus and
enters the forearm through the supinator muscle. It innervates the supinator, EDC,
EDM, ECU, APL, EPL, EPB, and EIP. The radial nerve is tested by having the
patient extend the wrist and fingers. Sensory function of the radial nerve is tested
on the dorsum of the hand between the first and second metacarpals.

The digital nerves travel on the volar aspect on each side of the fingers. The sensory
exam is ideally tested with two-point discrimination. This is accomplished by bending a
paper clip so that its tips are about 5 mm apart. Normal two-point discrimination is less
than or equal to 5 mm. The child’s finger is touched with just enough pressure to cause
skin blanching on both the radial and ulnar side of each digit with either one or two
points. Inability to discriminate one point from two with repeated testing is abnormal
and may indicate an injury. However, it should be emphasized that in children it is often
difficult to obtain the degree of attention and cooperation necessary to perform this
exam reliably. In these situations, when the location of the injury makes nerve transec-
tion likely, operative exploration is recommended.

Vascular Examination

The radial and ulnar arteries supply the hand. These vessels usually anastomose to
one another within the hand via a deep and superficial arch. Therefore, in an emer-
gency situation, one of these arteries may usually be ligated without threat of hand
ischemia. Ten to 15 percent of patients do not have an intact arch system and may
require both vessels to perfuse the hand. This can be tested using the Allen test. The
examiner compresses both vessels at the wrist, then the patient opens and closes the hand several times to fully exsanguinate it. One vessel is then released, and the hand assessed for its vascularity. This is then repeated with the other vessel. Failure of the hand to reestablish normal capillary refill (normal < 3 sec) with either the radial or ulnar artery indicates the likelihood of an incomplete vascular arch and dependence on both radial and ulnar arteries.

A general vascular exam is accomplished by checking both pulses at the level of the wrist on the volar surface, the color of the skin, and the capillary refill at the nailbeds. The digital arteries travel with the digital nerves along the volar aspect of each side of the fingers. When there is a question of injury, a Doppler should be used to test for a signal.

Other Diagnostic Tests

Very few diagnostic modalities add significantly to the astute clinical exam in the acute situation. However, plain three-view radiographs [posteroanterior (PA), lateral, and oblique] that include the joints immediately proximal and distal to the area of trauma can be helpful and are usually indicated. They are especially useful in penetrating trauma or when there is a question of a fracture or foreign body. It should be remembered to order the X-ray specifically of the area in which an injury is suspected. Simply ordering “hand X-rays” frequently results in inadequate visualization of the area of injury. In the child, particularly when there is suspicion of a wrist injury or dislocation, it may be helpful to also obtain an X-ray of the contralateral uninjured hand. Due to differences in the rate of growth and ossification, confusion may arise regarding normal versus abnormal anatomy. Comparing X-rays from both hands may clarify this.

Angiograms are rarely indicated in hand trauma. Even in cases with significant bleeding, the situation can usually be managed with direct pressure and operative exploration under tourniquet control. Information obtained from an angiogram rarely changes management, particularly as embolization is almost never performed in the upper extremity due to the risk of distal ischemia. An angiogram may be helpful in proximal penetrating wounds with a suspicion of vascular injury. Knowledge of the severity and location of the injury may facilitate proximal exposure, which can be difficult.

TREATMENT OF HAND INJURIES

Anesthesia

In the emergency room setting, local anesthesia can be used in a variety of ways. The most common are digital blocks, wrist blocks, and hematoma blocks; 1% or 2% of plain lidocaine (without epinephrine) is a good choice (7). If feasible, the ideal situation is to administer the block with conscious sedation. If conscious sedation is used, the child’s respiration and oxygen saturation must be monitored carefully and equipment and skilled personnel must be available to control the airway throughout the procedure.

Digital blocks can be carried out by the volar or dorsal approach. However, the dorsal approach is less painful, and will be described here. A 25- or 27-gauge needle is inserted at the base of the web space on the dorsal surface of the hand (Fig. 6). A skin wheal is made in this area to block the dorsal sensation. The needle is then advanced toward the palm until its tip is palpable beneath the volar skin at the base of the finger, just distal to the web space. Lidocaine is injected to block the proper digital nerve. Prior to removing the needle, it is redirected across the dorsum of the finger to the opposite side, where a wheal is made to block the other dorsal
nerve. The needle is then removed and replaced in the region of this wheal on the opposite side of the finger. It is then advanced toward the palm as previously described to block the proper digital nerve on this side (Fig. 6). A circumferential block around the digit should be avoided, as it is possible to create, in essence, a localized compartment syndrome and ischemia of the finger.

A wrist block is also useful when performing procedures in the hand. With this, the median, ulnar, and radial nerves are all blocked. To block the median nerve, the needle is inserted at the level of the proximal wrist crease at an angle of 30° from perpendicular directed distally in line with the axis of the ring finger. With the wrist in slight dorsiflexion, the needle is advanced slightly toward the long finger and enters just deep to the volar carpal ligament. An amount of 1–3 mL (depending upon the child’s size) of anesthetic is injected while palpating the palm with the other hand. A slight bulge may be palpated distal to the ligament as the canal fills with anesthetic.

The ulnar nerve is blocked by inserting the needle just dorsal to the flexor carpi ulnaris tendon, directed toward the ring finger, in the plane of the palm. An amount of 1–3 mL of anesthetic is injected. The dorsal sensory branches of both the ulnar and radial nerves are field blocked by infiltrating subcutaneously along the entire dorsum of the wrist.

Hematoma blocks are achieved by directly infiltrating local anesthetic into the hematoma of a fracture site, and are most often used when performing closed reduction of a fracture. They may be used in conjunction with digital or wrist blocks.

**Figure 6** Digital nerve block demonstrating the proper dorsal approach and sequence of injection.
Tourniquets

A tourniquet should almost always be used during the repair of hand injuries. It may be deflated at various times during the procedure to assess vascular perfusion after an anastomosis or to assess hemostasis prior to closure. The tourniquet used most frequently is the upper arm tourniquet. Several layers of soft cast padding are wrapped around the upper arm and a standard pneumatic tourniquet placed over it. Traditionally, guidelines state that the width of the cuff should equal the diameter of the arm, but more recent studies by Crenshaw et al. and Hargens et al. suggest wider cuffs allow a lower pressure to be used with the same effect (8,9). Disposable blood pressure cuffs are appropriately sized for infants and children.

Typical pressures needed in children range from 150 mmHg to 250 mmHg, with 200 mmHg being the most common. Most hand surgeons will allot a maximum of 120 minutes tourniquet time. After this, a period of reperfusion of 15–20 minutes with the tourniquet deflated is needed for the body to readjust pH in response to the ischemia. As a rule, 5–10 minutes of reperfusion is needed for every one hour of tourniquet time.

Finger tourniquets are typically used in the emergency room setting for digital procedures. After the instillation of local anesthesia (see previous section), a 0.25 in Penrose drain is wrapped around the finger distally to proximally to exsanguinate it, then clamped to itself at the base of the finger to achieve a tourniquet. Salem has described cutting the finger from a sterile rubber glove, stretching it over the operative digit, and rolling it proximally once the tip has been cut off to form a ring at the base of the finger (10). In practice, it is usually easier to place the entire glove on the hand, then cut the tip of the finger off the glove and roll this proximally. Keep in mind that excessive pressures can easily be generated using these finger tourniquets. They should only be used for very short procedures.

Tendon Injuries

Suspected injuries should be explored and repaired under tourniquet control in the operating room. There is no indication for wound exploration in the emergency room. Of note, suspected tendon injuries need not be operated on immediately. It is acceptable to consult a hand surgeon and simply suture the skin and splint the patient. The hand and wrist are placed in a dorsal splint with the wrist at 30° of extension, the MP joints in 70° of flexion, and the interphalangeal (IP) joints extended. Repairs should generally be performed within one week of the injury. Prolonged delay results in retraction of the proximal tendon and may result in the need to perform tendon grafting.

Occasionally, unlike flexor injuries, injured extensor tendons may be seen in the wound. Repair can be accomplished in the emergency room. However, consultation with a hand surgeon is still imperative.

Nerve Injuries

In the event of a suspected nerve injury, a hand surgeon should be consulted. Immediate repair is generally not necessary. The skin can be closed and the patient splinted. Nerve repair within the first two to three weeks is acceptable. Too long a delay, however, can lead to retraction of nerve ends necessitating grafting.
Vascular Injuries

If a vascular injury is suspected, the examiner should apply digital pressure to the bleeding wound. Blind clamping of structures is never indicated. A hand surgeon should be consulted immediately. If the injury is at or near the axilla, a trauma or vascular surgeon should also be informed because proximal control may require exposure of the vessel in the chest.

Nailbed Injuries

Nailbed injuries are commonly seen in children with crush injuries to the fingers, typically from catching the finger in a door. They are often associated with fractures of the distal phalanx. The problem with such injuries is the subsequent nail deformity that may develop. If the proximal portion of the nail is affected, nail growth may be a problem due to damage to the germinal matrix. Distally, the sterile matrix is involved and any loss of nailbed from injury or inadequate repair in this region becomes scar tissue that may result in a permanent ridge, split, or nonadherent nail. In these injuries, the nail plate must be removed and the bed repaired with interrupted 6–0 plain gut sutures under digital block and tourniquet. Following repair, the eponychial fold must be stented to prevent the germinal matrix from adhering to itself. This can be done by replacing the nail plate or inserting nonadherent gauze into the fold.

A subungual hematoma in the face of an intact nail plate often presents with severe pain due to pressure beneath the nail. These can be drained steriley by making one or several holes through the nail plate with a needle or portable cautery. Provided the puncture does not reach the nailbed itself, anesthesia is unnecessary. The finger can then be placed in warm water or hydrogen peroxide to help evacuate the hematoma. However, in the face of a large subungual hematoma, the likelihood of a significant nailbed injury is generally high enough to warrant removal of the nail plate and repair of the bed.

It should be mentioned that the distal phalangeal fractures so often associated with nailbed injuries rarely if ever need treatment. Generally, addressing the soft tissue injury alone is sufficient. A finger splint may be helpful to provide comfort while the fracture is healing.

Fractures

Fractures should be suspected after trauma to the hand resulting in significant pain, tenderness, swelling, or deformity. X-rays should be obtained; comparison views of the unaffected hand may be helpful. Fractures with overlying lacerations or soft tissue loss should be considered open fractures. They require irrigation prior to skin closure and reduction.

Essentially all non-displaced or minimally displaced closed fractures in children with a normal neurovascular exam can be splinted and referred to a hand surgeon (11). The “safe” position to splint the hand is with the wrist in 30° of extension, the MP joints in 60–70° of flexion and the interphalangeal joints in neutral (12). In very small children, it is difficult to actually splint the hand in this position due to the size of the hand and fingers. The priority should be given to simply preventing the child from moving or using the injured hand. As such, a bulky “boxing glove” dressing should be applied, completely covering the hand and fingers. It should be carried above the elbow with the elbow kept flexed at 90° to prevent the child from removing the splint. Care must be taken when splinting to avoid a tight
bandage. The dressing must account for subsequent swelling. For displaced fractures, closed reduction is sometimes possible. However, reduction and surgical stabilization are often necessary. A hand surgery consultation should be obtained in the emergency room.

**Injection Injuries**

Penetration of the hand by fluids under pressure (paints, lubricants, abrasives, solvents, etc.) is unusual in children. However, when present, these injuries require wide surgical opening of the hand, thorough irrigation, and mechanical debridement. Injection injuries often appear deceptively minor, as there may be only a very small puncture wound at the site of entry. However, there is potential for widespread contamination and necrosis. Rapidly increasing pain and edema are the hallmark of severe deep tissue damage. These injuries can easily develop into compartment syndromes and necessitate emergent referral for surgical debridement and fasciotomy.

**Amputations**

Indications for replantation in children are broader than for any other group (13). Any amputated part should be wrapped in a saline-soaked gauze and placed in a plastic bag. This plastic bag should then be placed in another bag filled with water and crushed ice. The amputated part should never be placed directly onto ice. Xrays of the part and the remaining stump must be taken. The decision to replant is based upon the type of injury, the condition of the hand and amputated part, and the overall condition of the patient (14). Contraindications for replantation include associated major life-threatening injuries, major medical conditions precluding prolonged surgery, severe avulsion or crush injury, prolonged ischemic time (more than 12 hours warm ischemia for a digit or more than six hours warm ischemia for a proximal limb amputation), multiple levels of injury, extreme contamination of the part, and psychiatric instability of the patient. Replantation should be considered for nearly all amputated parts in children, provided these contraindications do not exist.

The results of replantation depend a great deal on the level at which the amputation occurs. The most problematic level for replantation is in Zone II of the finger, within the flexor tendon sheath. This is also one of the most common sites of amputation. Just as with isolated flexor tendon injuries in this area, subsequent adhesions frequently result in stiffness that inhibits function. Although children tend to do better than adults, it is still a problem that must be considered.

