Chapter 4
Fractures and Skeletal Injuries

Angela Bachim and Nancy S. Harper

General Principles

The identification of a skeletal injury may be the first indication of abuse. Estimates of the frequency of fractures in abused children vary from approximately 10–50%, depending on the population studied, the type of diagnostic imaging used to detect fractures, and the age of the patients seen (Ebbin et al. 1969; Herndon 1983; Leventhal et al. 1993). Recently, large population-based studies have been used to estimate the incidence of inflicted skeletal trauma. While the majority of fractures are still attributed to falls, child abuse accounts for 12% of fractures in children less than 36 months of age (Leventhal et al. 2008). Infants and young children sustain significantly more abusive skeletal injuries than do older children, with the majority of inflicted fractures occurring in children under 12 months of age (Leventhal et al. 2008, 2010; Loder and Feinberg 2007; Sibert et al. 2002). Fractures of the ribs, arm, and leg account for over half of the inflicted skeletal injuries in young children (Leventhal et al. 2008; Starling et al. 2007). These injuries are often occult and detected only with detailed skeletal imaging.

Determining whether a fracture is abusive versus accidental is not an easy task. One study found that over 20% of children under 3 years of age who presented with an abusive fracture had been seen by another medical provider for the same injury

A. Bachim (✉)
Baylor College of Medicine, Houston, TX, USA

Texas Children's Hospital, Houston, TX, USA
e-mail: angela.bachim@bcm.edu

N. S. Harper
University of Minnesota, Minneapolis, MN, USA

Child Abuse Pediatrics, University of Minnesota Masonic Children's Hospital, Minneapolis, MN, USA
e-mail: nsharper@umn.edu

in which the diagnosis of abuse was missed (Ravichandiran et al. 2010). If abuse is not on the differential diagnosis when evaluating a fracture in an infant or child, it cannot be diagnosed. The presence of a fracture does not prove abuse. A comprehensive medical evaluation that includes clinical examination, past medical history including development, and a history of the injury with the application of biomechanics (force, stress, bone tolerance, etc.) will help to differentiate accidental from non-accidental injuries. A detailed review of biomechanics is not included in this chapter (Pierce et al. 2004).

Bone Anatomy and Fracture Description

The anatomic and physiologic characteristics of the immature skeleton affect the frequency, type, location, and healing of pediatric fractures. Bones such as the femur are comprised of two types of bone: compact (cortical) bone and trabecular (spongy, cancellous) bone. Cortical bone has multiple concentric rings of lamellae housing the haversian canals. Mineralization and thickness of the cortical bone contribute to its strength and stiffness. Developing and cancellous bone is more porous than cortical bone, affecting both the stiffness and flexibility of the bone, as well as the extent and type of fractures seen in children. Less dense, porous bone may help stop the propagation of a fracture line, but this quality also makes the bone more vulnerable to compression. This is well-demonstrated in the metaphyseal region where the thinner porous cortex surrounding the trabecular bone makes compression injury and buckle fracture more likely. This region where the metaphysis transitions to cortical bone has been referred to as the internal "stress riser" (Pierce et al. 2004) (Photos 4.1 and 4.2). The strength of the bone is related to its mineralization. The bones of children are less mineralized, less stiff than adult bone, but are more elastic.

The periosteum is the fibrous membrane that covers the surface of a bone. It is quite vascular, supplying nutrients to the bone. It is loosely adherent to the diaphysis and tightly adherent to the metaphysis and epiphyseal region contributing to the formation of the bone collar (Pierce et al. 2004). The periosteum of the child is more osteogenic or bone forming. The diaphyses of a child are formed through intramembranous bone formation. The periosteum retains this ability and can form bone without a cartilage scaffold (Shopfner 1966). Bone healing is much more rapid in children than in adults and more rapid in infants than in older children. For example, the healing of a midshaft femur fracture may take only 3 weeks in an infant but 20 weeks in a teenager (Ogden 1990). This difference is mostly due to the contribution of the periosteum in the healing of young bones.

The morphological features of the fracture include the bone involved, the location of the fracture within the bone, the type of fracture sustained, and the relationship of the fracture segments (Pierce et al. 2004). The mechanism of the injury as reported by the caretaker is also noted in the fracture assessment. Table 4.1 describes

Photo 4.1 A 9-month-old female fell from the arms of her caregiver striking knee on floor. Radiographs notable for a buckle fracture of the distal right femur on anteroposterior views of the lower extremities

the anatomy of the bone, and Table 4.2 describes different types of fractures (see Figs. 4.1 and 4.2).

