

Injury to the Immature Skeleton



Engraving of a type 2 distal femoral growth mechanism injury. (From Poland J. Traumatic Separation of the Epiphysis. London: Smith Elder, 1898)

Fractures and dislocations involving the developing skeleton may differ significantly from those of the mature, adult skeleton.⁵⁰ The first text dedicated to these biologic differences was the classic work of Poland.²⁵ This treatise attempted to collate historical vignettes with an array of clinical and morphologic material and experience throughout Europe. The principal emphasis was on epiphyseal injuries. Over the ensuing century and particularly during the past 20 years there has been an increasing amount of literature dedicated to a better understanding of the acute and chronic effects of trauma to the immature skeleton. Particularly, a number of textbooks have addressed fractures and dislocations involving the growing chondro-osseous skeleton.^{1-24,26-36} The increasing volume of literature specifically addressing the immature skeleton is evident in the reference sections of each ensuing chapter.

The pattern of injuries children may sustain via a certain injury mechanism usually differs from that of adults and so often requires different diagnostic and treatment algorithms.³²⁰ These differences additionally vary during the progressive stages of chondro-osseous maturation and growth until skeletal maturation is reached. Any primary physi-

cian (pediatrician, family practitioner), radiologist, or orthopaedist who is assessing, diagnosing, or treating skeletal injuries in neonates, infants, children, or adolescents should be familiar with the probable mechanism of injury, the cause, the acute response, the appropriate treatment, and the long-term biologic response of any injured skeletal component (particularly when a growth mechanism is involved). The appropriate, often age-related guidelines for the treatment of the specific injury must be carefully considered.

Because these patients have their pliable formative and productive years ahead of them, they should be treated with skills based on both individual experience and a detailed knowledge of the intrinsic capacities of repair and remodeling of the growing skeleton. When a treating physician relies only on those principles of treatment applicable to injuries of the mature (i.e., adult) skeleton, errors in judgment and technique may progressively or eventually manifest in a permanent defect or deficit to the involved skeletal region and an alteration or deprivation of normal function in the involved limb. Any physician involved in the diagnosis or treatment must be aware of obscure diagnoses such as a toddler's stress fracture or potential complicating factors such as a compartment syndrome.^{135,245,261,318}

Childhood injuries are a continual problem for treating physicians and the entire social community. Accidents are the leading cause of death and permanent disability among children older than 1 year of age.* Trauma ranks second only to acute infections for causing morbidity in the pediatric age group and, more significantly, accounts for approximately one-half of all deaths in children. About 15,000 children under 15 years of age die annually from accidental injury in the United States alone. Accidental death during childhood is usually due to shock, respiratory depression or obstruction, or brain or brain stem drainage. The leading causes of death include motor vehicle accidents, drownings, burns, and exposure to toxic chemicals (poisons).

Another 19 million (3 in every 10 children) are injured severely enough to seek hospital care. It has been estimated

* Refs. 15,22,33,40,45,52,64,66,68,69,73,76,78,84,87,92,97,98,109,116,118,119,121,122,140,144,145,151,152,155,156,164,167,168,169,172,176,177,181,184,191,193,197,201,202,207,209,212,216,221-226,247,269,271,272,276,281,294,314,324,328,334,354,382,383,386,399,406.

that 47% of all patients receiving care in this nation's emergency rooms are under 14 years of age. One of four of these children are treated because of violence or accidents. More than 100,000 children are permanently crippled annually, and another 2 million are temporarily incapacitated for 2 weeks or longer by accidents.^{66,216,217}

Approximately 25% of all injury victims are in the pediatric age group, and one in four injured children may "require" a pediatric trauma center. A committed relationship between adult trauma surgeons and pediatric internists is favorable for outcome if a pediatric surgeon is unavailable.

More than 100,000 children are *permanently* crippled each year as a result of accidents.¹¹⁰ Long-term morbidity is directly related to the severity of any head and musculoskeletal injuries.^{175,195} Fortunately, most injuries involving children are minor. The common skeletal injuries are caused most often by short distance falls resulting in a single extremity injury [usually the upper extremity (distal radius or distal humerus) or the hand].

Cheng and Shen showed that approximately 13% of the children being evaluated in the emergency department of an urban teaching hospital had serious injuries.¹¹³ Gallagher and colleagues¹⁵² showed a bimodal age distribution of traumatic injuries in children, the first during the first year of life and the second being an increase through the adolescent years. They showed a steady increase in the number of age-associated injuries with respect to both total number and severity.¹¹³

Although the exact incidence and rate of severe traumatic injuries are not truly known, it has been shown in multiple studies that the incidence increases as the child begins to interact with the adult world, especially with motor vehicles.^{162,167} Most injuries occur where young children spend the most time, usually in or about the home, at school, or in play areas.¹⁶⁵ More than 40% of childhood accidents occur in or around the home. For preschool children this rate may be as high as 70%. Playgrounds are the site of more than 1 million injuries.^{290,359}

Automatic garage door opening/closing devices may cause serious injury to children.^{213,332} Such injuries can be avoided by placing sensors that automatically stop closure when motion or contact occurs.

Rivara et al. studied the risks of injury to children less than 5 years of age in day-care versus home-care settings.³⁰⁴ They found that there was no change in the rate of injuries per 100,000 child-hours of exposure.

Wesson and Hu assessed 250 consecutive children hospitalized with severe injuries.³⁸³ Altogether 217 survived, although 190 of them (88%) had one or more functional musculoskeletal limitations. A substantial portion of the whole group had ongoing physical disabilities that limited their participation in normal childhood or adolescent activities within the 6 months following their discharge, suggesting a need for greater emphasis on the rehabilitation of pediatric trauma patients and, specifically, greater attention to the treatment of any extremity injury while the child was hospitalized. Colombani et al. reviewed 267 children with life-threatening multitrauma injuries and claimed that full recovery from the life-threatening specific injury or injuries was usual.¹²¹ Unfortunately, they neither defined

"life-threatening" nor described the injuries by any objective injury-scoring system.

Backx et al. reviewed 233 patients with major trauma admitted to a pediatric trauma center.⁶⁵ The male/female ratio was 1.7:1.0. The highest incidence of trauma occurred during the spring months and was lowest during winter. Most children (almost 80%) were injured between noon and midnight. Among them, 36% had musculoskeletal injuries. The mean length of time spent for resuscitation and stabilization in the trauma room was 49 minutes. The mean intensive care unit (ICU) stay was 3.2 days, and the total length of hospitalization averaged 11.2 days.

Peclet et al. surveyed hospital admissions in an urban children's hospital (Children's National Medical Center).²⁸¹ Over a 3-year period 12.9% of the hospital admissions were trauma-related. The average age was 5.5 years, and 64% were boys. The mortality rate was 2.2%. In a Hong Kong study of a population catchbasin of 1 million predominantly ethnic Chinese, 35% of the children and adolescents seeking care in the emergency room had trauma-related presentations, and 20% of the hospital admissions were trauma-related.¹¹³

Annually 50,000 children are injured as pedestrians in motor vehicle accidents.¹³⁶ Motor vehicle-related trauma remains the leading cause of death in children older than 1 year.^{296,300,397} Approximately 1800 die, 18,000 are admitted to a hospital, and 5000 have significant long-term sequelae. The physical, psychological, and economic burdens of traumatic injury and death are enormous, not only for the young victims but for their families and society as well.

The most common cause of multiple injury to children is a motor vehicle accident, with the child an automobile occupant or a pedestrian/cyclist. This statistic is well documented in reports of multiply injured children.¹⁸⁸ Among 376 multiply injured children, motor vehicle-related accidents accounted for 58% of the overall injuries and 76% of the severely injured children.¹¹⁰ In one series there was a 91% incidence of motor vehicle-related mechanism of injury.²³³ The incidence of motor vehicle-related injuries increases with age. According to the *Injury Fact Book*, deaths from motor vehicle accidents are lowest from birth to 14 years (5.9/10,000 to 10/100,000 population), with the peak occurring in the 15- to 24-year age group (26/100,000 to 45/100,000).⁶⁶ Boys in this age group have twice the mortality rate of girls.

Virtually all states have pediatric seat-belt restraint requirements for passenger vehicles to help prevent these deaths and injuries.^{161,187,340,341,353,374,375} The introduction of compulsory automobile safety seats or restraints for children in Michigan led to a 25% reduction in the number of children injured in automobile accidents.³⁷⁶ These laws are useful only if the restraint systems are used appropriately.^{100,102,128,187,325,340,362,368,389,390} Modifications must be made for children in body casts or in special-needs devices.^{101,141} Similarly, car seats for infants and toddlers are effective only if they are properly used.¹⁹⁶

In contrast, only a few states and other countries have safety laws or restrictions for passengers of any age who ride in the back of trucks. Woodward and Bolte reviewed a 3- to 4-year period during which 40 patients sustained injuries as a direct result of being a passenger in a cargo area (bed) of a truck.³⁹⁸ The mean age of the patients was

7.75 years. Head trauma was the significant injury in most of these patients. They concluded that until legislation is passed and enforcement is effective children riding in the back of a truck should (1) be restrained, (2) not stand while the truck is in motion, (3) not sit on movable objects within the bed of the truck, and (4) avoid movable cargo that could shift with bumps and turns. With the increasing recognition of the dangers of three-wheel all-terrain vehicles, legislation may, and undoubtedly is, necessary to curtail this health hazard.

Skeletal trauma accounts for at least 10 to 15 percent of these childhood injuries.* If all musculoskeletal tissues are considered, they would constitute at least 40% of all childhood injuries. Such injuries include strains, sprains, tendon disruption, muscle tears, and joint pain from injuries such as bone bruising. The latter might be considered skeletal injury without obvious radiologic abnormality (SKIWORA), analogous to the phenomenon of spinal cord injury without obvious radiologic abnormality (SCIWORA), discussed in Chapter 18. Many of these radiographically "occult" injuries may be diagnosed effectively with magnetic resonance imaging (MRI) (see Chapters 5, 6, 7). The occurrence of such occult injury raises serious questions about selection criteria for obtaining radiographs.¹⁹⁷ What is applicable in the adult may not be as efficacious in the child.

Mann and Rajmaira reviewed 2460 long-bone fractures in children.²⁴¹ Physal injuries accounted for 30%. Girls with physal fractures were 1.5 years younger than boys with the same type of fracture in the same location. Nonphysal fractures occurred twice as often in the upper extremity as in the lower extremity.

Cheng and Shen reviewed the fracture patterns of 3350 children with 3413 limb fractures (spinal fractures were excluded).¹¹³ The boy/girl ratio was 2.7:1.0 for all injuries. In the adolescent group the boy/girl ratio rose to 5.5:1.0. Distal radial fracture was the most common (19.8%), followed by humeral supracondylar (16.6%) and forearm diaphyseal (13.4%) fractures. When broken down by age, supracondylar humeral fracture was most common in those 0–3 years old and those 4–7 years old, accounting, respectively, for 28.9% and 31.2% of all limb fractures. Distal radial fractures occurred in 27.1% of the 8- to 11-year group and 23.3% of the 12- to 16-year group. Open fractures were uncommon (2.2%). Greenstick fractures were found in 5.3%. Seasonal variation occurred, with more fractures during the summer and autumn months. The open reduction rate was 10.1% in those 0–3 years old and rose to 34.0% in those 12–16 years old.

Young patients with multisystem injuries that may be or are life-threatening (see Chapter 3) may experience failure to diagnose less obvious fractures and dislocations, especially during the acute resuscitative processes. Chan et al. reported a 12% failure rate to diagnose even "significant" musculoskeletal injuries in 327 patients.¹¹⁰ Even when an appropriate musculoskeletal injury diagnosis was made, the tendency was to assign the injury a low priority, a factor that could eventually lead to skeletal deformity and dysfunction. Adequate fracture diagnosis and care *must* be an integral part of the emergency and subsequent care of any multiply injured child.^{23,287}

Brainard et al. found the triad of head, pelvis, and knee injuries traditionally associated with pediatric pedestrian motor vehicle accident victims did not occur.⁹⁶ They did, however, find an association of femoral and pelvic fractures and an ipsilateral dyad of an upper and lower extremity fracture on the same side.

Oudjhane et al. reviewed 500 consecutively radiographed acutely limping toddlers.²⁷⁸ Twenty percent ($m = 100$) had a fracture as the underlying etiology; the fibula ($m = 56$) and femur ($m = 30$) were most common, although pelvis and foot fractures also occurred. There were 11 patients with metatarsal fractures.