Another common level for amputation in children is the fingertip. In very distal injuries, with only a small portion of the fingertip amputated, replacement of the part on the finger as a composite non-vascularized graft may be indicated. This works best in very young children.

In amputations proximal to the nailbed, the blood vessels are generally large enough to repair under the microscope. Replantations do well from a functional standpoint at this level, but the operation tends to be technically difficult due to the small size of the arteries and the relative paucity of veins in this zone.

**Bites**

Human or animal bites pose a significant threat of infection. *Staph aureus* and *Streptococcus* are the most common organisms, but *Eikenella corrodens* (gram
negative) can be found in one-third of human bite wounds. *Pasteurella multocida* is present in most cat and dog bites.

If no tendon or joint involvement is suspected, and there are no other abnormalities on physical exam, these wounds can be treated with copious irrigation and prophylactic antibiotics, then left open to heal by secondary intention (15). Generally speaking, the best antibiotic for treatment of bite wounds is ampicillin with a β-lactamase inhibitor such as Augmentin (Amoxicillin/Clavulanate) or Unasyn (Ampicillin/Sulbactam) if intravenous administration is necessary.

Bite wounds in the region of the MP joints should be expected to involve the joint and consideration given for joint exploration, irrigation, and intravenous antibiotics. Failure to diagnose and treat an intra-articular bite may result in a serious infection. Very large wounds can be closed in a delayed primary fashion at four to five days provided the wound has not become infected (16).

**REFERENCES**

INTRODUCTION

Trauma is the major cause of morbidity and mortality in children, and central nervous system trauma is the major determinant of the severity of injury. Because of the development of sophisticated trauma systems to care for the child with severe injuries, more children with severe injuries survive—many of whom will live a lifetime with acquired disabilities. The long-term burden of these disabilities ranges from negligible to staggering. To deal with these consequences, rehabilitation systems have been developed to assist these children and their families, helping them to optimize their function in their home, school, and community.

This chapter will focus on issues and principles of rehabilitation for children with traumatic injuries that are relevant to surgeons and other professionals within trauma systems. Issues discussed will include: (1) the efficacy of rehabilitation, (2) the importance of early rehabilitation—starting in the Intensive Care Unit (ICU), (3) the need for specialized rehabilitation systems for children, (4) the benefits of a rehabilitation continuum that allows rehabilitation to be done in natural, functional settings, (5) guidelines for the proper identification of children requiring rehabilitation, and (6) principles of rehabilitation.

EFFICACY OF REHABILITATION

Before discussing current rehabilitation practices, it is important to review some of the science supporting its efficacy. While certain aspects of rehabilitation can be intuitively recognized as efficacious and desirable, others may not. For example, it is easy to accept the benefits of an ankle foot orthosis (AFO) that normalizes gait patterns and decreases number of falls because of improved toe clearance, or a power “tilt-in-space” wheelchair.
that enables a person with C-4 tetraplegia (related to spinal cord injury) to independently drive a wheelchair, and to prevent pressure ulcers by using the power-tilt feature of the wheelchair to independently perform pressure relief maneuvers, or serial casting that results in the resolution of an ankle plantar flexion contracture, or a memory journal that allows a person with mild memory impairments after traumatic brain injury (TBI) to decrease the number of errors in their daily routine.

However, proving the efficacy of therapy for more complicated problems has been more difficult. This is partially related to the multiple dimensions that need to be taken into consideration when evaluating rehabilitation efficacy and outcome, including many sociobehavioral goals that are more complicated to quantify, as well as the multifactorial, diffuse nature of the rehabilitation process itself (1). Fortunately, with use of evidence-based medicine, proof of efficacy for certain components of rehabilitation is increasing. For example, there are recently published evidence-based guidelines for cognitive rehabilitation that support the use of specific interventions for functional communication deficits including pragmatic conversational skills and for specific language impairments such as reading comprehension and language formation, compensatory memory strategy training, and training in formal problem-solving strategies. These guidelines also recommend against therapies that rely on isolated use of microcomputer-based exercises, without extensive involvement and intervention by a therapist (2).

Many of the underlying questions related to the efficacy of neurological rehabilitation have centered on the plasticity of the brain (i.e., does the brain reorganize itself after injury, and if so, how?), and is this reorganization influenced by external factors such as sensory input and activity (i.e., will therapy influence the reorganization?). Of course, it has long been known that brain plasticity does occur and is responsible for improved outcome after focal brain injury (e.g., strokes, hemispherectomies) in infants and younger children, as compared to adults. (It should be noted that in diffuse injuries, such as severe traumatic brain injury, this age advantage is not as evident.) However, the extent of this plasticity, its presence in the more mature brain, and the influence of therapy upon recovery still remained difficult questions to answer. However, just as technology came to the aid of trauma patients in the form of neuroimaging and sophisticated monitoring techniques, technology is now coming to the aid of those who toil at defining the efficacy of rehabilitation. With techniques such as functional neuroimaging and transcranial magnetic stimulation, the reorganization of the brain after injury can be demonstrated. For example, in adults after recovery from stroke, functional imaging has shown that use of the affected hand can be associated with activity in the bilateral motor cortex and bilateral cerebellum, as contrasted with contralateral motor cortex and ipsilateral cerebellum in the unaffected hand (3). We also know that this reorganization is facilitated by activity (i.e., therapy). Direct cortical mapping in primates before and after induced cortical lesions has shown that cortical reorganization after focal infarct occurs, and that this activity-dependent process is facilitated by therapeutic activity (4). Now, we also have similar evidence in humans. Using focal transcranial magnetic stimulation to map the cortical motor output area of a hand muscle in chronic stroke patients before and after a 12-day period of constraint-induced movement therapy, demonstrated in humans the long-term alteration in brain function associated with a therapy-induced improvement of movement after neurological injury (5).

Reinforced with increasing evidence of the effectiveness of rehabilitation, we will now focus on the relevant issues and principles of rehabilitation for children with traumatic injuries.
DEFINITIONS

Rehabilitation is the process by which an individual with impairments and disabilities (defined below) is assisted in regaining maximal independence and function.

In 1980, the World Health Organization developed the International Classification of Impairments, Disabilities, and Handicaps (ICIDH), to complement the International Classification of Diseases (ICD) (6). This provided for the classification of consequences of diseases that are common to chronic conditions, disorders, and impairments. This classification model included impairments (disturbances at the organ level), disabilities (disturbances at the person level), and handicaps (reflecting the interaction with and adaptation to the individual’s surroundings). A revision of ICIDH is underway and will be titled International Classification of Functioning, Disability and Health (ICIDH-2) (7). This revision will reflect current models of disability, include environmental factors, address dimensional overlaps, and propose associations between dimensions, all in neutral terminology (8,9). Instead of using impairment, disability, handicap, the ICIDH-2 will use two domains each from the body, individual, and societal perspectives: (1) body functions and structures (impairment), and (2) activities (activity limitation) and participation (participation restriction), with contextual factors (environmental and personal factors) (Fig. 1) (Table 1).

This scheme is important for understanding clinical and research issues related to rehabilitation. It is possible to affect one domain, with or without resultant change in another. An example of the use of this classification system is as follows: a child

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![Figure 1](image-url)  
*Figure 1* Current understanding of interactions between the components of ICIDH-2. This algorithm is the current multi-perspective approach to the classification of functioning and disability. Definitions of the components are as follows: Body functions are the physiological functions of body systems (including psychological functions). Body structures are anatomical parts of the body such as organs, limbs, and their components. Impairments are problems in body function or structure such as a significant deviation or loss. Activity is the execution of a task or action by an individual. Participation is involvement in a life situation. Activity limitations are difficulties an individual may have in executing activities. Participation restrictions are problems an individual may experience in involvement in life situations. Environmental factors make up the physical, social, and attitudinal environment in which people live and conduct their lives. *Source:* From Ref. 7.
sustained a severe traumatic brain injury, with resultant hemiplegia and memory deficits. Her impairments of body function would include loss of muscle power on one side of her body and memory impairments. This could be associated with activity limitations in walking, dressing, washing herself, caring for herself, and learning in school, and could be associated with limitations in participation in school, recreation and leisure, and community and social life. Use of an AFO and therapy designed to improve the strength and control of the hemiplegic side could result in improved walking abilities (activity) and participation in recreational activities. Also, acquiring memory compensation strategies might allow her to perform her schoolwork (activity) better, and to participate in school and recreational activities more, even though the level of memory impairment itself may not have changed. Likewise, one can imagine changing an impairment to a small degree, without any clinically significant improvement in the level of activity or participation. From these examples, one can appreciate that clinically, it is important to keep the “whole” picture in mind, putting into perspective the goals of therapeutic interventions. It is important for everyone in the rehabilitation field to always ask themselves—what difference will my interventions or therapy have in this child’s ability to perform activities and to participate in daily life at home, school and in the community? In

Table 1  An Overview of ICIDH-2.

<table>
<thead>
<tr>
<th>Domains</th>
<th>Part 1: Functioning and disability</th>
<th>Part 2: Contextual factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body functions and structures</td>
<td>Life areas (tasks, actions)</td>
<td>Environmental factors</td>
</tr>
<tr>
<td>Activities and participation</td>
<td>External influences on functioning and disability</td>
<td></td>
</tr>
<tr>
<td>1. Body functions</td>
<td></td>
<td>Personal factors</td>
</tr>
<tr>
<td>2. Body structures</td>
<td></td>
<td>Internal influences on functioning and disability</td>
</tr>
<tr>
<td>Positive aspect</td>
<td>Functional and structural integrity</td>
<td>Facilitators</td>
</tr>
<tr>
<td>Functioning</td>
<td></td>
<td>Not applicable</td>
</tr>
<tr>
<td>Negative aspect</td>
<td>Impairment</td>
<td>Activity limitation</td>
</tr>
<tr>
<td>Disability</td>
<td>Participation restriction</td>
<td>Barriers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hindrances</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

Source: From Ref. 7.
research, one can also understand the importance of looking at multiple dimensions when assessing or evaluating the effect of an intervention, both to show clinical significance and important effects in other dimensions.

**REHABILITATION AS A MEMBER OF THE ACUTE TRAUMA TEAM**

The rehabilitation team should be an integral part of the acute trauma team throughout the entire hospitalization. This ensures that appropriate rehabilitation treatments are implemented at appropriate times, secondary impairments are prevented, and discharge planning starts at the beginning of the hospitalization, instead of at the end as an afterthought. This need for early rehabilitation involvement is well accepted. It is supported by evidence that shows that early referral to rehabilitation with timely discharge from the acute care setting results in shorter and less costly acute and rehabilitation lengths of stay (10).

Recognizing the benefits of early rehabilitation, the American Academy of Pediatrics (Committee on Pediatric Emergency Medicine, 1995) and the Emergency Medical Services for Children [“Coordinating Transitional Care for Children with Special Health Care Needs” (1996)] have called for the inclusion of coordinated rehabilitation and discharge planning to start at the beginning of trauma care.

In every pediatric trauma center, protocols should be developed that ensure the early involvement of the rehabilitation team in the care of the seriously injured child. In our institution, pediatric rehabilitation medicine is consulted within 24–48 hours of admission for every child with a new onset severe traumatic brain injury or spinal cord injury. Therapies are then progressively added, as dictated by the patient’s medical stability and needs. Many factors, including changes in clinical practice and pressure from third-party payers, obviously influenced this change. Yet, common sense says that early rehabilitation involvement that helps develop a timely discharge plan must facilitate earlier discharge from the acute hospital.

**MODEL SYSTEMS**

Much has been written about model rehabilitation systems (11). Ideally, they are adjacent to the acute medical center (enabling close cooperation between the acute trauma team and the rehabilitation team), encourage continuity of rehabilitation care from early in the acute care phase through rehabilitation, have a full complement of rehabilitation professionals and services available to meet the needs of the patients, have specialized expertise for specialized problems (such as cognitive and behavioral rehabilitation for children with brain injury), are able to accommodate early transfers to the rehabilitation setting where certain problems are better managed by this experienced interdisciplinary team (for example, the patient who is agitated post-traumatic brain injury), have resources to facilitate and optimize community/school reintegration, and have a continuum of services that flexibly provide services in a range of environments to best meet the individual needs of the child and their family (Table 2).

One of the advantages of an acute rehabilitation program is the availability of an interdisciplinary team that is able to address multiple areas of functional impairment in a coordinated fashion. This “team” is made up of the child and family, and various professionals, including rehabilitation medicine, nursing, nutrition, psychology, speech
and language pathology, audiology, education, occupational therapy, physical therapy, recreational therapy/child life, and social work. It is “interdisciplinary” because it works as a coordinated group made up of individuals of complementary but often overlapping expertise, who jointly establish appropriate goals and direction for the rehabilitation process, and work together in a coordinated fashion toward those goals, prioritizing when necessary. It also allows for the generalization of goals throughout other therapy sessions and the entire 24-hour period of time. With the interdisciplinary process, the whole should certainly be greater than the sum of the parts. This is contrasted to a multidisciplinary team, where multiple professionals would be interfacing with the patient without necessarily coordinating their goals and plans, such as might be seen in a home health model. Obviously, for children with multiple needs and impairments and their families, all who are involved in a strange, foreign and intimidating health care system, a coordinated, unified approach is essential for proper rehabilitation.