The history of the injury is important in identifying abusive fractures because historical information should be compatible with the morphological features of the fracture and the mechanics required to cause the fracture (Photos 4.3, 4.4, 4.5, and 4.6). Torsional loading, as seen with twisting or rotation of the extremity, often results in spiral fractures (O'Connor-Read et al. 2007; Pierce et al. 2004) (Photo 4.7). A bending load (both tensile and compressive forces occur) applied to the extremity can result in a transverse fracture, perpendicular to the bone (Photo 4.3). Direct trauma also produces transverse fractures with the degree of fragmentation or comminution (Photos 4.8 and 4.9) associated with the force of the impact. Oblique fractures are likely the result of combination loading (torsional, tensile, and compressive) (Photo 4.10). The buckle fracture, as noted previously, is the result of a failure under compressive forces and typically occurs from axial loading. Immature bone fails in compression first, with the fracture line at the weakest point of the bone. Distal femur buckle fractures occur as the result of the compression of hard, cortical bone into the softer, trabecular bone of the metaphysis (Pierce et al. 2004) (Photos 4.1 and 4.2). The field of biomechanics has advanced the understanding of the association between loading forces, history, and corresponding injuries. Pierce et al. (2005) found that the linear momentum associated with transverse fractures

Photo 4.2 The lateral view of the buckle fracture demonstrates the posterior cortical disruption. This fracture is the result of axial loading of the femur as the knee struck the floor

Table 4.1 Anatomy of the long bone

Bone	Characteristics
Condyle	The rounded articular (joint) surface at the end of a bone
Diaphysis	The shaft of a long bone

Epiphysis	The part of the long bone developed from a center of ossification
	   Separate from the shaft and separated from it by a layer of cartilage (the epiphyseal plate)
	   In infants and young children, not often visualized by radiograph because it is not ossified

Metaphysis	Growth zone between epiphysis and diaphysis, radiographically identified by the flaring portion of the long bone
Periosteum	Thick, fibrous membrane covering surface of a bone and consisting of two layers: inner osteogenic (bone forming) and outer connective tissue layer containing blood vessels and nerves that supply the bone

was almost 10 times greater than that seen with spiral or buckle fractures (Photos 4.1, 4.3, and 4.10).

   Fractures resulting from abuse are varied in their presentation. Clinically, the preverbal child may present with signs and symptoms indicative of pain such as irritability, crying with movement of the affected area, and decreased use of a bro-

Table 4.2 Types of fracture

Type of fracture	Characteristics
Comminuted	Bone broken into multiple pieces
Compound	Open fracture (i.e., through the skin)
Depressed	Skull fractures in which a part of the skull is inwardly displaced (toward the brain)
Diastatic	Fracture with significant separation of bone fragments; often used in relation to skull fractures
Distal	Fracture located away from center of body (near the feet or hands when describing fractures of the extremities)
Greenstick	An incomplete fracture—the compressed side of the bone is bowed, but not completely fractured. Young bones are more malleable, porous, and less brittle than an adult's and may bend and only partially break when injured
Hairline	Fracture without separation of the fragments (similar to a thin crack of a vase)
Impacted	A compression fracture
Linear	Resembling a line; often used to describe skull fractures
Oblique	Fracture line angled across long axis of bone (from approximately 30–45 degrees)
Occult	Condition in which there is clinical, but not radiographic, evidence of a fracture. Radiographs repeated in a few weeks show evidence of fracture healing
	May also indicate a fracture seen radiographically but without clinical manifestations (e.g., rib fractures and metaphyseal fractures)
Pathologic	Fracture that occurs in area of bone weakened by an underlying disease
Proximal	Fractures located toward trunk of body (for fractures of the extremities, near the hips or shoulders)
Spiral	Fracture line oblique and encircles a portion of the bone (resembles twist of a candy cane)
Stellate	Fracture lines of break radiate from central point; seen in some skull fractures
Supracondylar	Fracture to area above condyle, typically of the humerus
Torus	Impacted injury specific to children; bone buckles, rather than fracturing completely, and usually involves the metaphysis of the bone
Transverse	Fracture line perpendicular to the long axis of the bone

ken limb. While many children demonstrate immediate signs of injury as described, some children may not cry or will stop crying quickly with more than 10% continuing to use the fractured limb normally (Farrell et al. 2012). The majority of children with accidental injury do not have associated bruising (Worlock et al. 1986). Bruising has been documented in association with fracture in only 8–9% of children, including children with inflicted fractures (Mathew et al. 1998; Peters et al. 2008). Single skeletal injuries are most common. However, the identification of multiple fractures and/or fractures in different stages of healing should raise the suspicion of child abuse.