Early reviews developed primal concepts of approaches to fracture treatment in children. Walking, in 1934, reviewed patterns of healing and was one of the first to address concepts of longitudinal overgrowth and remodeling of angular deformities.³⁷⁷ Beekman and Sullivan, in 1941, reviewed 2094 long-bone fractures seen over 10 years (1930–1940) and presented many still usable basic principles for treating children's fractures.⁷⁵ Wong explored cultural studies of fracture incidence after comparing Indian (Asian), Malay, and Swedish children.³⁹⁶

Rosenthal pointed out that many simple fractures can be adequately managed, treated, and even reduced under appropriate conditions in an office setting rather than requiring the patient to go to an emergency room.³¹⁸ Furthermore, initial emergency treatment may be rendered in the office for some injuries that require definitive management in the hospital.^{49,179}

Particularly, pediatricians tend to see patients with greenstick and torus fractures because of the often innocuous nature of the injury. They may also be involved with patients who have undetected trauma due to abuse. Treatment of these injuries must be based on knowledge of not only the pathophysiology of the injury but also the ramifications for complications, additional soft tissue injury, and so on that might affect treatment. Obviously, treatment of these injuries by the pediatrician or family practitioner should be contingent on a feeling of "ease" during application of a cast or splint. By assuming care of these patients, rather than referring them to an orthopaedist, the primary care physician thus assumes the same standard of care that would be rendered by the orthopaedic specialist. Suboptimal treatment (e.g., inappropriate reduction) or failure to recognize a complication (e.g., compartment syndrome) exposes the primary care physician to liability at the same level as the orthopaedist. The standard of care for fractures and dislocations of the immature skeleton are the same no matter whether the treatment is rendered by an orthopaedist, family practitioner, or pediatrician. This same liability holds for the interpretation of imaging studies. If one assumes responsibility for reading radiographs, computer tomography (CT) scans, or MRI, that individual is liable for his or her action.

Prevention

Obviously an important parameter when dealing with childhood injury is to recognize injury patterns and, accordingly, to devise measures to prevent injuries or at least lessen the

* Refs. 75,83,90,104,133,139,173,178,182,225,232,242,243,246,262,288,290,326,337,352,358,365,371–373,387,392,395,404.

likelihood of their happening.* The American Academy of Pediatrics has a standing Committee on Accident and Poison Prevention that has developed a number of position papers and programs directed at the prevention of significant injurious factors in children.⁵⁴⁻⁶⁰

Education of parents is integral to making children aware of injurious factors in their environment.^{74,321} Rivara et al. presented an interesting study showing that although 94% of parents did not believe that 5- to 6-year-old children could reliably cross streets alone, one-third of the parents allowed kindergarten-aged children to walk alone to school.³⁰² These authors thought that parental expectations for their child's pedestrian skills were inappropriate and might be a fruitful target for injury prevention programs.

Having appropriate leaflets and posters in the waiting room may play an important role in this process.⁷² On a national basis Sweden has enacted an array of changes affecting traffic and childhood activities in an attempt to decrease childhood injury, with a significant success in reducing the injury rates.^{77,385}

Rivara et al. showed that although factors in a child's daily living environment and socioeconomic background contribute significantly to the risk of pedestrian injury little reduction in the incidence of childhood pedestrian injuries may be expected from any attempts to modify individual behavior.^{300,305} The inability to assess distances and speeds effectively and to localize sounds adequately, combined with the normal impulsiveness of young children, results in unsafe traffic or pedestrian behavior by most children younger than 12 years, no matter what the socioeconomic group.^{170,186,322,329,401} Teenagers probably are even more unlikely to respect the external milieu.

Basic Differences Between the Child and Adult Patient

Patient History

Historical details of any injuries may be totally lacking, erroneous, or purposely deceptive. This is particularly true of the battered or abused child. Frequently, no responsible adult has witnessed the specific accident. Any child's account of the details of the accident often tends to be oversimplified, halting, or incomplete. However, knowing how the injury specifically occurred often enables the physician to anticipate the full extent of the injury, including any important associated injuries. Appropriate treatment may be accomplished much more satisfactorily when the physician has detailed knowledge of the actual or probable mechanism of injury.

The variable lack of historical data on childhood injuries usually requires that particular significance be attached to the physical examination, which must thoroughly assess the type of deformity, location, degree of concomitant soft tissue swelling, and integrity of innervation and circulation. Physical examination, rather than historical data, often prevails in the child.

* Refs. 120,143,204,205,236,237,244,254,317,342,343,348,355,369,370,393.

Parental Involvement

An adequate discussion with the parents is often as important as the treatment of their child's injury. It is imperative to establish not only a good doctor-child patient relationship but also a satisfactory doctor-parent relationship, as the parents are instrumental in carrying out the essentials of subsequent care, especially rehabilitation. The troublesome areas of diagnosis and treatment should and must be elucidated in words the parents can comprehend. In a polyglot society this communication often entails using a translator capable of effectively communicating information between physician and family regarding diagnosis, treatment, and prognosis. However, the burden of responsibility for understanding the ramifications of the injury should be that of the parent, *not that of the physician*, whose primary responsibility is effectively treating the child. Whenever possible, parents should bring a family member or friend who can adequately translate.

The treating physician should be certain that the parent(s) adequately understands the various aspects of the injury, treatment, and prognosis. The parents should be counseled regarding the parameters of acute care and about any potential chronic or long-term problems. The doctor should discuss the possibilities of limping, temporary loss of full range of motion, nerve injury, loss of reduction after initial treatment, and the need for remanipulation; adequate follow-up care should be emphasized, in many cases until skeletal maturity is attained to assess growth and remodeling. Proper follow-up care is undoubtedly the most difficult compliance factor, especially after the child appears outwardly normal several months after injury. Nonetheless, it is the most significant element when anticipating and diagnosing subsequent problems of premature growth disruption or arrest during the early stages. During a growth spurt, seemingly minor problems may rapidly assume major importance, especially when dealing with growth mechanism injuries.

Childhood injury may lead to serious work and financial problems for families.^{277,384} Long acute hospital stay and four or more impairments are good predictors of potential family difficulties. Some school systems are reluctant to accept injured children back in school until they are free of casts.¹⁸⁹ Such a problem also affects family dynamics.

Susceptible Child

Certain children seem to be accident-prone.^{62,79-81,91,117,198,250,252,253,274,284} Wesson and Hu compared 92 injured children to a control group with appendicitis.³⁸³ About 54% of the minor-injury group and 71% of the major-injury group had persistent physical limitations 12 months after injury (none in the controls). Of the minor-injury patients, 38% had preexisting behavioral disturbances, as did 14% of the major-injury patients and 10% of the controls. The authors noted a significant increase of maternal malice in the injury groups compared to the controls. The family background may be an important factor in accident-proneness.^{95,99,199}

Loder et al. studied 52 children (2-16 years of age) with extremity fractures.²³³ The family functioning was usually normal; but there was a statistically significant

increase in the number of children with conduct problems, psychosomatic complaints, and impulsive/hyperactive behavior. There was a significant increase in children with social competence problems as well, such as externalizing behavioral problems.

The association of accident-proneness and hyperactivity is being increasingly recognized as a major factor in accident recidivism.^{127,240} Another risk factor may be left-handedness.^{166,231,259} A patient sustaining an ankle injury or fracture appears to be at greater risk for repeat injury. Karlsson et al. found that the study group with former ankle fractures continued to have a twofold increased incidence of all types of fracture.²⁰⁰

Bijur and colleagues showed that children with three or more separate injury events reported between birth and 5 years of age were six times more likely to have three or more injuries reported between 5 and 10 years of age than children without early injuries.⁷⁹ Children with one or more injuries resulting in hospitalization before 5 years of age were 2.5 times as likely to have one or more admissions to a hospital for injuries after 5 years of age. Other predictors of injuries between 5 and 10 years of age were male sex, aggressive child behavior, young maternal age, and many older and few younger siblings. Some authors have questioned whether the identification of accident-repetition qualities or individuals has any effect whatsoever in preventing further injury.¹³¹

Special Features

Multiple factors make fractures of the immature skeleton different from those of the mature skeleton. Fractures are more likely to occur after seemingly minimal trauma. The periosteum is thicker, stronger, more resistive to displacement, and more biologically active. Any specific diagnosis presents particular problems because of the variable radiolucency of the incompletely ossified epiphyses. There is a distinct perception that if standard radiographic techniques do not demonstrate musculoskeletal fracture the bone cannot possibly be injured. However, as is shown in Chapter 5, radiographically invisible or occult bone bruising and injury certainly may occur, as can separations at the chondro-osseous interface of the secondary ossification center and the epiphyseal cartilage. Some residual angular deformities may correct spontaneously, although not all do. Complications to the bone, cartilage, and soft tissues tend to be fewer and different. Methods of treatment receive different emphases, with closed reduction often receiving the most emphasis. Joint injuries, dislocations, or ligamentous disruptions are much less common.

Injuries may involve specific growth regions, such as the physis or epiphyseal ossification center, and may lead to significant acute or chronic disturbances of growth. The normal processes of bone remodeling in both the diaphysis and the metaphysis of a growing child may progressively realign many initially malunited fragments, making absolutely accurate anatomic reductions less important in a child than in an adult, although anatomic reduction should be attempted whenever possible. *The treating physician should not unequivocally rely on "spontaneous" correction of an angular rotational or bone length deformity.*

Fractures variably stimulate longitudinal growth by differentially affecting the blood supply to the metaphysis, physis, and epiphysis and by disrupting the periosteum and its tethering (restraint) mechanism on rates of longitudinal growth of the physis.⁸² Therefore some mild degree of longitudinal overriding with bayonet (side-to-side) apposition (approximately 1 cm) may be acceptable in certain age groups and may even be desirable, particularly with fractures of the femur or tibia. However, if such longitudinally aligned (nonangulated) overriding is accepted, rotational alignment should be anatomically corrected.

A group of 126 children with fractures of the femoral and tibial diaphyses had a temporary growth acceleration that reached a maximum at 3 months and returned to normal by 40 months in the tibia and by 50–60 months in the femur. The maximum acceleration occurred with overlap (overriding) of the fragments, in contrast to end-to-end reduction. The average increase in the femur was 0.7–0.8 cm and in the tibia 0.3–0.4 cm. A fractured femur often was accompanied by accelerated growth in the ipsilateral tibia. In contrast, however, tibial fractures were not usually accompanied by ipsilateral femoral overgrowth. Regardless of the child's age or the type of injury, it is unlikely that the *final* correction of discrepancy in length will exceed 0.5–1.0 cm.²⁹³

Effect of Age

Bone healing is much more rapid during childhood because of the thickened, extremely osteogenic periosteum and the abundant blood supply to most osseous regions. The younger the child, the more rapid are the usual callus response and subsequent union. The dependence of healing capacity on age is significant. At birth fracture healing is remarkably rapid, but it becomes progressively less rapid during childhood and adolescence. Healing of a femoral shaft fracture in a newborn may take only 3 weeks, whereas 20 weeks is not an uncommon length of time in a teenager. The rate of healing in the bone is directly related to the osteogenic activity and reactive ability of the periosteum and endosteum and to the relative maturity of the cortical bone (i.e., a thick diaphysis versus a thin metaphysis).

After acute trauma it is appropriate to follow any child until skeletal maturity to derive meaningful conclusions, especially any ramifications for alterations of normal growth. This principle applies to any study of the long-term consequences of fractures in children. The common tendency to cease follow-up care 6–12 months (if that long) after the injury may result in subsequent presentation of significant growth deformity and irate parents. Unfortunately, such continued assessment is *not* the usual situation in most practice situations. Parents also tend to discontinue follow-up when the child *appears* to have recovered. The physician should encourage long-term follow-up but must also realize that it is not always practical or possible. Always document any parental counseling regarding such potential problems.

The age groups from infancy to adolescence have varying injury patterns. Children also have certain reactions to injury, such as a pseudoparalysis of the limb of a newborn in response to a fracture of the shoulder girdle or proximal femur. Knowledge of these aspects, when considered com-

mensurate with the particular mechanism of trauma, is often helpful for establishing the diagnosis and rendering the most effective treatment and prognosis to the parents. During periods of rapid growth children may twist or strain an arm or leg, an "injury" that hardly seems to merit consideration by the parent or the physician. However, this twisting may cause chondro-osseous micro or macro failure, particularly of the tibia, which is susceptible to occult fracture in children 1–5 years of age (the "toddler's fracture"). Such injuries are not usually discerned on routine planar radiographs.