The physician who works with and leads this interdisciplinary rehabilitation team must have special expertise in both the medical and the functional problems that arise after traumatic injuries, and the full spectrum of therapies and medical care that is needed to restore function. Physiatrists, physicians who have specialized in Physical Medicine and Rehabilitation (PM&R), have been trained in this wide range of medical and functional problems associated with injuries and diseases. Their training includes at least four additional years of postdoctoral residency training (one year general internship, three years of specialty training). In addition to this training, there are fellowships available in areas such as musculoskeletal rehabilitation, pediatrics, traumatic brain injury, spinal cord injury, and sports medicine. Subspecialty board certification was approved in 1999 for Pediatric Rehabilitation Medicine (PRM).

Certification for this subspecialty will require completion of either two years of an approved fellowship in PRM after PM&R residency, or a one-year fellowship in PRM after a five-year combined PM&R/pediatrics residency. During the acute posttraumatic period, this specialty training allows the consulting rehabilitation physician to serve as the bridge between the trauma and rehabilitation teams, assuring that appropriate rehabilitation care is instituted in a timely, coordinated fashion during acute care; that medical problems which are common in the rehabilitation setting and possibly uncommon in the acute care setting are appropriately addressed or prevented during the acute period; and that discharge planning to the appropriate rehabilitation setting is implemented at the beginning of the stay.

Another characteristic of a model system is the provision of specialized expertise for specialized problems. Children who need rehabilitation are best served by specialized pediatric programs. These specialized programs are able to ensure the provision of

Table 2  Characteristics of a Model Pediatric Rehabilitation System

| Family-centered approach |
| Re却ation as part of the acute trauma team |
| Continuity of rehabilitative care |
| Interdisciplinary team |
| Specialized programs and expertise |
| Continuum of services |
| Collaboration with the educational system |
essential components of pediatric rehabilitation, including expertise in the areas of growth and development, and the rehabilitation of children; developmentally appropriate treatments and environment; a family centered approach; and attention to the education of the child as well as the reintegration of that child into the educational system. The CARF, the Rehabilitation Accreditation Commission, has long recognized the importance of specialty programs. It has developed accreditation guidelines for specialty rehabilitation programs, including pediatric rehabilitation in general, and subspecialty programs such as “pediatric brain injury” in particular (12). These clinically relevant guidelines assure that important standards of care are implemented. Of course, in order to foster specialty expertise, a program must provide care for a critical mass of patients. There are and will be regions of low population density without such specialty or subspecialty programs because of limited need and resources. However, attempts to provide care that meets the intent of these guidelines should be a goal of all pediatric trauma systems.

A family-centered approach is essential (13). This recognizes that the central, most important and unchanging parts of the rehabilitation, medical, and educational teams are the patients and their families. Depending on the age, condition and stage of recovery, the composition of these teams will change, but it will be the patient and family who always remain. It is important to foster self-advocacy in the child and family. They will be the most effective case managers, and of course have the best interests of the child at heart. In the rehabilitation process, time should be spent on educating and empowering the child and family in the issues of disability rights (14). Especially important in the school-age child are the laws governing the educational system. Much attention should be given to educate and train the family in these laws that govern the educational system, enabling the family to assume the role of advocate within the school system.

Just as a continuum of services is needed within a trauma center, from pre-hospital emergency care through rehabilitation, a continuum of services is also expected within the rehabilitation system. The rehabilitation continuum should provide different levels of care in different environments. These different levels of care may include acute and subacute rehabilitation, outpatient rehabilitation, community reintegration, and vocational and educational rehabilitation. Also, there may be multiple environments in which each of the above might be offered. For example, acute rehabilitation might be done by a coordinated, interdisciplinary team delivering a high intensity of therapy, not only in the hospital, but also in the home and community or a day hospital environment (15). Depending on the availability of such alternative programs, these different options allow the patient and family to tailor their rehabilitation program to meet their individual needs and resources.

Availability of such alternative programs may be limited due to local resources and insufficient population density to support them. However, if available, there are both economic and clinical advantages to rehabilitation programs that occur in the community in a more natural environment instead of the hospital or outpatient clinic (16).

Economically, it is obvious that inpatient care is the most costly way to deliver care (17). This is primarily related to the expense of 24-hour nursing and medical care. A system that delivered care in the community, with family and friends taking primary responsibility for the 24-hour supervision and care, would obviously be less expensive.

Clinically, there are advantages and disadvantages to inpatient versus community rehabilitation programs. The inpatient unit provides access to intensive medical and nursing care, 24-hour supervision for safety, ready access to equipment and technology, and
facilitates the interdisciplinary process. However, if a patient is medically and behaviorally stable, and does not require an awake caregiver 24 hours per day for safety, there would be many clinical advantages to receiving rehabilitation in the community. The most important advantage is that the rehabilitation occurs in the actual environment in which the person needs to learn to function, instead of an artificial, rigid institutional environment, and the tasks are the goals themselves. Consequently the evaluation becomes more reliable, the goals become more relevant, meaningful, and intrinsically more motivating, and the treatment is more efficacious. Learning to walk may mean going to the kitchen to eat a cookie that Mom is baking, instead of an exercise in a physical therapy gym. While the mechanics of providing well coordinated interdisciplinary or transdisciplinary care outside the hospital are challenging, effective models exist (15,18).

Our rehabilitation program has developed an expanded rehabilitation continuum of care. Previously, our options for the rehabilitation of children included acute inpatient rehabilitation, outpatient rehabilitation, and home health. Our rehabilitation continuum of care continues to provide the previous options, but additionally has two alternative sites for acute rehabilitation: a day hospital program (called Specialized Transition Program or STP) and our Home and Community (H&C) program. The STP is licensed both as a pediatric community brain injury rehabilitation program and a state certified educational program, and is located in our special education school. It provides rehabilitation, diagnostic-prescriptive teaching, and cognitive rehabilitation in a classroom. Most of the therapy is done in this functional classroom setting (e.g., language skills, handwriting, eating, keyboard access and computer use, and mobility skills), with “pull out” therapy to a rehabilitation gymnasium or an individual treatment room as necessary. Since it is in a school setting, we can also access school bus transportation and use of a library, media center, cafeteria, etc., all of which helps to normalize and improve the rehabilitation process, making it more relevant. By discharge, an educational plan that has been proven to work in a classroom setting can be effectively transferred to the local school.

The H&C program provides acute rehabilitation in the home and community, but this is not a home health program. The H&C rehabilitation usually starts within the home, establishing routines for activities of daily living and effective, safe means of mobility. Later it can branch out into the community for vital activities such as use of public transportation, shopping skills in the community, reintegration into school, or establishment of a workout at the local gymnasium that will meet many of the physical therapy goals. Both of these alternative site programs provide acute rehabilitation by an interdisciplinary team at a therapeutic intensity equivalent to that provided in the acute inpatient rehabilitation unit (Fig. 2).

Obviously, these alternative site programs are not for everyone. The family’s ability to utilize them depends on their geographical proximity to the programs and whether their resources and other responsibilities are compatible with the level of care and supervision that they will be required to provide upon discharge home from the hospital. However, when they can be used, there are clear benefits. In comparing 27 children who received services in one of the “alternative site” programs (with or without an inpatient rehabilitation stay) to 30 children who received inpatient rehabilitation only, the “alternative site” group received coordinated acute rehabilitation for a significantly longer period of time (78.1 vs. 43.0 days, \( p < 0.05 \)), for the same or less cost ($37,544 vs. $40,818, \( p > 0.05 \)), with improved outcome [as based on the Functional Independence Measure for Children (WeeFIM), \(<7\) years, 111 versus 74, \( p < 0.05 \)]. There were no statistically significant differences between the groups for
age, admission WeeFIM, or inpatient rehabilitation length of stay, although the latter was shortened in the “alternative site” subjects (34.5 vs. 43.0 days) (19). In addition to the above obvious advantages, the continued involvement of a team during the reintegration of the child into the home and school provides continued education for and support to the family by the rehab team, as the family assumes the day-to-day responsibility for the care of their child who now has new special needs. Also, we strongly believe that the rehabilitation is more beneficial when done in natural, functional environments, and for the child, this means home and school—exactly the environments that are used for their rehabilitation in this continuum.

The last major step of the initial rehabilitation process is community reintegration, and for children the focus of this is the return to his/her own school. This transition between the medical/rehabilitation and educational systems is arguably the most critical phase in the acute rehabilitation of children, especially for those with TBI. If this transition is not accomplished well, much of the previous effort will have been for naught (20). It is of great benefit if the school has a regional resource to assist with the process of reintegrating a student back into the school after a traumatic injury. However, since the number of students being reintegrated into any one school at any given time is low, it is not reasonable to expect that each school and teacher be an expert in this particular child’s needs. Consequently, it becomes the responsibility of the medical team to assure that the child is appropriately identified.

Figure 2  Flow diagram for optimal provision of care within a pediatric trauma system. This flow diagram illustrates the interactive nature of the continuum of care for a child with injuries. It highlights the need for coordination of care and flow of information between the medical, rehabilitation, and educational systems, and within the rehabilitation, continuum of care.
according to special education laws, and that appropriate knowledge and understanding are passed on to the educators (21). Failure to do this can lead to long-term inappropriate or inadequate utilization of resources. Unfortunately, we know that identification is a problem. Based on statistics in the Annual Reports to Congress on the Implementation of the Individuals with Disabilities Education Act, TBI—the most common cause of pediatric morbidity and mortality—is one of the least used classifications in the special education system. To facilitate the transfer from the medical to the educational system of specific knowledge and understanding of the child’s condition, the rehabilitation team and its liaison must understand the educational system well. This includes knowledge of the laws that govern it, as well as its mission and purpose, strengths, and limitations. Ideally, this liaison would be someone who has worked and “paid his/her dues” within each system, such as an educator. This results in more credibility, respect, and trust between the systems.

There are five major legislative principles concerning the federal right to education (Table 3). They are important for those in the medical/rehabilitation system to understand, because of their applicability to services for students after traumatic injuries.

1. Zero reject—Access to free public education must be provided for all children and youth regardless of degree of exceptionality or fiscal impact on the school system,
2. Integration—Education should be provided in the most integrated, normal setting possible that is consistent with the learning needs of the student,
3. Appropriateness—Education must be based on an individualized program that is appropriate to the needs of the child,
4. Due process—Opportunity must be made available for a notice or a hearing appeal with respect to placement or other changes in educational programs,
5. State of the art—The meaning and context of “appropriate education” are defined by the state of the art in both teacher training and effective methods of training children (22).

Knowledge of these rights helps those in the medical system to provide appropriate guidance and advice to families, to make certain that their children are receiving appropriate services. This is especially important when one realizes that it is the educational system that will provide much of the chronic rehabilitation that a child requires, especially in regard to the “cognitive remediation,” educational and behavioral programming that is required after traumatic brain injuries (23).

### CRITERIA FOR REHABILITATION SERVICES

The main criterion for referral for continuing rehabilitation services will be the presence of impairments that require rehabilitation treatment and management. The
number, type, and severity of these impairments, as well as the medical and behavioral stability of the patient, will determine the recommendations for the intensity of therapy and the therapeutic setting. As a general rule, acute, intense, and interdisciplinary rehabilitation is justifiable if the patient has multiple impairments and will benefit from a minimum of three hours of therapy per day. If there are continuing medical and behavioral indications for 24-hour care and supervision in a hospital setting, or if the appropriate intensity of therapy cannot be provided outside the hospital, then this acute rehabilitation must be done as an inpatient in the rehabilitation hospital. If intense therapy is indicated, but the patient does not require 24-hour care and supervision, an alternate setting for intense, acute rehabilitation, such as a day hospital model might be appropriate (if available). If the intensity of services needed is less than that described above, then a setting such as an outpatient clinic may be adequate.

It is the obligation of the trauma system in the acute care hospital to identify functional impairments and the need for rehabilitation, and make certain that appropriate rehabilitation services are arranged. The obvious team members that can help with this decision are the rehabilitation professionals who are part of the acute trauma service. Failure to identify impairments will result in failure to recommend appropriate services. However, even when they are identified, data from acute care hospitals participating in the National Pediatric Trauma Registry appear to support the apparent under-utilization of rehabilitation services. These data show that injured children with four or more functional limitations identified at discharge are often sent home rather than to inpatient rehabilitation programs (24).

If functional impairments that require rehabilitation services are not initially identified, follow-up must be done with a high index of suspicion for potential long-term delayed consequences from these injuries, and evaluation and treatment instituted when indicated.

REHABILITATION

Rehabilitation is the process by which an individual with impairments and disabilities is assisted in regaining maximal independence and function. It should include expert medical and nursing care, prevention of secondary deterioration, maximization of natural recovery, facilitation of incremental functional gains, learning of compensatory techniques, and provision of an optimal environment with appropriate environmental modifications and adaptive equipment (1).