The annual incidence of injuries is lowest during the first year of life.³⁰¹ The highest rates are during the next year (1–2 years), and in the age range 13–18 years. The boy/girl ratio is most equal at 1 year (1.05:1.00), changing to 1.9:1.0 in teenagers. The teenage boy has the highest susceptibility to injury.^{206,231}

Iqbal showed that upper limb fractures in children were seven times more common than lower limb fractures, and that the incidence of fractures was much higher during the preschool period.¹⁹² The only fractures showing a major variation from this pattern were forearm fractures, which demonstrated a progressive increase with increasing age, attaining maximal frequency during the prepubescent period. In contrast, clavicular fractures were most common during infancy and the preschool period but became less frequent during the school years. Other studies have shown that upper extremity fractures are three times as common as lower extremity fractures in children.^{192,216,217,290,384,387,399}

The site, frequency, and nature of traumatic bone lesions are all conditioned by the skeletal maturation of the patient.^{123,169,218,289,293} The fetal bones, which are effectively protected from external trauma by both the amniotic fluid and thick uterine wall, are rarely traumatized (see Chapter 11). However, chronic intrauterine stresses operating on a fetus may cause changes in the shape of fetal bones and joints, causing postural disorders such as prenatal bowing of the long bones, club feet, and developmental hip dysplasia. Localized deformations affecting the mandible, facial bones, and skull bones may occur. During birth, especially with breech deliveries, a wide variety of traumatic lesions may occur, including fractures of the shafts and epiphyseal cartilages (e.g., distal humerus and proximal femur). Common obstetric fractures involve the skull and clavicles.³⁴

Fractures are relatively rare during the first postnatal year. However, multiple, especially severe fractures may be the first indication of metabolic disorders or skeletal dysplasia (e.g., hypophosphatemic rickets or osteogenesis imperfecta) and *must be considered* in the differential diagnosis of any case of suspected child abuse. Most willful assaults (the battered child) occur during the first 1–2 years of life. From the age of 2 years on, particularly from the time the child starts to walk, the most commonly fractured bones are the clavicle and radius. The high incidence of radial fracture continues into adolescence, although the pattern changes from fractures of the shaft and distal metaphysis to fractures of the distal physis. Fractures of the phalanges and metacarpals are also common during the first 2 years while the child is learning to walk.²⁹⁰ Such hand (metacarpal and

phalangeal) fractures remain frequent throughout childhood, although they are underemphasized in most studies of fracture incidence.

It is important to realize that skeletal age and chronologic age are not always synchronous. One need only observe the range in sizes of children in a given school grade to realize that rates of growth and maturation differ not only between boys and girls but also among children of the same biologic gender. Unfortunately, physical demands, especially sports participation, are generally based only on chronologic age. Thus a child born in December of a given year may be compared with a child born in January of the same year. Thus almost a year of maturational difference and, more importantly, size difference (height, body mass, or both) may be present. Given the physical demands of any organized sport, this may have a dramatic effect on musculoskeletal injury susceptibility. Grouping based on chronologic age may put certain children at serious risk for injury from "similar-aged" but obviously physically larger peers.⁵¹ Efforts are being made to quantify muscular development and strength.^{257,258} Such studies may lead to more effective structuring of childhood sports.

Particular consideration should be given to the adolescent approaching skeletal maturity. Healing of fractures may be more prolonged than in the younger child. Peer and adult (parent, coach) pressure may encourage or "demand" return to athletic activity before the individual is physically or physiologically recovered. Remodeling of an injured bone in an adolescent is less likely to correct malunion.²⁶³ Internal fixation of long-bone fractures in the polytraumatized adolescent, particularly one with a femoral shaft fracture, may decrease morbidity in such a patient. Ligament injuries and joint dislocation become more common with the attainment of skeletal maturity. In one study 40% of the injuries during the 12th and 13th years occurred during sporting or similar physical activities.¹⁰⁷ The most common injuries were sprains or strains followed by fractures or lacerations. Most injuries were minor.

One of the most significant epidemiologic studies of children's injuries and fractures has been that of Langley and associates.^{107,221–224,234} They studied a group of 1000 children aged 1–15 years. They found, for each 2-year period, that approximately 20% of the children were injured. Most injuries were of soft tissues. Fractures slowly increased in frequency from 16% of injuries in the 6- to 7-year group to 24% in the 14- to 15-year group.

Landin and Nilsson showed that fractures are responsible for 10–25% of all injuries in children and adolescents.^{216,217} The fracture rate in the Malmö study increased in children of both genders up to the age of 11–12 years. It then decreased in girls but further increased in boys to age 13–14 years. The figures showed that the accumulated risk of having at least one fracture from birth to the age of 6 years is 42% in boys and 27% in girls.

Season

Variation of fractures occurs by age, season of year (which varies with regional climate patterns), cultural variations, and environmental challenges.⁶¹ Rural patterns differ from urban patterns. For example, multilating injury from farm

machines is more likely in a farm environment during planting and harvesting seasons, whereas falls from heights (multistory buildings) are more likely in the urban situation during the summer months.

The exposure time to outdoor sports activities may be greater for children who live in warm climates. However, many concepts have failed to discern the reality of outdoor cold sports (skiing, skating, sledding, tobogganning) and their attendant risks of injury.

With certain sports the climate has an effect. In subtropical parts of the United States (Florida, Texas, Arizona, Southern California) sports such as baseball are often played year-round. This makes the likelihood of certain injuries, such as Little League elbow, much more likely than in areas of the country with climates with short sport seasons.

Activity Levels

Children generally approach life with relatively unbridled exuberance. This factor must be considered in any plan of treatment. Once pain subsides, any child or teenager tends to forget that an extremity has been injured and quickly returns to the usual levels of preinjury activity. Such reversion to structured activity, however, may not be conducive to continued fracture healing and biomechanically responsive remodeling; furthermore, it may damage immobilization devices.

Fracture etiology reflects levels of activity during growth. Simple falls are the predominant cause in small children. In older children playground equipment and sports-related accidents are more common.

Sports and Recreational Injuries

Children are constantly exposed to recreational activities. There is increasing impetus to participate in structured athletics both during and after school. As such, the potential for contact and noncontact injury increases.^{37,108,129,157,214,220,235,248,276,285,364,366,378}

As participation (and accordingly injury) increases, the number of studies that document the general and sports-specific injury patterns grows. Krist et al. showed an increasing incidence of sports-related injuries, rising from 14% of all injuries in the 6- to 10-year-old cohort to 26% of all reported injuries in the 11- to 15-year-old group.²¹⁴ No sport seemed at higher risk than any other, although certain injury patterns prevailed in certain sports (see Chapter 12). Depending on the complexity of the details of the analysis, fractures have comprised between 7% and 26% of all reported injuries in childhood/adolescent sports activities.

Childhood is also a time of increasing emphasis on competitive individual and team sports, often with a greater drive coming from the parents or coach rather than from the child. Organized sports, which are progressively involving girls and younger children (e.g., soccer), particularly predispose the improperly conditioned child to injury.^{23,37,169,273,319,338,364}

Children frequently try to return to these athletic programs as quickly as possible after any injury, often before complete healing. The additional stress from a parent or coach to return the child to the playing field often makes

continuing medical care of these children difficult. Furthermore, sports for young children rarely emphasize the need for conditioning, sports-related training, and warm-ups. Children are invariably perceived as injury-resistant.

Zaricznyj et al. studied 25,000 school children in sports-related (organized) activities.⁴⁰⁵ The injury rates of total participants were 3% (elementary school), 7% (junior high school), and 11% (high school). Nonorganized sporting activities may have an injury rate twice that of organized sports. The overall percentage of fractures during sporting events is 18–20% of all injuries.⁴⁰⁵

Children may sustain fewer injuries in organized sports (4%) than in routine physical education classes (18%).^{65,94} This difference reflects the mandatory nature of physical education classes for all students of all physical ability, in contrast to organized sports, which tend to attract the more physically capable and coordinated youngsters.

A more detailed discussion of the role of sports in children injuries is presented in Chapter 12.

Hockey

Ice hockey is gaining in popularity and, accordingly, individual participation. Over the past decade an increasing assessment of injuries at various competitive levels has led to the mandatory use of safety equipment. Much of this has been directed at the use of masks and guards to prevent significant facial injuries.²⁶⁴ Extremity fractures may be relatively infrequent, as the feet are rarely rigidly fixed to the playing surface.

Soccer

Hoff and Martin studied injury patterns for indoor and outdoor soccer.¹⁸⁵ The number of fractures and injuries was greater for indoor soccer. This may be related to the smaller playing field and the impact against the walls (not unlike hockey).

Skateboarding/Rollerblading

Skateboarding has had variable popularity. Its recent resurgence seems coattailed to the increasing popularity of rollerblading. Most reported injury mechanisms are in children.^{53,63,67,103,105,282} Head injuries are frequent but tend to be mild because of requisites for helmet use. Upper limb fractures are much more frequent than lower limb injuries.^{180,194,239,292} The peak incidence for injury is in the 11- to 15-year-olds, which certainly correlates with the increasing willingness to take risks. One study noted more-serious injuries in children less than 10 years.¹⁰⁵ Another did not find such a difference.¹⁹⁰

A study of in-line skating evaluated 78 fractures in 61 children.²⁵⁵ Distal radial and ulnar fractures comprised more than 75% of the injuries. Almost half the patients were novices, with less than 4 weeks of experience.

Equestrian Sports

Horseback riding is experiencing increasing popularity and, accordingly, more exposure to injury (especially among

girls). Compared to other childhood sports, the sustained injuries tend to be more severe, with head and facial injuries being frequent.^{71,84,85,88,160,268} Upper extremity fractures are frequent, due to falls and the impact against barriers and jumps. In one series there were 152 injuries in 136 patients.⁷¹ Ten patients sustained spinal fractures. Five other children sustained pelvic fractures, which occurred when the horse fell on the rider.⁷¹

Head injuries caused 57% of the deaths.⁸⁵ The upper extremity was most commonly injured. Girls were injured more often than boys. A previous horse-related injury had occurred in 25% of those significantly injured.

Skiing

Winter sports enjoy increasing popularity but expose participating children to the risk of injury. Interestingly, whereas upper extremity and spine injuries are common in adults, children tend to have more lower extremity injuries.^{83,183,367} The thumb of children appears particularly susceptible to injury, especially in the physes at the metacarpophalangeal junction.¹⁸⁵ Lower limb injuries usually involve the knee and tibia/fibula in children and are most likely when the binding fails to release. Improvement in equipment is leading to a decreasing incidence.

Snowboarding injuries were evenly distributed between upper and lower extremities, and 41% were fractures.¹⁵³ The wrist was the most common injury site.

Playground

Both school and neighborhood playgrounds are frequent areas of childhood activity. Safety factors are not always evident in the design of activities. Even when a great deal of thought has gone into the design of certain structures, it may only predispose to a different injury pattern.^{165,382}

The increasing utilization of preschool facilities places young children in accident-susceptible situations.^{111,210,211,219,327,377} These children, whose motor skills and attention spans are incompletely developed, are often encouraged to engage in play activities that may be beyond their physical ability. Proper scrutiny of potentially hazardous environments should be undertaken by parents before enrolling their child in a given center.

Mott et al. reviewed injury patterns in public playgrounds.²⁶⁰ A total of 105 children fell from equipment (usually the climbing frame); 125 children had surface-related injuries (85 on bark, 30 on concrete). Fractures and sprains, interestingly, were more common on the bark surface; and lacerations and abrasions were more prevalent on concrete. Children may take more risks on bark surfaces. The play equipment is often more interesting and usually entails climbing. However, the depth and firm underlying (dirt) surface essentially fix the extremity as the fracture-producing forces continue. On a concrete or hard surface more slipping/sliding may occur, lessening the longitudinal loading associated with children's fractures.

Trampolines

Trampolines have become a significant risk to children.^{54,93,227,275,345,398} A 6-year study (1990–1995) showed an

injury increase from 29,600 in 1990 to 58,400 in 1995.³⁴⁵ The median age of injured children was 10 years. The male/female ratio was 1:1. Injuries to the extremities predominated among children of all ages and accounted for more than 70% of the injuries. There was an inverse relation between age and the relative frequency of upper extremity injuries, fractures, and dislocations. There was a direct relation between age versus lower extremity and soft tissue injuries. There was also an inverse relation between age versus facial injuries, head and neck injuries, and lacerations. Annually 1400 children required hospitalization, which represented 3.3% of all children with a trampoline-related injury. Fractures or dislocations accounted for 83% of injuries among admitted children. A disproportionate number of these injuries occurred on backyard, rather than commercial, trampolines.

Olsen reported injuries in children on trampoline air cushions and found that 70% of children explained that they had either been pushed or had lost their balance because of constantly changing rhythm on the "bouyant" surface.²⁷⁵ Olsen strongly recommended some type of control over the apparatus.