The process is begun by the identification of the impairments, resulting in evaluations that define impairments (body functions), activities, and participation. A plan is then made with the patient, family, and other team members to address these issues. Based on these evaluations, short-term goals (e.g., improved strength in muscles of wrist and elbow extension) and long-term goals (e.g., ability to participate in leisure activities, specifically playing basketball; using a wheelchair) are set. A plan of therapy (based on the above principles) is developed to address these goals. During the treatment phase, it is constantly reassessed and modified according to the patient’s progress.

One of the major differences in the rehabilitation of children as compared to adults is the effect of growth and development. The premorbid developmental level must be carefully defined, so that goals and expectations are appropriate. Age must be factored in to the prognostic equation. The quantitative measures used for the evaluation, the content and style of the therapeutic interaction, and the treatment
environment must all be developmentally appropriate. Examples: one would use quantifiable age-normed evaluation measures; the mode of engaging the child’s cooperation for exercises might be through playing highly structured games (i.e., limited choice making, to give child/adolescent a sense of control; shoulder strengthening accomplished by reaching for objects needed to play a game); the process of facilitating adjustment to disability and loss in an adolescent who has insight into their situation will include individual and family counseling, and potentially contracts to facilitate cooperation in the rehab process, while the process for a young child may be primarily through family education and counseling; and all the above done in a developmentally/age-appropriate environment (i.e., appropriate furniture, wall decorations, toys, games, computers, and music).

There are many well-validated, age-normed quantitative rehabilitation measures applicable to areas of general or specific function. Measures of global level of functioning and burden of care, such as the WeeFIM are frequently used as quantitative tools in pediatric rehabilitation facilities to describe patient progress and for program evaluation purposes (25). The WeeFIM is an 18-item performance measurement system that documents functional mobility, self-care, and cognitive abilities in children with special health care needs and was designed to evaluate change in functional status over time. There are also measures to evaluate and monitor status pertaining to specific abilities, such as general cognition (intelligence tests), specific neuropsychological function (e.g., memory, attention, and executive function), general language abilities, specific language abilities (e.g., naming, syntax, and semantics), speech, fine motor abilities, adaptive behavior, activities of daily living (ADLs: e.g., feeding, grooming, and bathing), postural and gross motor control, mobility, behavior, and social functioning (26,27).

Like development, physical growth also needs to be followed closely and managed appropriately after traumatic injuries. General growth can be affected by nutritional and endocrine problems. Bone growth can be altered and orthopedic deformities develop, related directly to orthopedic injuries or to the secondary effects of the neurological injuries.

The vast majority of children who require intense acute post-traumatic rehabilitation will be those who sustained TBI with or without associated injuries. Those with spinal cord injuries (SCI) represent a much smaller but important group. Included below are some important issues related to the rehabilitation of these disorders in children. For detailed rehabilitation guidelines, there are many excellent references (28–30).

REHABILITATION OF TRAUMATIC BRAIN INJURY

Cognitive and behavioral impairments are the major long-term challenges for survivors of TBI and their families. Children with mild TBI [Glasgow Coma Score (GCS) 13–15] usually recover well, without significant deficits. However, children with moderate (GCS 9–12) and severe TBI (GCS 3–8, coma duration ≥6 hr, or duration of post-traumatic amnesia one to seven days or more) usually have cognitive and behavioral impairments (31–34). The more severely injured may have motor impairments as well (35). Areas of function requiring rehabilitation after TBI may include some or all of those listed in Table 4.

Some of the pitfalls of TBI management that need to be appreciated by all who provide care for this population include the misclassification of severity of injury, the
lack of appreciation of the neuropsychological deficits and their cognitive and behavioral implications, and the lack of anticipation of delayed consequences.

**Misclassification of Severity of Injury**

TBI rehabilitation plan will depend on the severity of injury and the impairments identified. If a moderate or severe injury is misclassified as a mild injury, appropriate follow-up for cognitive and behavioral impairments will not be recommended, and secondary problems (especially academic and behavioral) may ensue. To prevent this misclassification, mental status changes must be carefully evaluated for the presence of post-traumatic amnesia (PTA). PTA is a post-injury period of confusion, disorientation and often agitation, during which the patient has no continuous memory (inability to lay down new memories, also referred to as anterograde amnesia). Long-term memory may be intact during this period. The Children’s Orientation and Amnesia Test (COAT) is a mental status examination used to define the termination of PTA (36). It is quickly and easily administered at the bedside, has norms for children 3–15 years of age, and correlates well with long-term cognitive and memory outcome. Administration of the COAT prior to discharge from the emergency department or hospital could decrease the misclassification of severity of injury and the resultant under-referral for appropriate services.

Appreciation of the neuropsychological deficits: The fact that measures of general intelligence usually return to the normal range after TBI can be misleading and confusing, especially to families and educators. In spite of this normalization of measures of

<table>
<thead>
<tr>
<th>Functional area</th>
<th>Rehabilitation professionals</th>
<th>TBI</th>
<th>SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognition</td>
<td>Psychology</td>
<td>Yes</td>
<td>Maybe (associated TBI?)</td>
</tr>
<tr>
<td>Behavior</td>
<td>Psychology, psychiatry</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Speech</td>
<td>Speech and language pathology (SLP)</td>
<td>Yes</td>
<td>Yes (tetraplegia and high thoracic SCI)</td>
</tr>
<tr>
<td>Language</td>
<td>SLP</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Educational needs and school reintegration</td>
<td>Education, psychology</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Swallowing</td>
<td>SLP, occupational therapy (OT)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Nutrition</td>
<td>Nutrition</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fine motor skills activities of daily living (ADLs)</td>
<td>OT</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gross motor skills, postural skills, mobility skills</td>
<td>Physical therapy (PT)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Continence</td>
<td>Rehabilitation nursing</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Adjustment to impairments, disability, and hospitalization</td>
<td>Psychology, social work, child life, recreation therapy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Recreational needs</td>
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<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Family adaptation</td>
<td>Social work, psychology</td>
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<td>Yes</td>
</tr>
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*aADL deficits related to cognitive and motor impairments.

*bADL deficits related to motor impairments.
general intelligence, cognition does not return to normal, due to the presence of specific neuropsychological deficits. The most important of these deficits are in memory, attention, and executive function (32,37–39). It is important to understand executive function (EF), since it is common in this population (related to the frontal lobe injuries). EF is the capacity for self-direction and self-control/regulation (40,41). The EF allows mental flexibility—the ability to initiate and sustain thoughts and plans appropriately, inhibit unwanted thoughts and actions, and yet mentally “shift gears” when appropriate. Memory, attention, and EF are critical to new learning and performance in daily life (be it school, work, or socialization) and impairments result in significant problems.

It is extremely important that these neuropsychological deficits are appreciated and evaluated appropriately. Evaluations must go beyond traditional intelligence tests, and must measure processes such as memory, attention, and executive function. Appropriate rehabilitation strategies must then be developed and transferred to the home, school, and community. If this is not done, secondary behavioral problems often result.

Delayed consequences: Specific neuropsychological abilities, such as EF, change and become more complex with development (42,37). In children after TBI, a failure or arrest in the expected development of EF is not unusual, given that frontal lobe injuries are common in TBI. Clinically, this can appear as if “new” deficits and problems are emerging. These “new” problems often manifest themselves during times of increased expectations for self-direction and self-control/regulation. This often occurs during transition from one school level to another, such as from a highly structured elementary classroom, to a less structured middle school. Anticipatory guidance is critical during these transitions.

Concerning the time course of recovery after TBI, the most rapid recovery will occur at the beginning, and the more rapid the recovery, the more complete it will be. Most of the recovery will be complete one year after injury, but small changes (which may have important functional implications) may occur up to two to five years post-injury. Obviously, the intense acute rehabilitation treatments will only occur during the beginning of this period, followed by a transition to outpatient therapy as needed. The long-term interventions will occur primarily within the school system. Consequently, it is essential to facilitate communication between the medical and the educational systems.

REHABILITATION OF SPINAL CORD INJURY

The goals of rehabilitation after SCI are to optimize health and independence. SCI is a multi-systemic disorder, affecting essentially all bodily systems—neurological (including the autonomic nervous system), skin, pulmonary, cardiovascular, gastrointestinal, genitourinary, and musculoskeletal. In order to optimize health and independence, the person with SCI must learn to manage a wide array of complex medical and physical issues.

In SCI rehabilitation, it is important to understand that the goals for physical independence can be predicted from the neurological level. Charts predicting the functional level and the appropriate adaptive equipment required are readily available (29). For example, someone with a C5 level can expect to be: independent, using assistive devices, for feeding and dressing upper and lower extremities; require assistance for bathing, bowel program, rolling in bed, transfers (level); may be independent, although it’s not expected, for bladder management, manual wheelchair use,
and driving a car; and independent for power wheelchair use. These guidelines provide a “road map” for the patient, family and rehabilitation professional, helping define achievable, appropriate goals.

Many aspects of the rehabilitation plan for children with SCI differ from that of adults, because of the influence of development on the mobility/orthotic management and learning of self care, the effects of growth on the orthopedic complications and management, and the need for school reintegration instead of vocational rehabilitation.

The timing for many rehabilitation goals will depend on the developmental level of the child. Learning of the complex medical care is done in a stepwise, progressive manner, when the child has acquired the needed cognitive and physical abilities, and is psychologically ready. Young children with SCI will obviously rely initially on their families to provide much of their care. When developmentally appropriate, they should learn not only how to do as much of their own care as possible, but also how to direct caregivers to assist them. For example: five-year-old children are usually independent in the activities of daily living, and should begin to learn self-catheterization for management of a neurogenic bladder.

Mobility and orthotic management are also affected by the growth and development of the child. When considering mobility issues, children as young as two years of age can learn to safely use a power wheelchair (43). The orthotic management and goals will be different depending on the age and size of the child. Prepubertal children with high neurological levels are often offered orthotics that enable standing or walking, because of the psychological benefits to the developing child, as well as potential physical benefits. This is done with the understanding that at puberty, the plan will be reassessed. At that time, the child will probably switch to exclusive use of a wheelchair, since increased body size makes assuming an upright position and attempts at ambulation physically difficult, extremely energy inefficient, and often unsafe.

Because of growth, there is a difference in the orthopedic complications in children with SCI, as compared to adults. The spine and hips must be followed closely and managed appropriately. Ninety percent of children who acquire a SCI before puberty will develop scoliosis, and two-thirds will require surgical management (44). Thoracolumbosacral orthosis (TLSO) use is recommended for trunk support and postural alignment in those with cervical and thoracic levels, and may be used for postural alignment in those with T12-L1 levels (usually not needed below that level) (29). A similar percentage develop hip subluxation or dislocation (45). Also, range of motion must be followed closely, especially during growth spurts, to ascertain that contractures are prevented.

For school reintegration, the major issues to address will be appropriate support for nursing/medical issues (e.g., bowel and bladder, pulmonary, skin, autonomic dysreflexia); physical access within the school, including classrooms and bathrooms; modified physical education activities; appropriate use of assistive devices for school work/ADLs (e.g., adapted computer, universal cuff to hold utensils or pens); and elimination of negative attitudinal barriers through staff and peer education. Also, cognitive issues may need to be addressed, especially if there was an associated TBI (seen in nearly one-quarter of persons with cervical SCI) (46).

**SUMMARY**

Rehabilitation must be an integral part of any trauma system. For best utilization of resources and delivery of state of the art care, rehabilitation expertise and care must
start at the beginning of the hospitalization and be integrated throughout the delivery of care. It is the responsibility of the trauma system to make certain that appropriate rehabilitation and follow-up is arranged and provided. And, just like the rest of the pediatric trauma system, the rehabilitation system needs to have continuum of services with special expertise in the needs and care of children.

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Long-Term Outcomes in Injured Children

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PEDIATRIC TRAUMA: SCOPE OF THE PROBLEM

As the leading cause of death and disability in children, pediatric trauma accounts for some 11 million hospitalizations, 100,000 permanent disabilities, and 15,000 childhood deaths every year in the United States. Regrettably, the incidence of pediatric trauma in the United States is among the highest in the world, reflecting both the dangers of our highly mechanized society as well as the reality of urban violence, including that related to firearms (1). Furthermore, despite an overall decrease in rates of violent crime, rates of significant pediatric trauma have not experienced the same decline, and fatal injury resulting from violence may actually be increasing (2,3). While children more often survive significant polytrauma than adults, long-term morbidity is all too common. Four children are left with permanent disability for every trauma-related mortality (1). This statistic highlights the need to assess long-term functional status and quality of life in this population.

The direct costs alone of childhood injury exceed eight billion dollars per year (1). While it is impossible to accurately quantify the indirect costs to families and to society in general, it is clear that they are staggering. Given this, the area of pediatric trauma represents perhaps the greatest public health challenge in pediatric health care. Efforts must be focused to better understand the ways in which we can both decrease the occurrence of pediatric injury and optimize the outcomes of those injured.