Common Injury Mechanisms

The constant exploration of intriguing aspects of everyday activity may lead to interesting ways of potential injury. Misuse of common "vehicles," such as a shopping cart, may cause significant injury.³⁴⁷ Fads such as break-dancing may cause acute and unusual chronic injuries.^{158,273,338}

Automobiles

At all ages the automobile is the principalcrippler of children, causing severe skeletal abnormalities.^{323,341,370,375,389} However, other powered vehicles are assuming increasing importance as causal mechanisms. They include off-road vehicles, bicycles (especially off-road or downhill), skateboards, in-line skates, and jet-skis. Traffic accidents account for 10–12% of the cases.

The serious hazards of snowmobiles, power lawn mowers, trail bikes, and other small powered vehicles are becoming increasingly evident.^{229,349,387} Even nonpowered vehicles, such as skateboards and in-line skates, are becoming a significant cause of fractures during childhood and adolescence. Trauma secondary to all-terrain vehicle use (and abuse) has become a significant health problem in the pediatric population and has led to a variable prohibition of the use of such vehicles.^{125,286,356,388}

In the Vehicle

Most severe and fatal childhood accidents occur to youngsters or adolescents who are in cars.^{38–47,208} The array of skeletal injury varies with the scope of the study. Many studies describe only mortality and morbidity statistics and various trauma score indices. Specific or likely fracture patterns are infrequently documented in detail.

Agran et al. studied 191 seat-belted children⁴¹; 33 (17%) children were injury-free. Among the 191 children, 6 had

extremity fractures (3 femur, 1 clavicle, 1 humerus, 1 forearm). There were no spine fractures. In a similar study of pickup trucks, 14 of 89 children sitting in the back and 10 of 201 sitting in the cab sustained fractures.⁴⁶ Most injuries involved the head or soft tissues.

By the Vehicle

Children do not rationally comprehend the potential for vehicles to harm them, nor do they adequately grasp concepts such as velocity even when they take the time to look both ways.^{130,170,186,289,322,323,329,360,394,400,401} Vehicles have become the most frequent cause of death for children aged 5–9 years. Extremity and head injuries are much less likely when the child is properly seat-belted in a car.^{41,215} Soft tissue injury to the arms or legs may be more frequent than fractures (38 of 60 extremity injuries versus 22 fractures.¹³⁰ Bell et al. described fractures in children run over by slowly moving vehicles.⁷⁶ They tended to be young children (all but one under 6 years). The thorax, cranium, pelvis, and femur were common injuries.³⁹

Bicycle

Wheeled vehicles are common to childhood activity and are frequently associated with injuries.^{89,137,146,151,191,266,270,330} Of all bicycle accidents, 70% result from falls rather than impact injuries. Tricycles tend to be kept within property boundaries, but that does not preclude injury. Small children may dart or ride behind vehicles while they are backing up. Bicycles provide “freedom” to the child. Because they are often associated with fun or play, the child’s attention to potential hazards such as traffic tends to decrease.

Head and neck injuries comprise approximately 20–30% of the injuries.³⁸ Head injuries are the most important etiologic factor in death, which has led to increased emphasis on the mandatory use of helmets.^{126,267,279,315,316,333,335,363,379,380} Sosin et al. studied bicycle injuries and deaths (0–18 years).³⁵⁰ They found an annual average of 247 brain injury deaths and 140,000 head injuries. They thought that as many as 184 deaths and 116,000 head injuries could have been prevented with the proper use of helmets while on the bicycle.

Statistics vary on finding more upper than lower extremity injuries and vice versa. In most series soft tissue injuries were most prevalent, with upper and lower extremity fractures being only about 14% 13%, respectively.

Seats on bicycles (front or back) expose small children to adult-level injurious forces.^{331,361}

Off the Road

Recreational vehicles have received increasing attention because of the rate of accidents and the lack of licensure to operate.^{52,125,132,163,229,283,348,356,386,388} Three-wheel all-terrain vehicles caused enough serious injuries such that further sale was banned in 1988.¹³² A variety of vehicles are available (minibikes, dirt bikes, mountain bikes, snowmobiles), as are water vehicles (ski-dos). Pyper and Black reviewed 233 children (injured by these vehicles) who sustained 352 fractures (60 physeal, 34 open).²⁸⁶ All-terrain vehicles were often associated with pelvic and spine fractures.

Infant Walkers

Infant walkers have been the cause of multiple childhood injuries.^{114,142,203,280,294,381} Mechanisms include falls from the walker, falls down stairs, and burns. Sheehan et al. showed that infant walkers are a significant cause of trauma.³³⁹ In this case they reported a 10-month-old girl who sustained bilateral fibular diaphyseal fractures.

Falls

Gratz reported that most pediatric injuries are caused by simple falls, either from a level surface or a variable height, accounting for 46% of injuries overall.¹⁶⁷ The most common falls come from playground equipment. Falls by children are frequent and account for almost 50% of all childhood deaths due to trauma.^{70,106,138,174,228,251,265,320,344,351} Musemeche et al. reported a fatality rate of 23%.²⁶⁵ One of the highest national death rates due to falls occurs among nonwhite children less than 5 years of age.³⁴⁰ Despite this statistic, falls are only the seventh leading cause of death in children from all causes. Chadwick et al. reported seven deaths in 100 children who fell 4 feet or less.¹⁰⁶ One death occurred among 117 children who fell 10–45 feet. The seven children who died in the short falls *all had other factors that suggested fabricated histories.*

Falls are of increasing importance in young children, being the third leading cause of mortality in children aged 1–4 years. Even simple falls by the infant or young child can be significant.⁴⁸ According to these investigators, falls contributed to 41% of the deaths in this age group. Musemeche and associates showed that falls occur predominantly in the younger population, with a mean age of 5 years and a 68% male preponderance.²⁶⁵ Seventy-eight percent of the falls occurred from a height of two stories or less and occurred at or near the home. Most of the patients sustained a single major injury that usually involved the head or skeletal system. Fortunately, children can survive falls from significant heights, though serious injuries do occur.²⁹⁶ As would be expected, morbidity and mortality increase with the height of the fall, the latter usually being related to falls of a distance exceeding 10 feet.

Falls may occur from a height (building, ski lifts), on a level surface, or from a moving vehicle (e.g., bicycle, skateboard). Falls from a height are an urban hazard, with fatalities being as high as 23%.²⁶⁵ Rural children have similar hazards (e.g., water towers, multistory barns) and so are not immune to this etiology. Falls are probably the most frequent cause of childhood fracture.^{154,156,347} Injuries to the pelvis and spine are less common in children.

Falls from heights constitute a significant portion of urban trauma.²⁶⁵ In one study 70 children (1985–1988) sustained a fall of 10 feet or more. The patients’ ages were usually 5 years or younger, and 68% were boys. About 78% of the falls occurred from two stories (20 feet) or less and usually took place at or near home. Most patients had a single injury, and *all* survived. Injuries usually were head or skeletal. Falls are the leading cause of nonfatal injury in the United States and are second to motor vehicle accidents as a cause of accidental death.

Falls down a set of stairs are also common.¹¹⁵ Joffe and Ludwig studied 363 such injuries¹⁹⁵: 50% were in children 5 years of age or younger. The severity of injury did not correlate with the height of the top stair of the fall. Head injuries predominated, but only 6 of 363 sustained an extremity fracture. Most of the patients sustained superficial extremity injuries. Osseous injuries occurred in only 7% of the patients (six fractures). Children younger than 4 years of age were more likely to sustain head and neck injury trauma than children older than 4 years of age. In fact, almost three-fourths of the injuries involved the head and neck. An injury to more than one body part occurred in only 2.7% of patients. *Children who fell down more than four steps had no greater number, or severity, of injuries than those who fell down fewer than four steps.* Therefore be suspicious of any extremity fracture if “stairway” is mentioned as the cause.

This injury pattern was common in young children learning to master the stairs.¹⁹⁵ It also was a source of injury as they gained more confidence and increased the rate of ascent or descent. Joffe and Ludwig concluded that when multiple, severe truncal, or proximal extremity injuries were noted in a patient who “reportedly” fell downstairs a different mechanism of injury (e.g., abuse) should always be suspected and the child carefully assessed as to its likelihood.¹⁹⁵

Chiaviello et al. studied stairway-related falls in 69 children less than 5 years old.¹¹⁵ Head and neck injuries occurred in 90%, extremity injuries in 6%, and truncal injuries in 4%. Injury to more than one body region did not occur. Fifteen patients (22%) sustained significant injuries: concussion ($m = 11$), skull fracture ($m = 5$), cerebral contusion ($m = 2$), subdural hematoma ($m = 1$), and a C-2 fracture ($m = 1$).

Nimityongskul and Anderson studied 76 children from birth to 16 years who were reported to have fallen out of a bed, crib, or chair *while in the hospital*.²⁶⁹ About 75% of the injuries were in children 5 years of age or younger. The height of the falls ranged from 1 to 3 feet. Most injuries were minor (hematoma, laceration). The only fracture involved a child with osteogenesis imperfecta. Severe head, neck, spine, and extremity injuries are *rare* when children fall out of hospital beds.^{181,230} Child abuse must be suspected in any child with a severe head or extremity injury following an alleged “fall from a bed at home.”^{212,238,249,269,349,391}

The exception might be the “bunk bed” fracture of the first metatarsal when the child falls or jumps from the top bed.³³⁶ However, this is a relatively innocuous fracture compared to those usually associated with child abuse. This fracture usually occurs as the child *jumps* (voluntarily) to the floor from the top bed. It is a torus or impaction fracture in the proximal metaphysis of the first metatarsal. It is not the typical shearing fracture of abuse. This injury pattern is discussed in more detail in Chapter 24.

Helfer et al. studied 246 children aged 5 years or less who fell out of bed (219 at home, 95 in hospital).¹⁸¹ The data revealed *no* occurrence of a serious injury.

Interestingly, in various series^{70,265,348} the fractures common with adult falls from a height (calcaneus, spine, pelvis) are infrequent. The upper extremity is more likely to be involved, and head injuries are common.

Vending Machines

Cosio and Taylor studied 64 patients with injuries secondary to being crushed by a vending machine.¹²⁴ All victims were male, except one. The average age was 19.8 years. Thirteen patients sustained multiple injuries. Fifteen were killed.

Biologic Differences Between Child and Adult Skeletal Trauma

Many if not all of the differences between the traumatized skeletons of an adult and a child relate to the fact that the child's skeletal elements are in more dynamic, constantly changing growth and remodeling modes. In contrast, the adult skeleton essentially has ceased the processes of elongation and apposition and is principally (and much more slowly) remodeling the established elements in accord with stress responses (i.e., forming increasing patterns of primary, secondary, and tertiary osteons). The major practical differences between childhood and adult skeletal trauma fall into three categories: anatomy, physiology, and biomechanics.

Anatomy

Because of the endochondral ossification process, the chondro-osseous epiphyses of children are variably radiolucent, making roentgenographic evaluation difficult, if not impossible, unless specific invasive (e.g., arthrography) or noninvasive (e.g., MRI) procedures are used. Specific skeletal injury is sometimes inferred on the basis of clinical judgment, as routine roentgenographic substantiation may not be possible, although subsequently trauma-reactive subperiosteal new bone formation may verify the diagnosis. In contrast, MRI may delineate the injury. The physis is constantly changing, with active longitudinal and diametric growth and in its mechanical relation to other contiguous components. Modes of failure thus vary with the extent of the chondro-osseous maturation. The involvement of the physal and articular cartilages in angular deformities is important to certain concepts of fracture treatment, both acutely and long term.

The periosteum also differs in a child, being thicker and more readily elevated from the diaphyseal and metaphyseal bone due to a subperiosteal fracture hematoma or stripping during fragment displacement. It is less readily completely disrupted and exhibits greater osteogenic potential.

There is a pronounced reaction of periosteum and endosteum that is significant in the correction of longitudinal deformities. The vascular pattern of cortical bone and its microscopic structure, as well as the vascular supply of the physis, assume great importance with specific fractures.

At birth developing cortical bone (primary bone) begins with minimal lamellar components and a relatively greater porosity than does mature bone. Intrauterine demands start some biomechanically reactive processes. Within any

given anatomic region of a bone, cortical changes progressively occur with increasing age, with the natural sequence being increased formation of lamellar and osteon bone within the diaphysis. This is a biomechanically sensitive (responsive), reactive process. There are also relative differences in the various regions within a given bone that predispose certain regions to fracture over others. These differences in microscopic and macroscopic architecture also affect the process of fracture healing, which is different in the more dense, lamellar bone of the diaphysis compared with the spongy, trabecular bone of the metaphysis or epiphysis.