THE CHALLENGE OF ASSESSING PEDIATRIC OUTCOMES

While we have indeed made great strides in our ability to care for injured children, we have made much less progress in our ability to assess the broadly defined long-term outcomes of these injuries. Of the articles reviewed for this chapter, none truly met Class-I criteria with regard to the degree of methodological rigor supporting the conclusions; retrospective reviews (Class III) predominated.
Admittedly, clinical research in the setting of pediatric trauma, including the assessment of pediatric health status and quality of life, has numerous intrinsic difficulties. First, any functional assessment in children must be performed in a developmental context. Key aspects of quality of life such as physical, emotional, and social function rapidly evolve as the child ages. Measures of health status for this population must allow for comparison to age-adjusted normative values. Second, many types of significant pediatric trauma are relatively rare. All but the busiest of pediatric trauma centers see only an occasional spine or pelvic fracture. Finally, given issues of growth and healing, long periods of follow-up are needed to document the “final” outcomes of affected children.

Despite these difficulties, rigorous patient-oriented clinical research, focusing on issues germane to the injured child, is a prerequisite for the timely evolution of clinical practice in this area. Fortunately, new clinical research methodologies present exciting opportunities to explore issues related to these outcomes.

**VOLUME OUTCOME RELATIONSHIPS**

Analysis of various administrative datasets including the National Pediatric Trauma Registry (NPTR), has provided an opportunity to examine issues of disease incidence, cost, and variability in practice patterns (4). Recently, these data have been also used in an attempt to examine the relationship between the clinical volume and patient outcomes. Although they have a number of limitations, numerous studies have documented a relationship between higher patient volumes for specific conditions and better outcomes for various cohorts of adult and pediatric patients. For example, Solano et al. have shown that there is a significant inverse relationship between the volume of surgical repair of congenital heart defects at a given hospital and in-hospital mortality (5,6). Patoka has shown that there is a significant inverse relationship between risk-adjusted mortality and the volume of pediatric ICU admissions (7).

In many areas of the country, trauma care has been regionalized, with specialized centers for pediatric trauma. In fact, the American College of Surgeons recommends minimum patient volumes for trauma centers and surgeons. Using data from the Pennsylvania trauma registry, Konvolinka concluded that mortality might increase when surgeons treat fewer than 35 seriously injured patients per year (8). Several recent studies have examined the relationship between dedicated pediatric regional trauma centers and patient outcomes. In a comparison of survival rates of pediatric trauma, Cooper et al. found that children treated within a specialized pediatric trauma system had higher severity-adjusted survival rates (9). Doolin et al. found a strong relationship between in-house specialized personnel and outcome (10). Specifically, the presence of an in-house pediatric surgeon was associated with a lower rate of mortality among severely injured children. Pollack noted lower severity-adjusted mortality for children treated at tertiary care facilities (11). Moreover, Nakayama et al. showed that mortality was higher in rural non-pediatric centers (6.2%) in comparison with pediatric centers (4.1%) (12). Finally, Patoka has shown that children treated at regional pediatric trauma centers have better functional outcomes at discharge in comparison with children treated at adult centers and non-specialized centers for trauma (7). Collectively, these studies support the relationship between specialization, patient volumes, and outcomes in pediatric trauma.

While it may be intuitive that we do best what we do most often, forces within our beleaguered health care system sometimes discourage specialization. However,
as will be obvious by the following review, we have much room to improve the outcomes of children who sustain significant trauma.

FUNCTIONAL STATUS AND QUALITY-OF-LIFE ASSESSMENT IN A PEDIATRIC POPULATION

While children are more likely to survive traumatic injury, many endure significant problems in physical function and overall health. Aitken et al. recently reviewed the experience of the NPTR and found that, even when excluding head injuries, 14.5% children captured in this six-year study of NPTR had persistent disabilities (1). The ability to quantify deficits in functional status and health-related quality of life is germane to the assessment of injured children.

Fortunately, measures to assess functional status and quality of life in children have recently become widely available. The Child Health Questionnaire (CHQ) is perhaps the best-validated measure for the assessment of general health status in children (13). Akin to the Short Form-36 (SF-36), which has been widely used in the adult literature, the CHQ consists of a short questionnaire, which is scorable and generates multiple domains that span the spectrum of physical, psychosocial, and social health in injured children (14). Age-adjusted normative values are available and play an important role for the comparison of health status in children after trauma, for which pre-morbid scores are not available. The Pediatric Orthopedic Society of North America has developed another health status questionnaire, which also exhibits good validity and reliability across a range of pediatric musculoskeletal conditions (8).

A large prospective epidemiological study of outcome after adult trauma utilized a similar adult quality of life measure, the Quality of Well-Being scale, and documented profound perturbations in quality of life at 12–18 months after major injury. The authors concluded that the magnitude of dysfunction has likely been underestimated by more traditional measures of patient outcome and that quality of life measures have an important role in the long-term assessment of patients who have sustained traumatic injury (15). Hopefully, clinical research efforts will incorporate these newly available, patient-based measures of pediatric health status as a means to provide meaningful data to guide evidence-based decision making in the area of pediatric trauma.

PEDiatric POLYTRAUMA: OUTCOMES

Despite the difficulties of performing rigorous, controlled clinical research in children who sustain trauma, the literature does document a marked improvement in mortality rates of injured children over time. The mortality rate attributable to accidental deaths in children has fallen by 50% between 1970 and 1990 (16). This is a result of both successful prevention strategies and improved medical care.

Much less has been documented concerning the long-term outcomes of injured children. In a review of the literature in this area published in 1997, Van der Sluis et al. identified only seven studies that focused on the “long term” (the maximum follow up in this group was two to four years) outcome of injured children and concluded that there was a “dearth of outcome studies on severely injured children” (17). The authors went on to collect information regarding functional status (as measured
by the Functional Independence Measure, the FIM) and quality of life (as measured by the SF-36) at an average of nine years after injury on a cohort of children who sustained significant polytrauma. Despite the fact that 42% of these patients had some degree of resultant cognitive impairments, SF-36 scores were generally satisfactory. On the other hand, Wesson et al. found that pediatric trauma had profound effects on the physical and psychological health of children and their families at 12-month follow-up (18). Among children who experienced major trauma, 71% had persistent physical limitations, 41% had behavioral disturbances and many children exhibited a decrease in academic performance. Another study by the same author showed that 88% of children surviving severe injuries had functional limitations at discharge with 54% still having limitations at the six-month follow-up (19). Valadka et al. recently published the results of a retrospective study, which assessed health status of children via a telephone interview at a minimum of one year after significant trauma (20). At a minimum follow-up of six years after injury, half of injured children were found to have long-term sequelae. Thus, the available literature suggests that a large percentage of children who sustain significant trauma have persistent functional limitations and disability, despite modern day improvements in patient care.

OUTCOMES OF TRAUMATIC BRAIN INJURY (TBI)

TBI has, both by incidence and severity, the greatest influence on long-term outcome of any childhood injury. TBI is the leading cause of injury mortality and long-term injury disability in children. In addition, many more of the approximately 200/100,000 children who are admitted to a hospital annually following a brain injury go on to have significant, life-long sequelae from their injury (21). These children typically return to their communities and schools, where primary care physicians, educators, and families often poorly understand their problems. Many children make significant cognitive improvements, only to be plagued by ongoing behavioral, social, and psychological problems. Current work in this area revolves around the recognition of these long-term deficits and the development of techniques to maximize cognitive function and social reintegration.

Expected functional outcome following TBI varies with the initial severity of the brain injury. The Glasgow Coma Scale (GCS) is most often utilized to determine the degree of acute neurological dysfunction following traumatic brain. The GCS may be used to divide children with brain injuries into three groups: mild (GCS 13–15), moderate (GCS 8–12), and severe (GCS <8). Ultimate functional outcome has been demonstrated to correlate with the GCS on presentation in a study of over 500 adults and children in Finland (22). In a study of 81 consecutive children with brain injuries, O’Flaherty found that fine motor skills, self-care, and academic performance correlated directly with the severity of initial injury, even at two years post-injury (23). In a case–control series of 76 children with mild, moderate, or severe brain injuries, Yorkston found a significant correlation between the severity of brain injury and a range of cognitive measures (24). Jaffe and co-workers found a relationship between the severity of brain injury and residual impairment at one year after injury in a case–control series of 94 brain-injured children (25).

Mild brain injury is associated with few changes in neurological function, which may not persist. Polissar, in a case–control study of 53 children with a mild TBI, used a broad battery of neuropsychological tools to disclose a mild association between brain injury and neurobehavioral variables initially and one year after
injury (26). In a case–control study of children with a mild TBI, a severe TBI, or an orthopedic injury, Max found that children with a mild TBI had abnormal teacher-rated adaptive function scores (27). However, children with a mild brain injury have been found to be similar to controls in reading comprehension and spelling at 12 months after injury, and in memory skills and academic performance at 24 months after injury (23,28,29). Other studies have found that a mild TBI had no effect upon behavioral problems, neurobehavioral functioning, or memory (28,30,31).

Severe TBI, defined as a GCS of less than eight for six hours or more, has the most profound effect upon functional outcome. In a series of 105 children survivors of severe TBI, only 44% were found to have a good functional outcome five years after injury (32). Significant persistent deficits have been noted in memory, sustained attention, behavioral problems, and educational performance (28,33–35). Certain factors may help predict which children will have a worse outcome. Children with a severe TBI, defined by an initial GCS of 3–5 and a delay in return to GCS 15 of more than one month, have more profound, persistent deficits (36).

Among children with a severe TBI, approximately 3% persist in a vegetative state (32). Kriel studied a group of 26 children who remained unconscious for more than 90 days after TBI and found that 20 regained some consciousness, 11 of whom were eventually able to communicate. They found that improved outcome could be predicted by the degree of atrophy on brain computerized tomography performed two months after injury (37). Ricci found that the ratio of N-acetyl aspartate and choline noted on brain magnetic resonance spectroscopy was able to differentiate between eight patients who remained in a vegetative state and six patients who ultimately regained some consciousness (38).

The outcome of TBI has been found to vary with age, with an improved outcome in children compared to adults (39). A good outcome may be expected following severe brain injury in 43% of surviving children and in only 28% of adults (40). The reason for this difference remains unknown, but has been ascribed to differences in the mechanisms of injury suffered by the different ages. When Johnson analyzed a series of adults and children who suffered brain injuries secondary to motor vehicle collisions, he found an equivalent neurological outcome between the groups (41). Significant TBI in the youngest children has been found to produce long-lasting deficits, which persist and adversely affect the child’s development (42). In a group of 97 children referred for rehabilitation following a severe brain injury, Kriel found worse cognitive and motor deficits, as well as more brain atrophy, among children under six years of age, compared to children six years of age or older (43).

There is conflicting evidence in the literature about the prospect of functional improvement after severe brain injury. Carter, in a longitudinal study of over 100 children with severe brain injuries, found that 12 of 61 survivors had an improved functional outcome at five years after injury as compared to one year post-injury (32). However, other series have failed to demonstrate an improvement in functional outcome following the first months after injury. Ewing-Cobbs et al. found no improvement in educational scores between six and 24 months in a series of children followed prospectively (44). Jaffe found significant improvement in cognitive function during the first year after TBI, but only negligible change over the next two years (45). Kriel, Ricci, and Berger reported significant improvements in outcome after the first few months following TBI in children with devastating injuries (37,38,46).

Investigators have noted a difference in outcome within groups of children having similar degrees of TBI that may be ascribed to other factors, such as the levels
of parental stress and coping skills. In a group of 18 children with severe TBI, Rivara found a high level of strain in their families three years after injury that correlated with the child’s outcome (47). Max found that family dysfunction was associated with deficits in child adaptive functioning (48). Kinsella found that parental coping skills had a significant impact on a child’s behavioral sequelae after severe TBI (49).

Various long-term cognitive problems have been reported in children following severe brain injury. Roman examined verbal learning and memory in a group of children following mild, moderate, or severe brain injury. The children with mild to moderate injuries scored similarly to control patients, while deficits were found in children with a severe brain injury (50). Catroppa et al. also found a difference in sustained attention, reading comprehension, and arithmetic between children who had sustained a mild to moderate or a severe brain injury (51). Attempts to address the attention difficulties through medication have met with mixed results. While Mahalick found that methylphenidate administration improved attention skills in 14 children following TBI, other authors, such as Williams, have found no effect (52, 53).

The ability to actively participate in educational activities is one of the key duties of childhood. Children with a traumatic brain injury have a variety of school-related difficulties. They suffer from cognitive deficits and behavioral and psychological problems that may adversely affect their ability to participate in social situations. Kinsella found a high rate of special educational needs among children following severe TBI (30). Ewing-Cobbs found, in a prospective longitudinal analysis of 33 brain-injured adolescents, lower reading recognition, spelling, and arithmetic scores six months after brain injury. At two years after injury, despite the return of test scores to an average level, nearly 80% of the children had either failed a grade or required ongoing special education assistance (35). Nybo found that the majority of toddlers who had suffered a severe TBI had cognitive and social problems that persisted into adulthood (54).

A portion of these persistent problems may be secondary to behavioral and personality disturbances. Max found an increased incidence of psychiatric problems in the second year after brain injury (55). Emanuelson found that, despite a normal IQ and ambulation, none of 23 children treated in a regional rehabilitation center for a severe brain injury had been able to adjust to a normal life because of behavioral and personality disturbances (56). In fact, Catellani et al. found that a group of adults who had suffered a severe TBI in childhood were poorly adjusted socially and still had problems related to behavioral and psychiatric disorders. These problems did not improve with age, despite an improved ability to conduct activities of daily living (57).

OUTCOMES OF TRAUMA TO THE EXTREMITY IN CHILDREN

Musculoskeletal injuries continue to constitute the predominant category of pediatric trauma. A recent retrospective review of 601 patients treated at a Level I regional pediatric trauma center found that half of all consultations to the emergency room were done by the orthopedic service (58). Moreover, treatment of musculoskeletal trauma is the most likely cause for admission and for surgical intervention among children sustaining pediatric trauma.

Improved methods of bone and soft tissue management have markedly improved the outcome of severe injury to the extremity. Femoral fractures, which are common
among children with polytrauma, demand prompt treatment in order to reduce early complications and improve long-term outcomes. Intramedullary and external fixation are increasingly used even in young children in order to achieve prompt early stabilization and improve management of the injured child. Multiple studies have documented excellent long-term outcomes with regard to acceptable bony healing and return to function (1,59).

Open fractures of the extremity continue to pose a significant challenge, though improvements in early management and techniques of limb salvage including bone transport and myocutaneous free flap transfer have led to higher rates of limb salvage. As in adults, the classification of Gustillo predicts complications and risk of limb loss, though rates of infection, including limb-threatening osteomyelitis are lower than those found in adults (60,61).

Lawn mower injuries still account for too many avoidable, significant injuries to children, with amputation resulting in about one-half of cases (62). Mehlman recently reviewed cases of traumatic hip dislocation and noted a strong association with delay in reduction >6 hours and an increased risk of avascular necrosis to the femoral head (63). Although limb replantation continues to present a significant technical challenge, rate of successful upper extremity replantation seem to be higher in children less than nine years of age (64).

OUTCOMES OF PEDIATRIC PELVIC FRACTURES

Although significant pediatric pelvic trauma is much less common than other injuries, these injuries can have an immense effect on the health of affected children. Mortality is less common than in adults with one recent study reporting a 5% overall mortality rate for 722 pediatric pelvic fractures reported in the NPTR compared to a 17% mortality rate among similar injuries in an adult population (65). However, associated injuries, including abdominal, genitourinary, and head trauma, are commonplace in both adults and children (66,67).

Pelvic fractures in children differ significantly from those found in adults. The pediatric pelvis is plastic and thus deformable, and will absorb significant energy prior to failure. Thus, pelvic fracture in a child is indicative of a high-energy injury. Furthermore, injuries to the pediatric growth plate may result in progressive deformity, although the effect of growth disturbance on long-term outcome has not been adequately characterized. On the other hand, remodeling may occur during growth, leading many orthopedic surgeons to opt for non-operative treatment of injuries which would require open reduction and internal fixation in an adult population (68,69).

An improved understanding of the issues related to the early management of these injuries has resulted in a marked improvement in short-term outcomes including mortality and early complications. Children are much less likely to have life-threatening exsanguinations as a result of pelvic fracture, and there has been an increased awareness that hemodynamic instability in this setting demands an aggressive search for other sources of bleeding (2). Another study found that children who present with a pelvic fracture and additional bony fractures are much more likely to have head and abdominal injuries and have twice the risk of death as those presenting without concomitant skeletal injuries (70). The fracture classification of Torode and Zieg (avulsion, iliac wing, simple ring, or ring disruption) has been shown to be an accurate predictor of blood loss, associated injuries, and expected outcomes.
Long-term morbidity is often more related to associated injuries, most notably head injury, rather than the bony injury (66,67).

Much less is understood about more broadly defined, important long-term outcomes including functional status and quality of life. In a review of 17 children under 12 years of age who sustained unstable pelvic ring fractures, Schwarz et al. found that bony asymmetry and malposition resulted in low back pain and functional impairment (73). On the other hand, in a retrospective review of 54 children at a mean follow up of 11 years, Rieger et al. found that long-term disability was rare and related to severe pelvic ring disruptions, acetabular fractures, or concomitant injuries (74). Noting that little is known about functional outcome in pelvic fractures in children, Upperman et al. reviewed the FIM, which is part of many pediatric trauma registries, for a group of children who sustained pelvic fracture (75). He found that a majority of children have significant limitations in locomotion and transfers at discharge.

The relative lack of data describing long-term outcomes in this area has led to significant controversy regarding the appropriate treatment of these uncommon but potentially devastating injuries. Some orthopedic surgeons have opted for a non-operative approach, even to unstable injuries, citing the potential for remodeling inherent in the immature skeleton (68,69). On the other hand, others have opted for surgical intervention (60,73,76,77). Pelvic fractures can result in significant disability, pain, reduction in quality of life, sexual difficulties, and problems at work in adults. There is good evidence in the adult literature that the quality of anatomical reduction correlates with functional outcomes in this area (76,77). No study to date has specifically examined the effect of non-anatomical reduction or bony malunion on arthritis, though this is a concern.

External fixation has been advocated as a means to decrease blood loss and control unstable fractures during the acute period and as a means of definitive treatment. Although there are no Class-I data in this area, multiple studies support the use of the external fixator in this setting in the adult population which is the standard of care for a large subset of adult pelvic fractures. However, appropriate indications for use in children are still evolving. Nevertheless, the external fixator is often used in an effort to improve outcomes of open pelvic fracture, anterior pubis injury and pelvic fracture associated with polytrauma (60).

Generally speaking, treatment recommendations over the last decade have evolved toward more aggressive surgical treatment, in an attempt to improve anatomical reduction of the pediatric pelvis (66,74,76). Nevertheless, there is substantial variability in the orthopedic management of pediatric pelvic fractures. This variability reflects clinical uncertainty and demands rigorous, patient-based clinical research in this area comparing various treatment strategies and improved information regarding long-term, broadly defined outcomes of pediatric pelvic fracture. Further research is necessary to elucidate the intermediate and long-term outcomes of children with specific pelvic injuries and to help guide the appropriate indications for surgical intervention in this area.

OUTCOMES OF SPINAL CORD INJURIES

Epidemiology

Spinal cord injuries in childhood are uncommon, but devastating. Out of 11,000 persons who suffer a spinal cord injury each year in the United States, approximately 1000 are aged 15 years or less (78). Nearly one-half of these children suffer a complete spinal cord
injury with little prospect for improvement. About 60% of the children with spinal cord injury suffer from tetraplegia, a higher percentage than in adults. Children surviving the first month after a spinal cord injury have an average life span of 60 years when paraplegic, and 52 years when tetraplegic (Table 1). The majority of children with spinal cord injuries complete high school, attend college, and are ultimately employed (79).

Functional outcome after spinal cord injury is dependent upon whether the injury is complete or incomplete and the level of injury. Outcome may also be affected by the development, or avoidance, of a variety of post-injury medical and psychological complications (81).

**Functional Outcome Measures**

The International Standards for Neurological and Functional Classification of Spinal Cord Injury or American Spinal Injury Association (ASIA) scale is the most widely used method of codifying residual function below the level of spinal cord injury (Table 2) (82). The ASIA A injuries are sensory and motor complete. The ASIA B injuries are sensory incomplete and motor complete. The ASIA C injuries are motor incomplete with the majority of affected muscles having less than three-fifths strength. The ASIA D patients are motor intact with the majority of affected muscles having greater than three-fifths strength. The ASIA E patients have normal sensory and motor function.

Although motor function may improve over time after injury, the ASIA impairment scale measured one week after injury may predict the prospects for ambulation. Of patients with a complete, or ASIA A injury, 80–90% of injuries will remain complete and, of those who do become incomplete, only 4% will ambulate. Patients with incomplete injuries have a much better prognosis for subsequent ambulation. The ASIA B patients at one week have a 50% chance of regaining adequate motor strength to walk. This may be positively predicted by the presence, or absence, of sacral sensory sparing. Those without sacral pin sensation have a much poorer

### Table 1  Life Expectancy of Children with Spinal Cord Injury Surviving at Least One Year Post-injury

<table>
<thead>
<tr>
<th>Current age</th>
<th>No SCI</th>
<th>Paraplegia</th>
<th>Tetraplegia</th>
<th>Ventilator dependent</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>71.6</td>
<td>59.5</td>
<td>52.6</td>
<td>39.4</td>
</tr>
<tr>
<td>10</td>
<td>66.6</td>
<td>54.6</td>
<td>47.6</td>
<td>34.9</td>
</tr>
<tr>
<td>15</td>
<td>61.7</td>
<td>49.8</td>
<td>43</td>
<td>30.4</td>
</tr>
</tbody>
</table>

Life expectancy in years.

*Abbreviation:* SCI, spinal cord injury.

*Source:* Ref. 80.

### Table 2  American Spinal Injury Association Classification and Ambulation

<table>
<thead>
<tr>
<th>ASIA Level</th>
<th>Sensory</th>
<th>Motor</th>
<th>Ambulation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Complete</td>
<td>Complete</td>
<td>&lt;1</td>
</tr>
<tr>
<td>B</td>
<td>Incomplete</td>
<td>Complete</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>Incomplete, weak</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Incomplete, antigravity</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Normal</td>
<td>Normal</td>
<td>100</td>
</tr>
</tbody>
</table>
prognosis for ambulation. The ASIA C and D patients have a 75% and 95% chance of walking, respectively (83). The ASIA E patients have no discernable deficit and should return to their full preinjury level of function.

Significant recovery of motor function may occur over the first three months after injury. Further motor recovery, at a slower pace, may be noted over the next six months, with smaller improvements in functional recovery documented up to two years after injury (84). The recovery of motor function occurs more rapidly with incomplete spinal cord injuries and is more likely to occur in younger patients (85).

Despite this recovery, a motor examination performed one month following injury may be prognostic of ultimate recovery (86). The presence of even one-fifths strength in a muscle group one month after injury is associated with a 97% chance of recovery of antigravity strength three-fifths in that muscle group by one year after injury. In contrast, muscle groups with no strength zero-fifths at one month have only a 10% chance of achieving antigravity strength by one year after injury (84).

A number of late effects of spinal cord injury, as well as a number of medical complications, may adversely affect ultimate functional outcome. Sadly, 64% of adults report ongoing significant musculoskeletal or neuropathic pain six months after their spinal cord injury (87).

Scoliosis is common following spinal cord injury in children, and its severity is increased by younger age at onset, complete lesions versus incomplete, and paraplegia versus tetraplegia (88). Kyphosis also commonly occurs, and has been associated with an increased risk of syringomyelia when greater than 15° (89). Whether associated with kyphosis or not, post-traumatic syringomyelia may occur in 25% of paraplegic patients, and may lead to progressive neurological deterioration (89,90). Progressive non-cystic tethering of the spinal cord has also been reported, and may lead to similar neurological deterioration (90). It is hoped that this late deterioration may be prevented with more aggressive spine stabilization.

Children with spinal cord injuries are at significantly increased risk of low-energy orthopedic injuries compared to patients without spinal cord injury (91). These fractures most commonly occur in the lower extremities. The femur is 32 times more likely to be fractured in a patient with a spinal cord injury (91).

Urinary tract complications are common in children with a spinal cord injury. Shortly following injury, the majority of children are placed on a clean, intermittent catheterization schedule, which results in a lower urinary tract infection rate than an indwelling catheter (92). The use of prophylactic antibiotics is controversial, and was not recommended by a national consensus panel (93). Renal calculi, typically struvite calculi, develop in a small percentage of children (94). Stones occur more frequently in children with complete spinal cord injuries, vesico-ureteral reflux, and permanent indwelling catheters (95).

Pressure ulcers are the most frequent medical complication secondary to spinal cord injury, occurring in 60% of adults within 30 days of injury in one series (96). The risk of pressure ulcer development in children correlates with a period of spinal immobilization for more than six hours, and with a complete spinal cord injury (97).

Unlike other pediatric injury victims, children with a spinal cord injury are at risk for the development of venous thromboembolism (VTE) and pulmonary embolism. The VTE develops in children with a spinal cord injury at the same rate as adults, in approximately 10% of patients (98). The period of greatest risk is in the first two weeks after injury and persists for 8–12 weeks. Long-term sequelae of VTE in children with a spinal cord injury includes postphlebitic syndrome, which occurs in approximately 3% of children (99).
Children with a spinal cord injury return quickly to school, a mean of 10 days following discharge from rehabilitation for paraplegic children and 62 days for tetraplegic children (100). Educational performance among children with a spinal cord injury is excellent. In Dudgeon’s study, most patients graduated from high school and pursued higher education. Many schools modified their curricula to accommodate the needs of the children, most of whom had teacher aides (79).