Physiology

The developing skeleton is continuously undergoing active, frequently rapid growth and remodeling in response to biomechanical demands. Accordingly, most fractures usually heal rapidly, nonunion is rare, overgrowth may occur, and certain angular deformities may correct totally. However, damage to the capacity of the bone and cartilage to accomplish these reparative and physiologic functions may impair subsequent growth and development in several significant ways. Various portions of the longitudinal bones respond differently to hormones, growth factors, mechanical factors, vascular changes, and trauma.

The child responds differently from the adult to the metabolic and physiologic stresses of trauma. Because the total blood volume is smaller, depending on the size of the child, less blood loss may be tolerated before signs of hypovolemic shock develop. This is because the smaller volumes lost represent a larger percentage of the total. The higher surface area/volume ratio also makes the child more vulnerable to hypothermia. There is a significant difference in the metabolic response between the adult and the child. Whereas the adult has a significant increase in metabolic rate resulting from the stresses of trauma, the child has minimal or no change. This is believed to be caused by the child's significantly higher metabolic rate, which needs to be increased only a small amount to accommodate the increased metabolic demands. The accelerated metabolic rate response, together with the ability to metabolize lipid stores, provides a possible explanation for the increased survival rates in children after severe trauma.

Biomechanics

The major changes undergone by developing bone are increases in the density and thickness of the cortical component, particularly in the diaphysis but also in the metaphysis. There are also alterations in the proportions of trabecular (endosteal) and cortical bone within the diaphysis, metaphysis, and epiphysis (especially the subchondral periphery). The porosity, which in the cross section of a child's bone is much greater than that of an adult, plays a significant role in affecting or even stopping fracture propagation in a trauma situation. This factor is undoubtedly important, as obviously comminuted fractures (discerned by routine radiographs) are distinctly uncommon in children. The increasing amount of bone in the expanding epiphyseal ossification center undoubtedly alters the stress and strain

response pattern throughout the epiphysis. Furthermore, it is likely that the progressive establishment of the subchondral plate of the epiphyseal ossification center adjacent to the physis alters its response to fracture-induced stress and strain.⁵ Adult bone usually fails initially in tension, whereas a child's bone may fail in either tension, compression, or both. Shear failure obviously compounds any such reaction to injury.

Patterns of Injury

Satisfactory treatment necessitates an understanding of what constitutes each anatomically specific fracture. In essence, a fracture may be defined as disruption of the normal continuity of the bone, cartilage, and contiguous soft tissues. Such disruptions may or may not cause a radiologically evident disruption of the continuity of the cortical bone. The latter situation may occur in children when the cortical bone, because of a greater capacity for elastic and plastic deformation prior to failure, buckles (plastically deforms), rather than "breaks." This often represents compression failure, rather than tension failure, of bone. This structural failure pattern essentially occurs only in children. Tension failure, which certainly occurs in children and is the prevailing mode of failure in adults, leads to disruption in the structural continuity of the bone. However, tensile failure may be incomplete in children, leading to the greenstick pattern of incomplete failure.

Any fracture pattern in the child or adolescent needs to be described adequately.^{21,22} Such a description should include (1) the anatomic location of the fracture, (2) the type of fracture, and (3) the physical changes caused by and associated with the fracture. Although a verbal description of any fracture is the usual response, the use of digital images transmitted over E-mail and other evolving technologies will probably be increasingly utilized and are capable of more accurate visual description of the actual fracture and patient.

Anatomic Location

Descriptive fracture terminology should accurately indicate the location of the injury; it becomes especially important for comparative treatment studies. As is seen in the subsequent clinical sections of this text, subtle differences in the particular anatomic site of the fracture in children may have a major impact on any acute treatment and potential long-term problems. The anatomic definitions are illustrated in Figures 2-1 and 2-2 and described below.

Diaphyseal: Indicates involvement of the central shaft of any longitudinal bone, which is composed of progressively mature (i.e., remodeling) lamellar bone. The thickness and extent of osteon bone formation (which characterizes this anatomic region) relates to both age and imposed physical demands.

Metaphyseal: Denotes involvement of the flaring ends of the central shaft of a longitudinal bone. The metaphyses are usually composed of a composite of endosteal trabecular bone and cortical immature fiber bone, both of which

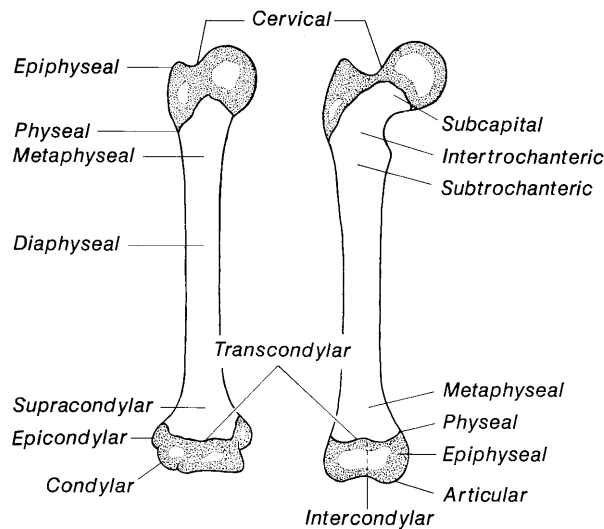


FIGURE 2-1. Humerus (left) and femur (right) from a 10-year-old child showing the various anatomic locations and definitions. See text for details.

predispose the metaphyses to the torus fracture pattern. The cortical bone of the metaphysis is more porous than diaphyseal cortical bone (Fig. 2-3). Osteon bone within the metaphyseal cortex is variable, being present in the region of progressive blending into the diaphysis, and

absent near the physis (zone of Ranvier). Many torus fractures occur near the transition between the metaphyseal and diaphyseal cortices (Fig. 2-4).

Physeal: Involves the endochondral longitudinal-latitudinal growth mechanism. Variable fractures involve this region (see Chapter 6).

Epiphyseal: The chondro-osseous end of a long bone is involved in basic growth. Fractures may selectively involve the expanding ossification center. It is important to realize that the epiphysis may be injured only in the cartilaginous portion, which makes diagnosis extremely difficult (see Chapter 6). As is shown subsequently and in ensuing chapters, such fractures are referred to as “shell” fractures, reflecting this chondro-osseous separation. Fractures may occur within the trabecular bone or the subchondral plate, creating an area of edema and hemorrhage. This injury pattern, which is generally invisible radiographically, is referred to as a bone bruise on an MRI scan.

Articular: Indicates involvement of the epiphyseal joint surface. Such injury may be part of an extensive epiphyseal injury, or it may be localized (Fig. 2-5). In the latter case, the fragment may include only articular cartilage and juxtaposed, undifferentiated hyaline cartilage or both subchondral bone and cartilage (e.g., osteochondritis dissecans) (see Chapters 6, 22).

Epicondylar: Involves regions of the bone, especially around the elbow, that serve as major muscle attachments and have extensions of the physis and epiphysis.

FIGURE 2-2. Radiographs of humeri from a neonate (A) and a 10-year-old child (B) showing changes that occur during progressive proximal and distal secondary ossification. The radiologic technique visualizes the cartilaginous portions of the epiphysis. These cartilaginous regions normally appear radiolucent in clinical radiographs.

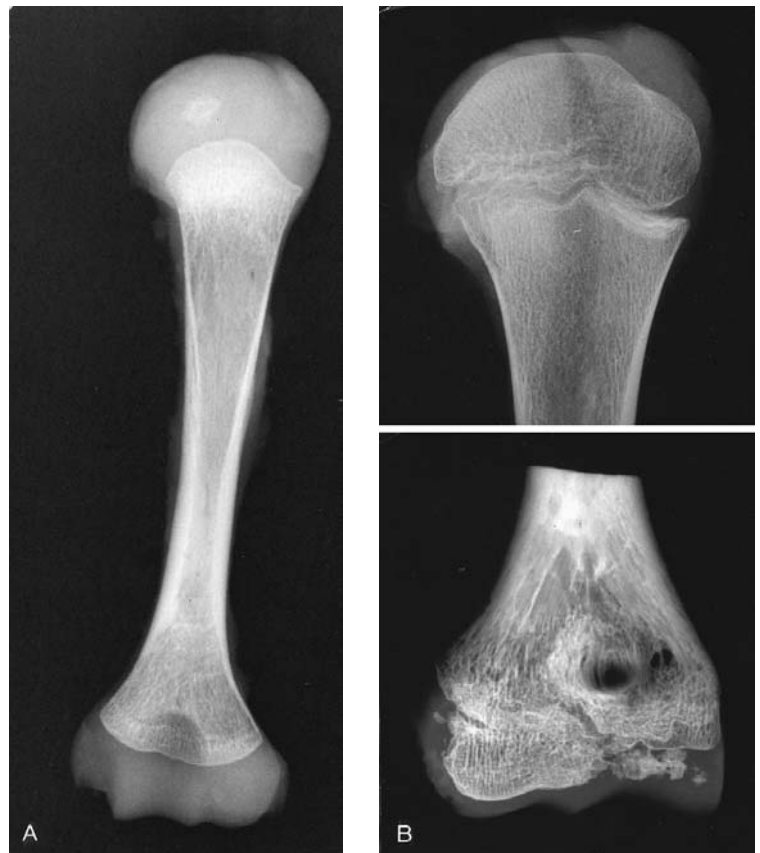




FIGURE 2-3. These osseous preparations of the distal radius (A) and distal femur (B) from an 11-year-old boy show the relatively porous, fenestrated cortex of the metaphysis (M), in contrast to the smooth cortex of the diaphysis (D).

Subcapital: Denotes involvement just below the epiphyses of certain bones such as the proximal femur or radius.

Cervical: Indicates involvement along the neck of a specific bone, such as the proximal humerus or femur.

Supracondylar: Pertains to involvement above the level of the condyles and epicondyles (e.g., distal humerus or femur).

Transcondylar: Indicates a location transversely across the condyles (e.g., distal humerus or femur). These lesions usually are complete physal disruptions.

Intercondylar (intraepiphyseal): Involvement within and through the epiphysis, with any fracture separating the normal condylar anatomic relationships.



FIGURE 2-4. Fracture of the transition of the relatively thin metaphyseal cortex to the thicker, biomechanically remodeling diaphyseal cortex. The microvascular injection shows vascular proliferation within the anterior callus. In contrast, the posterior callus and vascular reaction is minimal.

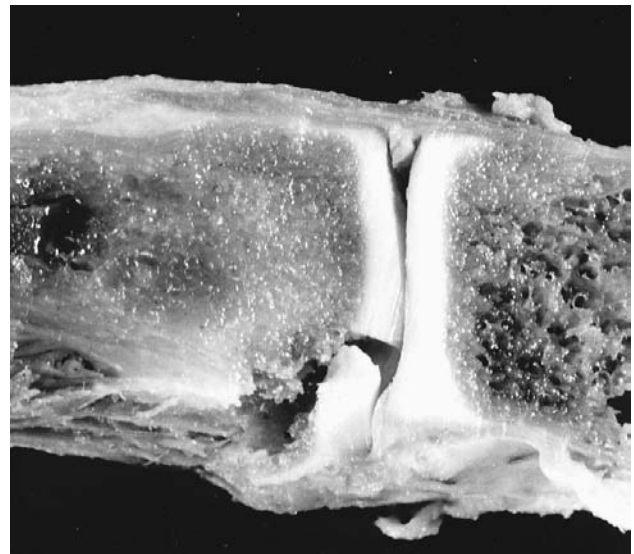
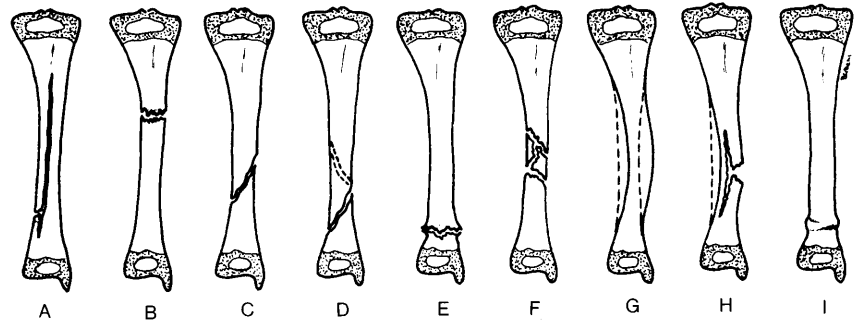


FIGURE 2-5. Articular fracture of the second metatarsal of an 8-year-old girl sustained when the foot and leg were run over by an automobile tire. She required a below-knee amputation to control ischemia and infection. This particular injury, with minimal osseous involvement, was not evident on clinical films.