The prognosis may seem bleak for children with a high cervical spinal cord injury who leave the hospital ventilator-dependent. However, Oo found that of 107 adult patients who were ventilator-dependent upon discharge, 21% subsequently recovered adequate diaphragmatic function to allow them to be weaned from the ventilator (101). Many of these patients required more than a year to recover sufficient diaphragmatic strength to not require ventilator support.

Bowel problems are common following spinal cord injury. Goetz studied 88 children with spinal cord injuries and found that 68% reported that their bowel habits interfered with school and other activities and resulted in dissatisfaction (102). Most patients require the long-term use of oral and/or rectal medications for bowel control. Krogh reported that up to 75% of patients report at least a few episodes of fecal incontinence per month, and that nearly one-third felt that their bowel problems were more burdensome than their sexual or urologic dysfunction (103).

Issues such as these contribute to dissatisfaction with the quality of life after spinal cord injury. Using the standardized measures of quality of life, Kannisto found that patients with a spinal cord injury scored significantly lower than the population sample. Not surprisingly, patients with spinal cord injury placed greater significance upon the measures for mental functioning, communicating, and social participation (104). Gorman examined the psychological health of 86 children who suffered a spinal cord injury prior to 16 years of age, and found that self-esteem, depression, and self-perception were lower than average, regardless of the age or level of injury (105).

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Communication with Families of Injured Children

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INTRODUCTION

The ability to communicate effectively with patients and their families is one of the most valuable skills a physician can possess. It is the bridge to a relationship of trust between the physician and the child and family. This skill becomes even more important when a physician must communicate distressing information, when a child’s condition deteriorates, or if death occurs. How such information is conveyed during catastrophic events has a profound impact on the coping and grieving process of families (1). It is vital that a physician be educated in and adhere to principles of compassionate communication. The informant’s behavior and preparedness during these times of crisis will have a lasting effect on the family.

There are three primary components of successful communication: compassion, clarity, and a proper environment (2–4). Much useful information is available from retrospective reviews of family members’ experiences during times of change or sudden death.

Compassionate delivery of information is one of the most important factors in acute event notification (5,6). While a caring manner is often naturally displayed by physicians who have been directly involved in a patient’s care, there are certain circumstances that complicate this interaction. One situation involves the initial care of an unstable trauma victim, in which a prior relationship has not been established with family members. Whether a trauma victim is hemodynamically normal or abnormal, the simple fact that their child has been injured will qualify as bad news to parents.

It is important for the family to know that helping their loved one is of paramount importance. Using the child’s name during conversations about care is
a simple action that immediately brings the interview to a more personal level. It is equally important to use correct pronunciation and gender references.

Basic public speaking skills such as eye contact and timing are important adjuncts to use when speaking with families. Look at all persons gathered together while talking in order to acknowledge the individuals present. It is equally important to pause during the conversation, allowing adequate time for questions. Actually asking, “Are there any questions?” often prompts parents to seek answers they otherwise would not have. It also provides confirmation that their thoughts and questions are valid, and reinforces that the child and the family are equally important to the physician (7,8). Ultimately, the message and the messenger are inseparable (1,5).

After compassionate delivery, clarity of the message is the most important factor in communication. During an acute crisis, it is not uncommon for family members to unconsciously repress intolerable facts. Even if they do hear what the physician has said, comprehension may be delayed. For this reason, the physician must be clear, honest, and give simple explanations. Repetition and patience are often required. The physician must set aside an ample amount of time to spend with a given family (7). This is time well spent, as it paves the way for future interactions.

It is vital that the health care provider be aware of the facts related to the medical situation before the interview begins (7,9). Possessing accurate knowledge allows a physician to be more confident and in control and conveys a sense that the family member has received care from an informed, prepared provider. Often, it is not possible to relay all of the facts at one setting. This is when pacing becomes important. This means that the family is given time to process a fundamental but finite amount of information. After a period of time, the physician can return and add more information to this frame of reference. This facilitates understanding and more effective decision-making, if required (10,11). In addition, it dampens the initial dismay when families are told of a concerning change in their loved one’s condition. It is helpful to provide a summary of findings as each interview is completed, including a discussion about when the next meeting is likely to occur. Although the above concepts are pertinent to most encounters, it is important to adapt communication style to the given situation, as parental responses will be dependent on individual circumstances.

The conditions of the information session include the physical environment and the timing of the interaction. The best time to talk with families, particularly about acute change, is as soon as possible after the change occurs. This can be especially difficult in the emergency department, as the focus of the physicians’ attention is on assessing and treating the child. A compounding factor is that the family may not arrive at the hospital until the child has been there for some time. The child may already have been taken to the critical care unit or operating room, resulting in a necessary delay before the physician can speak with family members. In this circumstance, one member of the trauma team may be asked to leave and communicate with the child’s family.

The physical environment is extremely important for effective communication. Privacy is vital. Even in an acute setting such as the emergency department, a quiet area away from other people should be set aside, where the physician can sit down with the family and speak freely and openly. Ideally, the person who speaks with a family should be the health care provider who has had the most interaction with them, and with whom the family has formed a relationship of trust. Since this is not feasible in the acute trauma setting, it is helpful to allow such interactions to take place in the presence of the family’s support system and a member of the hospital’s
family support team. Family members want to be advised of distressing information expeditiously and in the company of their loved ones (12).

The manner in which families are told of their child’s status should be tailored to the individual situation. The approach will be dependent upon whether or not the child is likely to recover. Family responses will vary depending on the circumstances, and the physician should be prepared for this.

Fortunately, the most common scenario an individual physician will encounter when speaking with a family is one in which a child is likely to recover. However, in some circumstances the child will recover and be normal, and in others the child will more likely recover with impairments. In either situation, the key to an effective interaction is clarity and honesty. The informant must be informed and forthright about every aspect of the patient’s care and prognosis. Family members will understandably have questions. The medical-care provider who is able to adequately address the questions will quickly and deservedly earn a family’s trust, whether or not the answers to the questions are apparent when the conversation occurs (13).

WHEN A CHILD DIES

Delivery of the news of a child’s death has an impact that will last a lifetime (1). In the case of sudden death, preparation is not possible. While the principles of communication already discussed apply, it is often difficult during times of acute crisis for families to remember what is told to them (14). It is beneficial for a third party, often the chaplain or another member of the family support staff, to remain with the family for a time or meet with them again to ensure that there are no unresolved issues or unanswered questions. This is helpful in preventing some aspects of pathologic grief that can stem from a lack of complete understanding on the part of the family (1,15).

Families of children who are chronically ill or have a more protracted course prior to death have a unique set of needs (6). The physician and family have often had time to establish a relationship of trust and understanding. This scenario allows the health care provider to more adequately prepare the family for the possibility of death (16,17). However, there are situations where parents are not open to discussions about the eventuality of death. They naturally do not want to feel that they have given up on their child. Although more challenging, it is still the physician’s responsibility to provide continual support and honest information.

FAMILY PRESENCE DURING RESUSCITATION

A concept that is receiving more attention but remains contentious in the setting of acute trauma is family presence during cardiopulmonary resuscitation (CPR) (8,18). Interestingly, most family members have a desire to be present during the resuscitation of their child. It is conceivable that this will be the last time their child is “alive” and parents want to be there at the time of death. In interviews with family members who have been present during end-of-life procedures, there is a common theme of overwhelming gratitude for having been given the opportunity to be present. This seems to be constant, regardless of the outcome of the medical efforts. For the surviving family members, it removes doubt about what occurred and helps them understand that everything possible was done to save their loved ones. This allows for a more healthy grieving process (18–21).
There also seems to be a strong desire on the part of family members, particularly parents, to be present during invasive procedures. The ability to stay with the child decreases the anxiety level of the parents and child. There is no consistent evidence that family presence distracts from the provision of optimal medical care.

**UNDERSTANDING BRAIN DEATH**

While there are clear-cut medical criteria for brain death, this information is often very difficult to communicate to families (22). Further, a misunderstanding of what brain death represents can be a source of parental guilt if volitional withdrawal of care occurs. Such grief can later stem from misconceptions that the family was an instrument in the child’s death or gave up on the child too soon. The lay press and other media venues can be particularly misleading about recovery from “deep coma” (1,23). One way to provide comfort to patient’s families is to clearly explain that waiting longer would not have helped. There are books available to help with communication efforts. Some families may wish to view test results or witness the apnea test.

Each state has criteria for brain death. An example of a legal definition for the determination of brain death is as follows: The occurrence of human death shall be determined in accordance with the usual and customary standard of medical practice, provided that death shall not be determined to have occurred unless the following minimal conditions have been met:

1. when respiration and circulation are not artificially maintained, there is an irreversible cessation of spontaneous respiration and circulation, or
2. when respiration and circulation are artificially maintained, there is total and irreversible cessation of all brain function, including the brainstem.

Individual state criteria may require verification of brain death by more than one licensed physician. If pharmacologic agents have been used that preclude doing an apnea test, a brain flow study may be needed.

An example of the clinical criteria for the diagnosis of brain death is as follows:

1. determine and document the probable cause of death,
2. the patient must be normothermic (temperature >36°C),
3. the absence of narcotics, sedatives, and hypnotics,
4. exclude high cervical spine fracture,
5. Glasgow Coma Scale of 3 (i.e., no motor or verbal response to pain and no eye opening),
6. absent brain stem reflexes, including the pupillary light reflex, corneal reflex, gag reflex, cough reflex, oculocephalic (doll’s eye) reflex, and the oculovestibular (cold water calories) test,
7. valid apnea test.

The specifics of the test include:

1. monitor cardiac rhythm and arterial blood pressure. Stop test if moderate to severe hypotension or dysrhythmia occurs,
2. preoxygenate with an FiO₂ of 100%,
3. start test with a PaCO₂ of 40 mmHg,
4. obtain arterial blood gases (ABG) prior to disconnecting the patient from the ventilator,
5. disconnect the patient from the ventilator. Supply 6-7 L/min of 100% oxygen though tubing inserted into the endotracheal (ET) tube,
6. watch the patient for any evidence of spontaneous respiratory effort,
7. approximately 10 minutes after disconnecting the patient from the ventilator, obtain an ABG,
8. connect the patient to the ventilator and adjust to pretest settings,
9. PaCO₂ must be 60 mmHg or greater or 20 mmHg above the patient’s baseline on the post-test ABG for the test to be valid.

ORGAN DONATION ISSUES

In seeking consent for organ donation, effective communication is essential and should take place in a comfortable, private area and not at the patient’s bedside (7). This interaction should occur after the family has been notified of brain death and has had time to comprehend this information, and in the presence of a limited number of persons who have been chosen by the parents. The process of temporally separating brain death determination and potential organ donation is called decoupling. Decoupling gives the family time to grieve their loved one’s death.

The optimal time to address organ donation is when the family begins to ask what the next step will be (1). While there is no perfect way to discuss donation, an effective approach has been suggested. The individual who has the best established relationship with the family should be the communicator. Usually, this individual is a physician or chaplain. This person should sit down with the family in a private area and ask if they have unanswered questions about the clinical events or declaration of brain death. After all questions have been satisfactorily answered, a discussion about organ donation may be initiated. An opening statement that has been suggested is, “The law requires me to, and I believe it is important that you be offered the opportunity to consider organ donation.” During this time, the benefits, process, and timing of organ donation should be clearly outlined. If the family is receptive, the next step is to invite the organ procurement organization representative to participate in the interaction.

If organ donation is not chosen, it is an optimal time to begin explaining and discussing the process for discontinuing ventilator support. In either case, the goal of the physician is to lead surviving family members to a decision that is personal, thoughtful, and comfortable for them.

BEREAVEMENT

Losses are inevitable, but there is no greater acute stress for a family than the loss of a child due to injury. There are predictable windows for building resilience in the midst of an emotionally charged environment, for both providers and the patient’s family.

THE FAMILY—COPING WITH UNPREDICTABILITY

Nothing in a parent’s experience prepares them for the emotional chaos and lack of predictability that is characteristic of pediatric trauma. By the time their child arrives
at the emergency room, the accompanying adults are understandably overwhelmed by feelings of shock, confusion, and fear for their child’s safety. They literally place their child and their faith in the competent hands of the trauma team. The trauma team’s first response is to the medical/surgical assessment and treatment of the pediatric patient. However, the focus of this section is to describe the accompanying psychosocial issues for the family that inform our handling of their needs.

**THE FAMILY’S ACUTE GRIEF REACTION**

What do families need as they enter the emergency department? They look to the trauma team to assure them that their child will be all right. All parents want two characteristics in a physician during a crisis: expertise and experience. They want their surgeon (and hospital) to have the ultimate expertise and level of skill and they want their surgeon to be performing this skill on their child not for the fourth time but for the fourth thousandth time.

Expertise and experience: the perfect answer to the unpredictable event that has put their precious child at risk. In the midst of trauma, therefore, the family must receive assurance about the team’s expertise and experience.