FIGURE 2-6. Tibia in a 3-year-old child showing the various types of fractures: (A) longitudinal; (B) transverse; (C) oblique; (D) spiral; (E) impacted; (F) comminuted; (G) bowing (plastic deformation); (H) greenstick; and (I) torus. See text for details.



Malleolar: Indicates that distal regions of the fibula and tibia are involved. Because of anatomic differences, there are significant differences in the fracture patterns of the medial and lateral malleoli.

Type of Fracture

Any method of description should also be based on an appropriate roentgenogram of the injury pattern of disruption. The basic types, shown in Figure 2-6, are as follows.

Longitudinal: Fracture plane follows the longitudinal axis of the diaphysis (Figs. 2-7 to 2-9).

Transverse: Fracture plane is essentially at a right angle to the longitudinal axis of the bone (Fig. 2-10).

Oblique: Fracture plane is variably angled relative to the longitudinal axis, usually about 30°–45° (Fig. 2-11).

Spiral: Fracture plane encircles, in a twisting manner, a portion of the shaft.

Impacted: Compression injury in which the cortical and trabecular bone of each side of the fracture are crushed together (Fig. 2-12).

Comminuted: The fracture planes propagate in several directions, creating variable-sized fragments (Fig. 2-13). This type of fracture is uncommon in infants and young children but becomes more common in adolescents, particularly involving the tibia as the cortical bone matures.

Bowing: The bone is deformed beyond its capacity for full elastic recoil (back to its normal anatomic shape) into permanent plastic deformation (see Chapters 1, 5). The younger the child, the more likely it is that this type of skeletal injury can occur. It is particularly common in the fibula and the ulna, both of which may bow, whereas the paired bone (i.e., tibia or radius) is more likely to fracture (Figs. 2-14, 2-15). This permanent deformation of the “nonfractured bone” may limit reducibility of the overall injury. As primary osteons form and progressively remodel into secondary and tertiary osteons, the diaphyseal bone becomes more brittle and less likely to plastically deform. Plastic deformation has been described even in adults (see Chapter 5).

Greenstick: This is a common injury in children (Fig. 2-16). The involved bone is fractured, but a portion of the



FIGURE 2-7. Combination of a longitudinal fracture (solid arrows) and a spiral fracture (open arrows). This pattern of “comminution” is relatively typical in the more resilient immature skeleton.



FIGURE 2-8. Incomplete, undisplaced longitudinal diaphyseal fracture. There is no plastic deformation of the intact portion of the cortex.



FIGURE 2-9. Anteroposterior view shows a torus fracture (white arrow) and a longitudinal fracture of the cortex (black arrows), separating it from the endosteal bone and terminating in the torus injury. Also note the torus ulnar fracture (open arrow).



FIGURE 2-11. Oblique fracture of the tibia. The cortices appear relatively intact. This is a twisting injury.



FIGURE 2-10. Transverse fractures of the radius and ulna.



FIGURE 2-12. Impacted distal radial fracture.



FIGURE 2-13. Comminuted radial fracture with a double fracture of the ulna that included a transverse failure (open arrow) and a torus failure (solid arrow).



FIGURE 2-14. Oblique view of radial and ulnar fractures in a 6-year-old boy. The fracture of the radius shows an intact but plastically deformed dorsal cortex (white arrowhead) and a partially fractured palmar cortex (black arrowhead), a characteristic greenstick injury. The fracture is angulated because of plastic deformation (bowing) of the dorsal cortex. A significant ulnar injury is not evident in this projection.



FIGURE 2-15. Plastic deformation (bowing) of one cortex of the distal femur, along with complete failure of the apposed cortex.



FIGURE 2-16. Greenstick fractures of the radius.

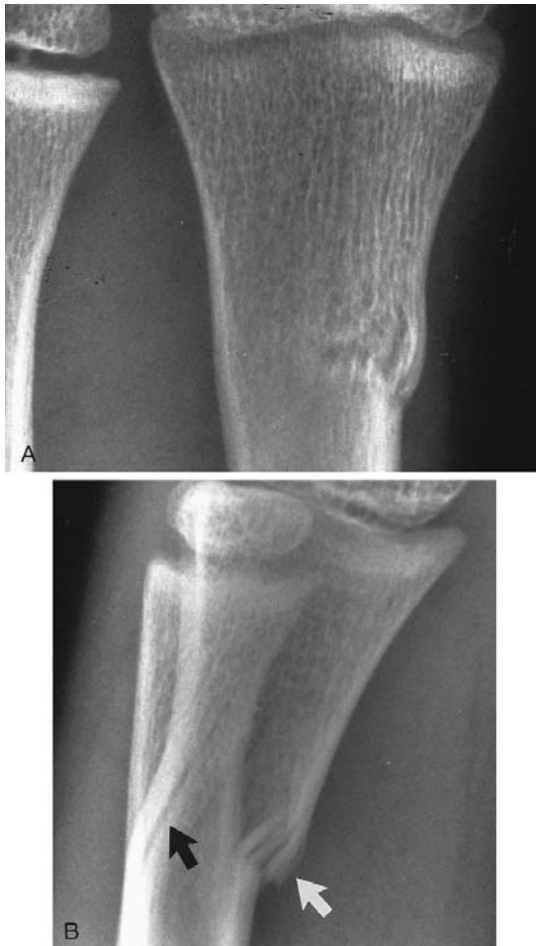


FIGURE 2-17. (A) Anteroposterior view of a metaphyseal torus fracture. Note that it does not extend completely across the diameter of the shaft. (B), Oblique view shows longitudinal (striated) disruption (white arrow) paralleling the longitudinal axis and a longer longitudinal disruption (black arrow) of the opposite cortex.



FIGURE 2-18. (A) Apparent torus fracture (solid arrow) of the proximal humerus. The open arrow indicates a fracture of the opposite cortex. (B) Histology shows the fractures (open arrow) and an intact periosteum (solid arrow).

cortex and periosteum remains relatively intact on the compression side. Because this intact cortical bone is usually plastically deformed (bowed), angular deformity is common; reversal of the deformity may necessitate conversion to a complete fracture. Furthermore, as swelling dissipates after an initial reduction, the angular deformation may insidiously occur even when the extremity is casted.

Torus: This impacted injury occurs during childhood. Because of the differing response of the metaphyseal bone to a compression load, the bone buckles (Figs. 2-17, 2-18), rather than fracturing completely, and a relatively stable injury is created. This type of fracture primarily affects developing metaphyseal bone. It is important to realize that cortical disruption (fracture) occurs, but that such disruption does not entail the entire cortex.

Shell (sleeve): This fracture pattern involves traumatic separation of articular or epiphyseal cartilage from the contiguous bone. There may be no bone attached to the cartilage, or there may be a thin (lamellar) piece (Figs. 2-19 to 2-21). The anterior tibial spine fracture, which is usually composed of a small fragment of bone and a much larger fragment of cartilage, is a typical example of this failure pattern. The Legg-Perthes subchondral fracture also represents this type of failure.

Bone bruising: This pattern of microtrauma occurs within the trabecular or subchondral bone of the metaphysis or epiphyseal ossification center (Fig. 2-22). Such focal hemorrhage may be detectable by alterations of signal intensity in the MRI but is not usually detectable by routine radiography.

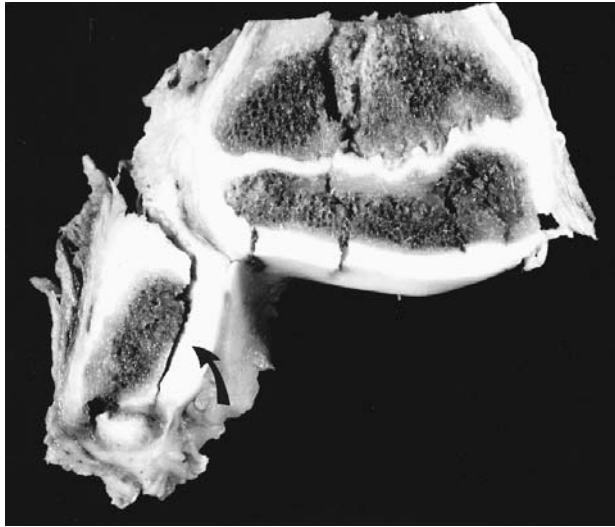


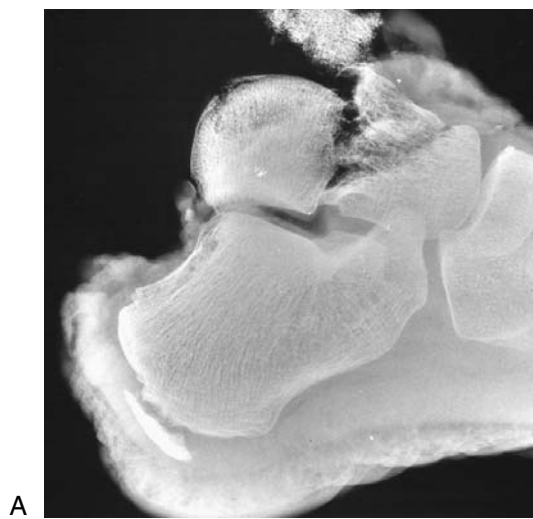
FIGURE 2-19. Shell or sleeve fracture of the distal fibula (arrow).

Physical Change

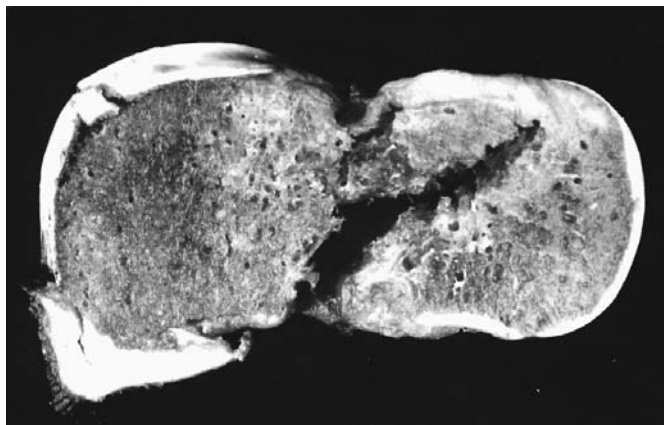
Whereas the aforementioned terms have been primarily descriptive, the following terms indicate conditions that are of practical importance clinically. These terms denote not only the nature of the clinical problem but also the general type of treatment that is probably required.

Extent: The fracture may be *incomplete*, in which case some of the cortex is intact, or it may be *complete*, in which case the fracture line crosses the entire circumference. Furthermore, the fracture line may be *simple* (a single fracture line), *segmental* (separate fracture lines isolating a segment of bone), or *comminuted* (multiple fracture lines with multiple fragments).

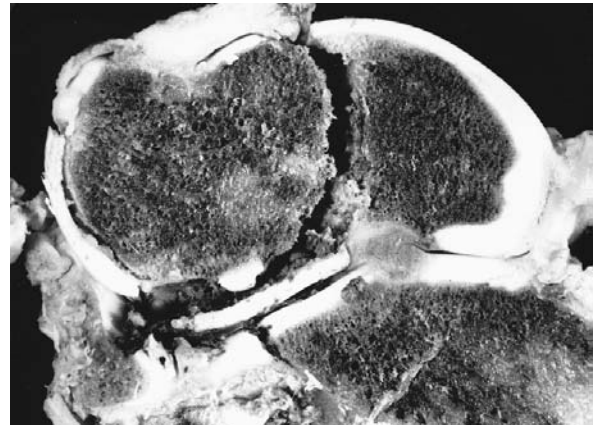
Relationship of fracture fragments to each other (Fig. 2-23): These relationships define a deformity as it exists during roentgenographic evaluation. However, because of elastic recoil, especially in children, these relationships may not represent the full extent of deformity or angulation maximally present at the time of injury, especially in a greenstick injury. The fracture may appear undisplaced or displaced, in which case the distal fragment is shifted away from its usual relationship to the proximal fragment. This shift may assume several types of deformation, which may be present singly or in any combination: (1) sideways



A



B



C

FIGURE 2-20. Shell fracture of the talus in an 11-year-old boy. (A) Radiograph. (B) Slab section. (C) Similar shell fracture of the talus from a 12-year-old boy.

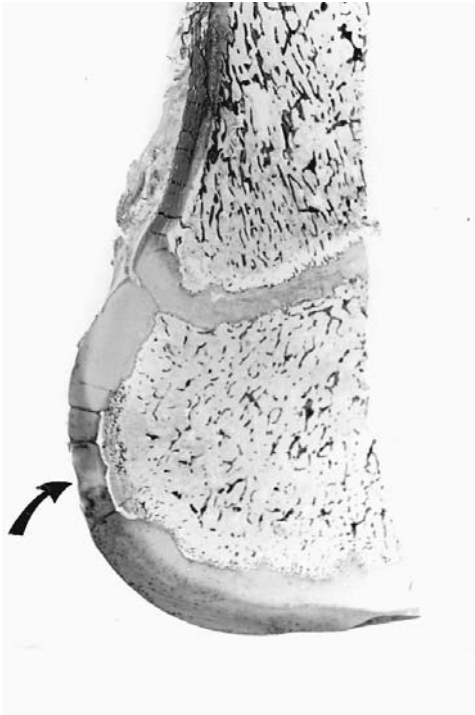


FIGURE 2-21. Shell fracture (undisplaced) of the distal femur (arrow).

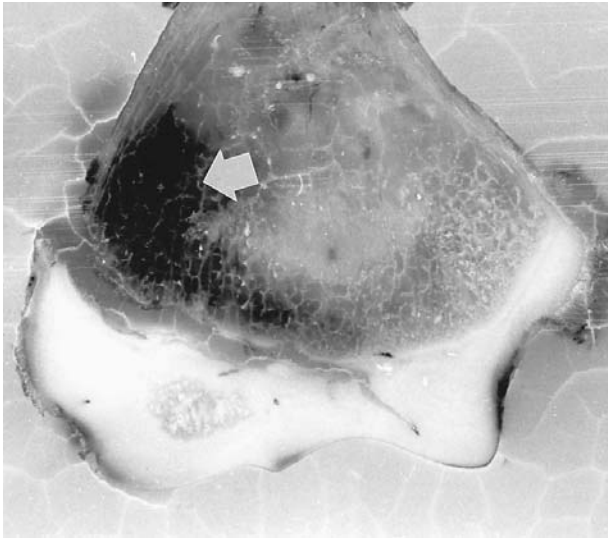


FIGURE 2-22. Bone bruising in the lateral metaphysis (arrow) due to microtrauma and intratrabecular hemorrhage. This child sustained an incomplete lateral condylar fracture and a traumatic amputation.

shift, (2) angulation, (3) overriding, (4) distraction, (5) impaction, and (6) rotation. The most important to correct are angular and rotational deformities. Whereas the former often corrects spontaneously, though unpredictably, the latter usually does not correct and must be adequately treated initially. So long as the reduction emphasizes restoration of longitudinal and rotational

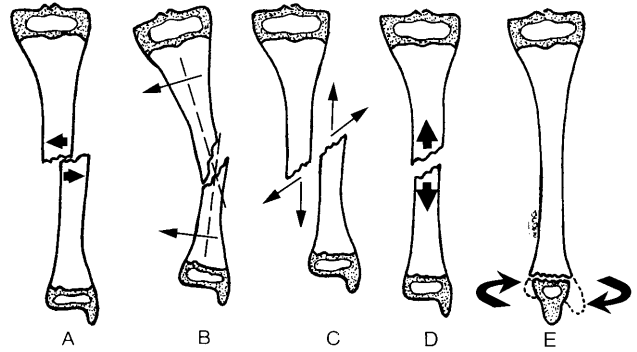


FIGURE 2-23. Tibia in a 6-year-old child showing the relations of fracture fragments to each other: (A) translocation; (B) angulation; (C) overriding; (D) distraction; and (E) rotation in a distal epiphyseal fracture.

alignment, sideways shifts and overriding are acceptable in many children's injuries.

Relationship of the fracture to the external environment:

Basically, a fracture is either closed (skin covering intact) or open (compound, a break in the skin). An open fracture, in which a break in the skin allows communication between the fracture and the external environment, may be caused when a fracture fragment penetrates the skin from within or when an external object penetrates or ruptures the skin from without. Such fractures carry the risk of infection. The basics of treatment of open fractures are covered in Chapter 9.

Periosteum

Throughout most of childhood the periosteum is thicker and more resistant to disruption than in the adult. Because of its increased contiguity with the underlying bone, however, it may be injured whenever the bone fractures. Because the periosteum separates more easily from the bone in children, it is less likely to rupture completely, and a significant portion of the periosteum often remains intact, usually on the concave (compression) side of the fracture (Fig. 2-24). This intact periosteal hinge may lessen the degree of displacement and may be used to assist in the reduction, as it imparts a certain degree of intrinsic stability (Fig. 2-25). As is detailed in Chapter 6, the periosteum blends imperceptibly into the perichondrium of the epiphysis and attaches densely into the zone of Ranvier.

It is important to realize that the extent of separation (elevation) of the periosteum from the metaphyseal and diaphyseal cortices is rarely easily appreciated on the initial radiograph (Fig. 2-26). However, as the subperiosteal hematoma organizes and subperiosteal new bone begins to form, any extent of soft tissue disruption becomes progressively more easily appreciated. In the neonate, periosteal stripping may extend from proximal physis to distal physis.

Because the periosteum creates some soft tissue continuity at the injury site, the subperiosteal new bone bridges the

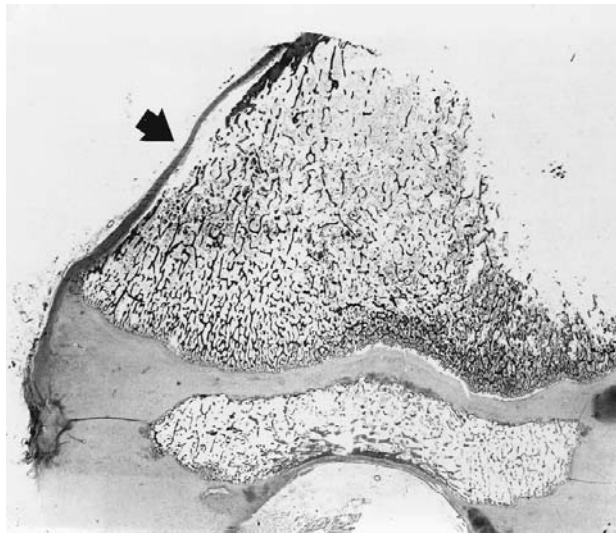


FIGURE 2-24. Fracture of the distal femur from a 3-year-old child fatally injured in an automobile accident. Histologic section showing cortical damage (arrow) associated with an *intact* periosteum.

fracture gap, leading to increasing stability. With severe trauma, especially open injury with segmental loss of bone, the periosteal sleeve may even make enough new bone to negate any need for bone grafting to bridge the fracture gap (Fig. 2-27). The role of the periosteum in basic bone development, maturation, and replacement was discussed in detail in Chapter 1.

Joint Disruption

Even though the soft tissues of the joint exhibit a greater degree of laxity in the child than they do in an adult, the capsule and ligaments are relatively more resistant to stress than are the contiguous bone and cartilage, especially the physal cartilage.¹³⁴ Consequently, discrete ligament rupture and joint dislocations are much less frequent in children.¹¹² When major ligaments attach directly into an epiphysis, physal fractures are the more common failure mode. Joint dislocations in the child commonly affect the elbow and hip. Shoulder and knee dislocations are less common. Other joints only rarely are dislocated prior to skeletal maturity (i.e., physal closure).

The most common “dislocation” in young children is the pulled elbow. Usually, no obvious roentgenologic findings are evident, and the condition is often relieved during radiography of the elbow when the radiology technician inadvertently supinates the elbow and relocates the subluxated annular ligament (see Chapter 14).

Injury to the joint cartilage may involve only superficial portions of the specific articular cartilage, or it may also involve the ossification center of the epiphysis. If only the cartilage is involved, traumatic lesions may not be visualized initially without arthrography (i.e., the “shell” or “sleeve” chondro-osseous separation fracture described in Chapters 5 and 6). Osteochondritis dissecans is, in many

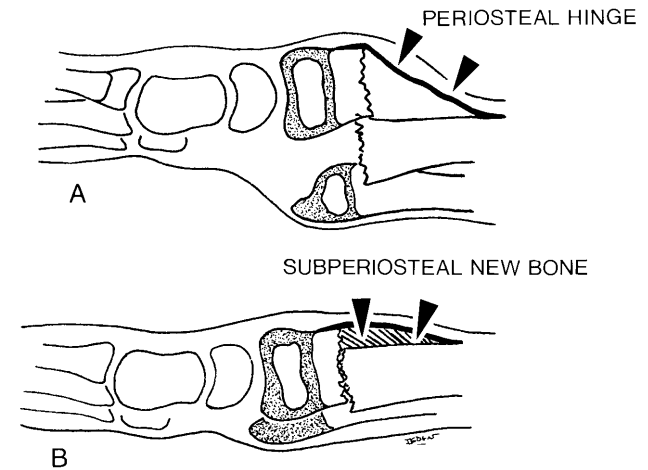


FIGURE 2-25. Dorsally displaced (A) and reduced (B) distal radial metaphyseal fracture. The periosteum is connected with the proximal fragment by an intact dorsal periosteal hinge. When the fragment is reduced, this periosteal hinge prevents overreduction. Fracture hematoma accumulates underneath the elevated periosteum and contributes to extensive callus formation.

cases, posttraumatic (a transchondral fracture), rather than some type of underlying, more generalized disease (i.e., an osteochondrosis). Complications of articular trauma are often not recognized until long after the injury, when interference with joint function or growth disturbances become evident. The use of continuous passive motion may be an important factor in lessening intraarticular consequences.¹⁷¹

Remodeling

Most children's fractures are relatively easy to treat, but they do not always remodel, and the results are sometimes unsatisfactory. The remodeling capacity of a deformity caused by a fracture or epiphyseal injury is determined by three basic factors: (1) the age of the child, (2) the distance of the fracture from the end of the bone, and (3) the amount of angulation.^{22,147-150,159,256,357} Physiologic remodeling of a bone depends on periosteal appositional bone formation, resorption of some bone, and physal growth.^{82,376}

The criteria for an acceptable position of a fracture are based on the predictability of remodeling. For an axial deformity, remodeling capacity is better in the young patient (Fig. 2-28) and for deformities near the physis (Fig. 2-29). For lateral displacement and shortening, remodeling capacity is good; but for rotational deformity, essentially *no* remodeling capacity exists. Additional factors that must be taken into account include (1) the skeletal age of the patient, which may differ from the chronologic age; (2) the relative contributions by different physes to the longitudinal growth of a given bone; and (3) in some bones, stimulation of the longitudinal growth due to the fracture (reactive hyperemia with physal stimulation).

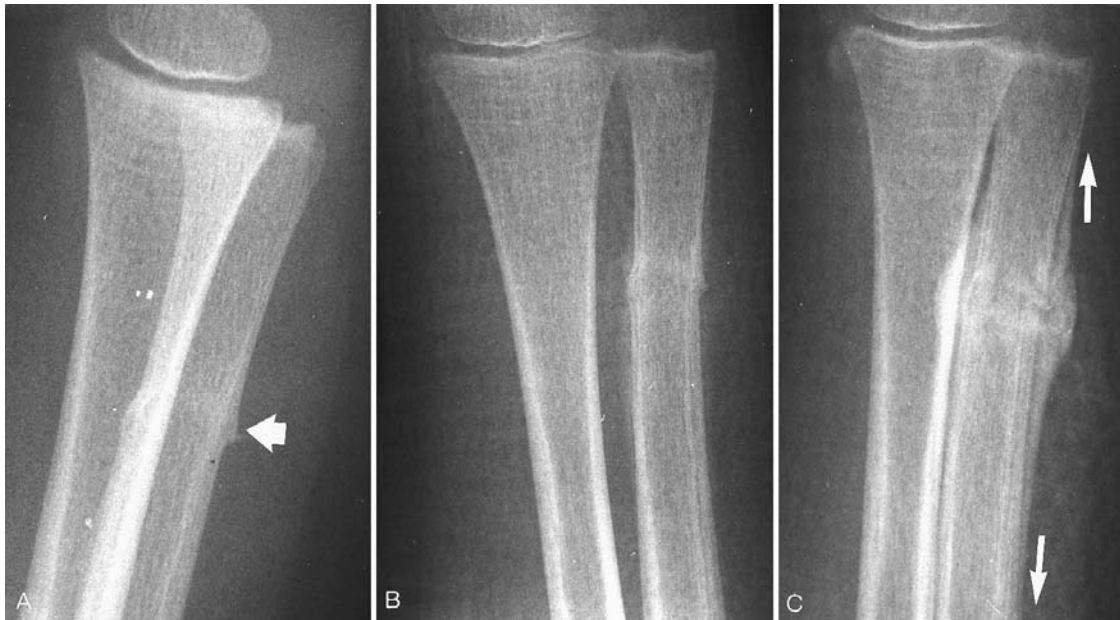


FIGURE 2-26. Sequence of subperiosteal new bone formation. (A) Original fracture (arrow). (B) Six days later. (C) Twenty-one days later. The longitudinal extent of the subperiosteal elevation (arrows) was certainly not suggested by the minimally evident fracture.