- Who should communicate with the family?
- What can be expected as an understandable and predictable response to their acute grief reaction?
- What is “best practice” or protocol in this psychosocial arena that antici-pates the family’s needs?

The term “protocol” suggests a prescribed procedure that responds in kind to the acute grief reaction from the family members as well as the child if he or she is conscious. Often a lack of time compromises the ability to foster a completely satisfactory communication. The family needs to know: (i) the status of their child, (ii) what is being done, (iii) what is the expertise and experience of those treating their child, and (iv) their child be okay? In some hospitals, written pamphlets or photos that introduce the various members of the trauma team are on display. In any event, a designated first person, who acknowledges the adult accompanying the child soon after arrival, can provide the needed reassurance by a simple direct statement “your child (use the child’s name as you learn it) is in the very best place. Our team is ready and equipped to help her. What is unique to you is all too familiar to us.” There is no need for more explanation as more is not necessarily better. This simple sentence provides much-needed reassurance.

This designated first person may be a chaplain or a member of the family support services team and can also ask the family about past medical history and provide important information to the trauma team resuscitating the child. This individual acts as a liaison between the trauma team and family.

**THE GRIEVING PARENTS’ DEFENSE MECHANISMS**

The three defense mechanisms employed by grieving parents are denial, projection, and detachment. These defense mechanisms are most often seen by medical providers as barriers between parents and providers.
Denial:
“I’m sure Anthony will be fine. He is a real fighter.”—parent
“Mrs. Terry is in such denial. I need to get her to accept that her child is not responding.”—nurse

Projection:
“Doctor, why didn’t you tell me he was not going to live?”—angry parent
“I only want that nice nurse to be with my child; I like the way she looks at him.”—parent

Detachment (not typical in acute grief reactions):
“I can’t get to the PICU more than every few days to see my toddler, Althea; I have too much else going on in my life.”—parent

NEXT STEPS: SURGERY OR “THE IMPOSSIBLE OUTCOME”

One of the most difficult aspects of caring for a family during trauma is the lack of time to create a trusting relationship. Following stabilization, some children will be sent immediately to surgery. The trauma team has done its job and has transferred the patient to the next set of capable hands. An expectant family still needs information and support as they identify a new set of providers in whom they entrust their child’s care. If a child dies in the emergency department, the family has little or no time to understand what has happened, or how it is possible that their child could have been fine one minute and dead in a matter of minutes or hours.

If a child dies in the emergency department, the relationship that was initiated between the team and the family will serve the bereaved family for years to come. Anecdotal responses from bereaved parents suggest best outcomes when the pediatric trauma team demonstrated empathy, and provided them with timely answers and understanding of their child’s unique medical situation. A nurse that used their child’s name or rubbed a mother’s tense neck, a surgeon whose eyes filled up with tears as he described efforts made to save the youngster’s life, a chaplain’s sensitive tone of voice or presence throughout an impossible wait, all translate to reassure parents and family members that their child was cared for in a personal way.

LONG-TERM BEREAVEMENT

When a child dies, particularly as a result of unintentional trauma, parents suffer from “complicated mourning” (24). In addition to making sense of how their precious child was healthy and alive one moment and dead the next, they need to revise two assumptions about their world:

- their child will outlive them,
- they could protect their child.

These basic assumptions about their world have been shattered, and normal mourning must work through these shattered assumptions. It is highly recommended that professional counseling be considered within the first three months following a child’s death. No death is more isolating than parental loss of a child, as extended family and friends often feel inadequate to comfort and provide solace, and the survivor’s grief may lead to detachment from family relationships following sudden bereavement (23).
As is often the case with a childhood trauma, understanding the precipitating events and processing and resolving the guilt that parents or caregivers may experience, is an additional stressor that deserves a professional’s assistance. Professionally facilitated grief support groups, specifically for parents who have lost children, are often useful.

Within the first year of bereavement, grieving parents often find themselves ready to understand the medical details surrounding their child’s death. A compassionate surgeon who treated their child, and is willing to interpret the autopsy report with the parents, can help parents accomplish the powerful and significant task of understanding their child’s death. This is a necessary requirement of their grief resolution.

**COPING SKILLS: PERSONAL, PROFESSIONAL**

**Patient Families**

*Parents*

Parents’ bereavement response to the death of their child varies greatly, and is influenced by their sense of culpability, whether they have surviving children, their own coping skills, and perceived support from extended family and friends (1,25). Parents who report a strong religious belief often draw upon that strength during difficult times in the bereavement process. Grieving parents must be made aware of masculine-style grief and feminine-style grief so that these differences do not create additional isolation for the couple. At Kosair Children’s Hospital in Louisville, Kentucky, a Bereavement Intervention Program (BIP) has been developed for parents suffering the loss of a child (1).

*Surviving Siblings*

Surviving siblings often experience the loss of their brother or sister as a dual loss, as they also have lost their parents as they know them. Family life will never be the same. The task of creating a “new normal” is painful at best and is realized by each family member at their own pace.

The Good Grief Program at Boston Medical Center is an example of a bereavement program (25). This program provides grieving parents information about what to expect from their child or children over the weeks and months following a family member’s death. The Heart to Heart Consultation Project anticipates the normal bereavement response as it relates to the surviving child’s age and stage of development. It offers strategies and language for the adults in the child’s life. Parents find this information invaluable in understanding their grieving child. Each child must understand a sibling’s death according to their own developmental level.

**Children’s Understanding of Death**

For adults, death creates a sense of disequilibrium or a disruption in their usual “steady state.” For children, however, death represents a “developmental interference that results in a suspension of their ongoing growth.” The goal of a clinical intervention with children is to get them “unstuck” and to help them get through, over, under, or around a temporary barrier to their normal and healthy forward
movement (15,26). The clinician should view the child’s ability to cope with a significant loss or death in relation to three factors:

- the child’s ability to make sense of the death developmentally,
- the child’s history of loss and death,
- the child’s normal ability to cope with change.

Although Piaget did not specifically address a child’s ability to understand death, much of the current thinking about how children perceive death comes from his theories about cognitive development. This framework is very helpful in assessing a child’s reaction to the death of a loved one and the clinician’s role in providing anticipatory guidance to the adults in the child’s life (Table 1). As useful as this framework is children regress under stress and the boundaries are meant as developmental markers only. A child’s history with loss or death, personal temperament, and prior ability to cope with change all inform us of an individual child’s reaction to death.

**Medical Providers**

*Nurses and Physicians*

The pediatric trauma team confronts the stressful possibility of a death every time a patient arrives for medical treatment. When the outcome is death, everyone involved in the child’s care understandably grieves. Even the most seasoned physician may frame the death in terms of his own perceived failure. Every nurse understands the profound grief that the family now faces. Routine debriefing of the treating team is seldom the norm in hospital emergency departments or even in neonatal and pediatric intensive care units. Medical providers are often understandably reluctant to become vulnerable and participate in the unfolding of the psychosocial aspects of treating the pediatric patient, particularly in the real-time context of treating other trauma patients. They are purposely “defended” and that defense needs to be respected.

At Boston Medical Center, home to the Good Grief Program, a different approach to debriefing is implemented (25). Wrap-ups, as they are called, are routinely conducted when a pediatric patient dies. The one hour wrap-up is multidisciplinary and planned within a 48-hour period of the death. The approach is strongly weighted in the cognitive domain as each provider is asked to share how they experienced the treatment, care, and death of the patient. The providers’ defenses are respected. At no time during the wrap-up is anyone asked to share feelings, although feelings are often expressed because the discussion is held in an environment of safety. Although findings at this time are only anecdotal, doctors and nurses, attendings and medical students, interpreters and chaplains sit together and experience a sense of closure and gratitude for each other’s contributions. The participants are on time and in full attendance. Comments to team members after the wrap-ups have included:

- I feel that we did our best, even though the outcome was death.
- I feel more ready to return to work.
- I appreciate your honesty.
- I value your sensitivity.
- I appreciate the words you used as you talked with the patient’s parents.
- I learned from your approach.

At Columbia Babies’ and Children’s Hospital in Manhattan, a comprehensive bereavement program, designed with concurrent tracks for providers and family
<table>
<thead>
<tr>
<th>Developmental stage</th>
<th>Perception of death</th>
<th>Reaction to death</th>
<th>Anticipatory guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infant (0–2 years)</td>
<td>No cognitive understanding of death, perceived as separation or abandonment</td>
<td>Distress, frustration, regression</td>
<td>Identify a surrogate caregiver to learn caregiver’s routine and provide nurturing and dependable environment</td>
</tr>
<tr>
<td>Preschooler (3–5 years)</td>
<td>View death as temporary or reversible, or possibly as punishment</td>
<td>Associated with magical thinking that wishes can come true</td>
<td>Respond to questions with concrete, simple explanations. Avoid euphemisms such as “lost, sleeping, gone to heaven, with the angels”</td>
</tr>
<tr>
<td>Latency age (6–8 years)</td>
<td>Understand death to be final, irreversible, but not universal</td>
<td>Children this age do not think that they themselves will die; find death difficult to understand</td>
<td></td>
</tr>
<tr>
<td>Pre-adolescent (9–12 years)</td>
<td>View death as final, irreversible, and universal (adult understanding)</td>
<td>Intellectualize death, often unemotional, may be sarcastic or seemingly insensitive</td>
<td>Be authentic. This age needs to know that in spite of grief, parents are still able to care for their other children</td>
</tr>
<tr>
<td>Adolescent (13–18 years)</td>
<td>Have an adult understanding of death, but behave as if they are immortal</td>
<td>Interested in exploring society’s attitudes about life and death. Often reject traditional adult rituals surrounding death and create their own using abstract and philosophical reasoning</td>
<td>Need adults to help sort out often colliding feelings of sadness, anger, disbelief, and isolation</td>
</tr>
</tbody>
</table>
members, has been developed by the Good Grief Program and implemented at the request of the Pediatric Trauma Program.

To be effective, the wrap-ups need to be viewed as “best practice,” not an art form that comes and goes dependent on the person facilitating or the perception of the bereavement overload. When a pediatric death occurs, the effective pediatric trauma team will use the wrap-up as an opportunity for mastering coping skills and promoting resilience in the face of loss.

Post-traumatic Stress Disorder

Post-traumatic stress disorder (PTSD) is not uncommon after many types of traumatic events, and can affect the victims of trauma, their family members, witnesses, or health care workers. The individual must have been exposed to an extreme traumatic event or stressor to which he or she responded with fear, helplessness, or horror (26–29). Given time, most people will recover from the psychological effects of a traumatic event. PTSD represents a failure to recover and is characterized by distressing memories or nightmares related to the event, attempts to avoid reminders of the event, and symptoms of hyperarousal. Treatment involves educating the person about the nature of the disorder, providing a safe and supportive environment for discussion, and relieving the distress associated with memories and reminders of the event. The judicious use of medications can also benefit traumatized patients by alleviating the symptoms of PTSD and improving ability to function. PTSD can be diagnosed and treated by primary care physicians. Debriefing programs for health care workers may be inherently useful in helping individuals cope with traumatic events sufficiently to alleviate the symptoms or signs of PTSD.

SUMMARY

It is important to remember that families don’t “get over” their loss. Rather, they change their lives to accommodate the loss. It is estimated that 19% of the adult population has experienced the death of a child. In studies of how the relationship of the family member to the deceased affects the level of grief, it is well known that parents surviving their child’s death have significantly higher intensities of grief than other studied groups. Interestingly, no differences are noted between parents of children who die from chronic illness compared with sudden death.

Very few parents seek help from therapists or formal support groups. This underscores the importance of medical care providers and the health care system as a whole taking the initiative to offer support services to surviving parents and family members (30,31).

Three terms aid in understanding: denial, wish, and hope. Denial is the unconscious repression of intolerable facts. To wish is imagining a future despite the available facts. Hope is imagining a future in light of the available facts. The principal goal of the health care team is to provide the framework for families to begin again to hope. This involves helping them reach a point where they can understand what has happened to their loved one, recognize the long-term consequences, and work toward a realistic future under these conditions.

Many institutions, particularly children’s hospitals and trauma centers, have family support teams. The purpose of these individuals is to support families in crisis or newly bereaved and to provide comfort measures. The goal of the intervention is to
positively impact the grieving process by supporting parents and other family members as they make the drastic transition into life without their deceased loved one.

Another adjunct that can be provided is a resource center that lists resources to address grief caused by the loss of a loved one, as well as other associated forms of loss such as bankruptcy, chronic illness, divorce, and loss of employment.

Allowing parents and other surviving family members to discuss their feelings about the deceased and relay memories of their loved one seems to have countless benefits. By allowing parents to secure the memory of their child in the people around them, it permits validation of the child’s life. Otherwise, parents may feel that they’ve lost the child’s presence and the memory of the child. Sadly, friends and family members that are potentially one of the greatest sources of support may avoid even mentioning the child for fear that it’s too painful for the parents. The family’s support network needs to know that recalling the past is one of the forms of therapy that parents need most.

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