Remodeling *cannot* be predictably relied on (Fig. 2-30). *Every effort should be expended to attain as adequate an anatomic reduction as possible.* Remodeling, in general, may be counted on in children with 2 years or more of growth ahead, in those with fractures near the ends of the bones, and in those with

deformities that are in the plane of movement of the joint. Remodeling does not help with displaced intraarticular fractures, fractures toward the middle of the shaft of a bone (particularly when shortened, angulated, or rotated), displaced fractures in which the axis of displacement is out of the normal plane of movement, and displaced fractures crossing the physis. Remodeling in the diaphysis is largely a process of smoothing the bone and surrounding callus; it is *not* a true correction of longitudinal malalignment. With fractures of the shaft, the intact but displaced periosteum produces abundant callus on one side of the fracture, whereas the other side is stripped of normal periosteum and resorbs. This process eventually makes the fracture look less obvious when, in reality, there is minimal improvement in the alignment. Near an epiphysis, however, the physis may realign and assume a more normal growth pattern, by means of which metaphyseal remodeling improves the overall appearance. With a supracondylar fracture that has healed with some posterior displacement, the shaft acts as an anterior bone block and restricts movement until growth moves the epiphysis farther away from the bone block. As the child grows, movement increases. The wrist, one of the areas most commonly left to remodel, is a place in which altered longitudinal alignment corrects relatively readily, although not necessarily rapidly.

Complications

The difference between complications in children and those in adults is mainly due to the state of growth of the skeleton. Delayed union and nonunion are rare in children because the healing capacity is better.³⁶⁵ In Beekman and Sullivan's series of more than 2000 fractures in children, there was not a single case of nonunion.⁷⁵ Posttraumatic joint stiffness is uncommon if the joint is not directly damaged. Mechanical



FIGURE 2-27. (A) Periosteal new bone (arrowheads) in the posteriorly displaced periosteal sleeve 11 weeks after multiple trauma and head injury to a 14-year-old boy. Following manipulation, the fragments were placed in better alignment. (B) Film taken a year later shows extensive remodeling and incorporation of the subperiosteal new bone.

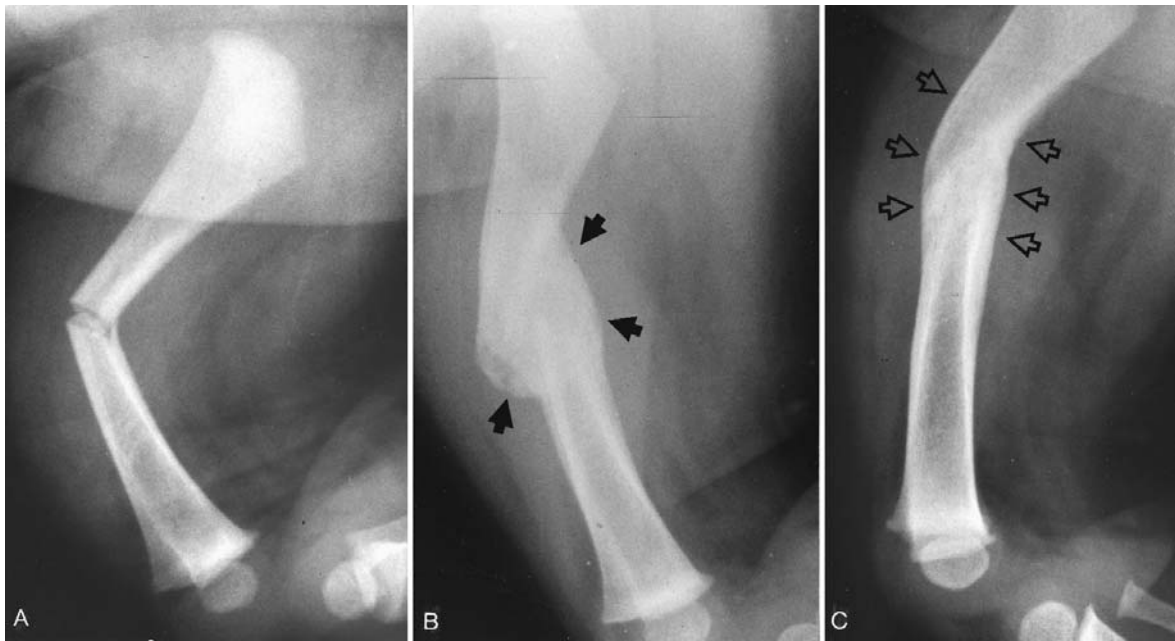


FIGURE 2-28. (A) Fracture of the mid-shaft of the femur in a 7-month-old girl. (B) Callus formation (arrows) 2 months after the injury. It is limited by the relatively intact periosteal sleeve. (C)

Beginning remodeling (arrows) 7 months after the original fracture. The angular malalignment, however, is still present.

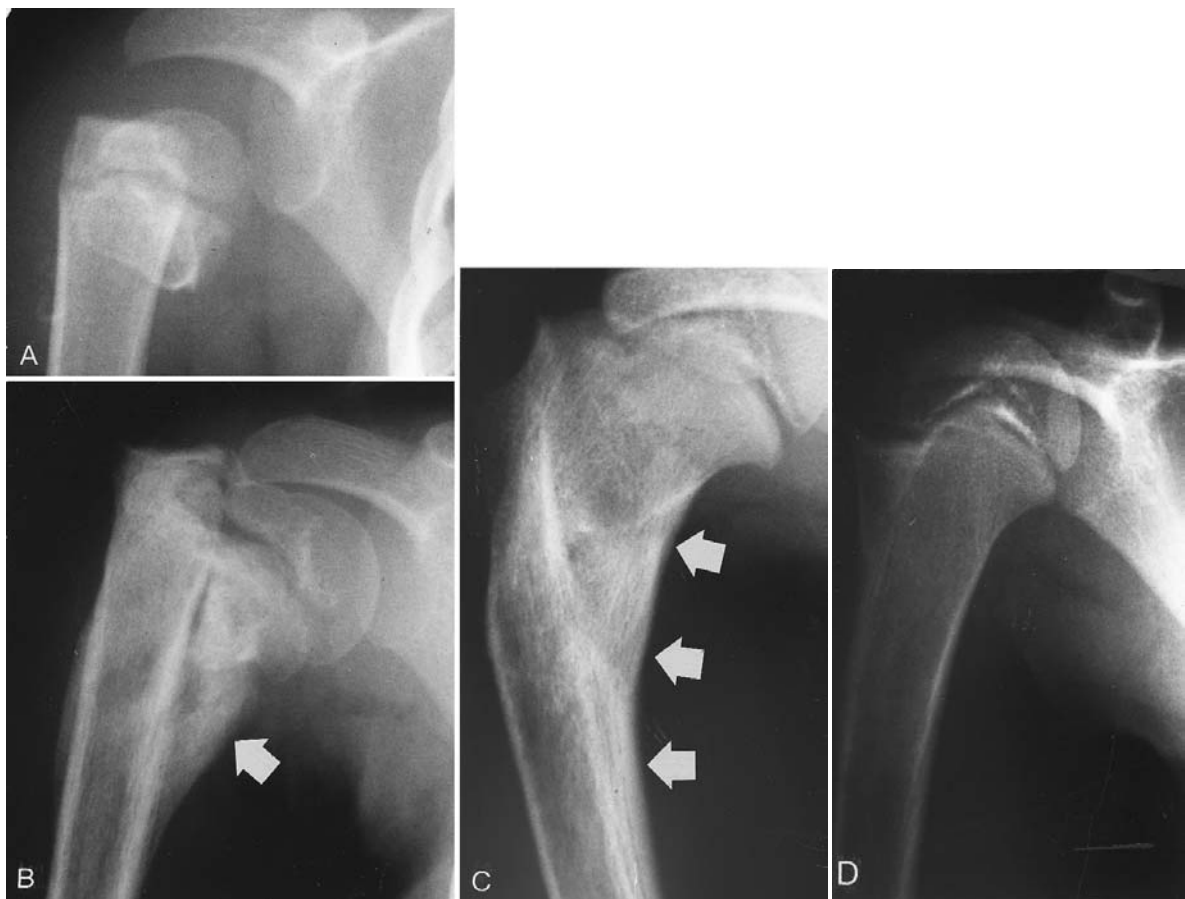


FIGURE 2-29. Extensive remodeling and longitudinal overgrowth in a metaphyseal/epiphyseal fracture. (A) Displaced fracture fragments in a 3-year-old girl who was thrown two stories (child abuse). She also sustained ipsilateral distal humeral and distal radial injuries. Repeated attempts at reduction with the patient under general anesthesia were unsuccessful. (B) Four months after the injury extensive subperiosteal new bone is evident,

although it is still partially separated from the original cortex (arrow). (C) Beginning realignment and correction of angular deformity 9 months after the injury. The patient has full use of her gleno-humeral joint. Extensive subperiosteal new bone has formed and is making a new medial cortex (arrows). (D) Appearance of the remodeled fracture 2 years later.

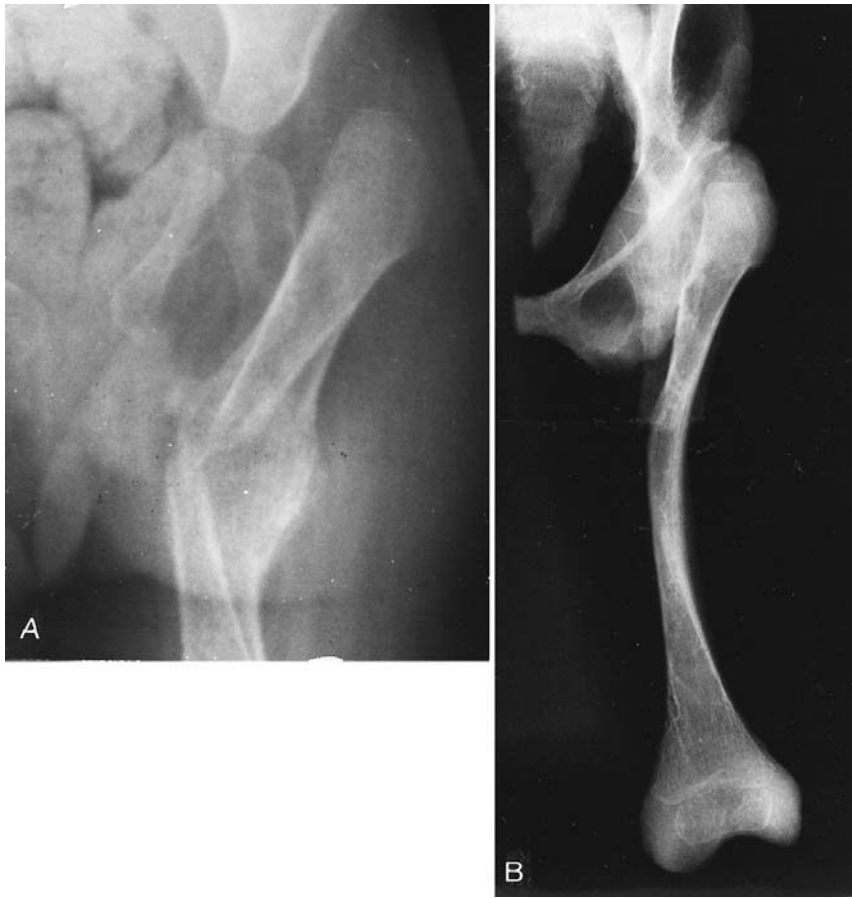


FIGURE 2-30. (A) Fracture of the left femur in a 7-month-old girl with arthrogryposis multiplex congenita. Bilateral hip dislocations are also evident. (B) Postmortem roentgenogram at 15 months of age showing some remodeling and minimal remaining callus. The angular malalignment has not corrected at all.

(functional) hindrance resulting from malunion of the fracture rarely exists. Refractures and myositis ossificans are less common in children than in adults. Generalized complications are discussed in detail in Chapters 6, 9, and 10; and specific complications unique to certain injuries are discussed in Chapters 12–24.

Disability Evaluation

Young, Wright, and colleagues developed scales measuring physical function levels in children.^{402,403} They also reviewed a large number of tabulated assessments applicable to normal children, injured children, and children with impairments (e.g., cerebral palsy) who might sustain an injury. Anyone interested in developing outcome scales for pediatric injury should review this article and the array of measures and scales in the appendix of their paper.

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