The identification by a healthcare professional of an inflicted fracture is dependent on multiple factors. They include the ability to obtain a complete and detailed
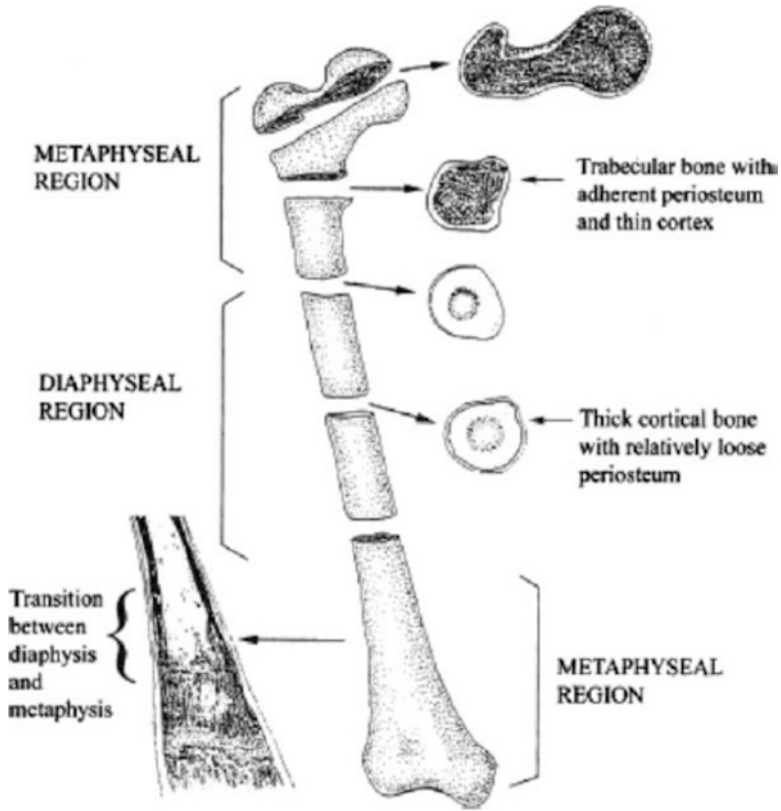
Fig. 4.1 Illustration of bone architecture. (Pierce et al. 2004. Used with permission)
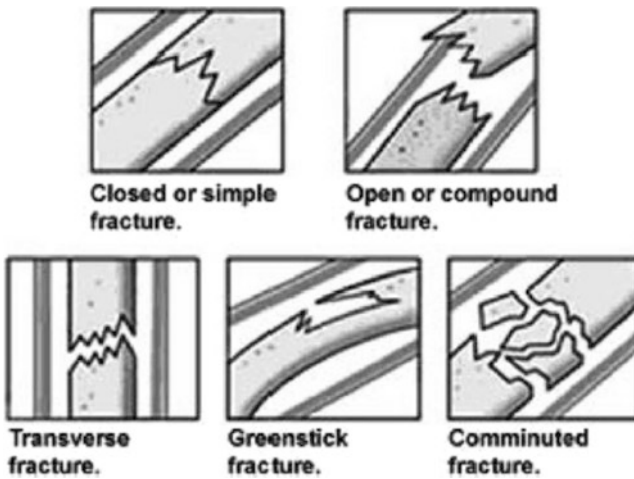

Fig. 4.2 Illustration of fracture types. (Reproduced with permission from Moseley 2009)

Photo 4.3 A 6-week-old male presents with leg swelling. Father reports falling on baby. Skeletal survey notable for right proximal transverse femur fracture with classic metaphyseal lesions of proximal and distal tibia

Photo 4.4 Additional angled lateral view of 6-week-old male's leg shows a "bucket-handle" classic metaphyseal lesion of the proximal right tibia

Photo 4.5 Bruising noted on the right leg of the 6-week-old male appears consistent with grip marks

Photo 4.6 Left leg of 6-week-old-male is notable for multiple fractures including a proximal femur and proximal tibia classic metaphyseal lesions. Extensive traumatic periosteal reaction is seen along the lateral femur extending into the metaphysis. The distal femur has a classic metaphyseal lesion versus physeal fracture

Photo 4.7 A 16-month-old female who presented to the ER with arm swelling and pain with a reported fall. Child had multiple bruises, traumatic alopecia, and failure to thrive. Skeletal survey notable for a left humerus spiral fracture as well as a skull fracture

Photo 4.8 This 4-year-old male fell from window landing on his feet. The lateral view of the tibia and fibula demonstrate comminuted fractures

Photo 4.9 This 18-month-old also has a comminuted fracture of his distal right tibia and fibula and buckling of the fibula in the middle of the diaphysis without a known history of trauma. Both Photos 4.12 and 4.13 show the results of axial loads to the tibia and fibula

Photo 4.10 4 month-old-male found crying in crib lying on chest. Skeletal survey notable for oblique fracture of left humerus

Photo 4.11 This 9-month-old female presented with swelling of her left lower extremity and multiple bruises after being left in the care of the mother's boyfriend. The mother's boyfriend reported tripping on the baby. Multiple extremity fractures were found including the transverse fracture of the left tibia and comminuted fractures of the right tibia and fibula

Photo 4.12 The 9-month-old also had a healing transverse fracture of the distal right radius

history of the trauma causing the fracture, knowledge regarding fracture mechanisms in childhood, an understanding of pediatric development, and a complete and thorough evaluation of children who may have skeletal injuries that are the result of abuse. Male gender, fracture in an extremity (versus axially), and presentation to a primary care or general emergency department (versus pediatric emergency department) are all factors associated with missed diagnosis of abusive fractures (Ravichandiran et al. 2010). There are certain pediatric fractures that, in isolation, are so highly suspicious for child abuse that they raise concern of abuse in the absence of clinical history. These include metaphyseal and rib fractures in infants. Although diaphyseal fractures are the most common fractures that result from abuse, they are not specific for abusive injuries (Photos 4.3, 4.7, 4.10, 4.11, and 4.12).

Imaging Techniques

Skeletal Survey

The diagnosis of skeletal injuries is made by history and physical examination and confirmed by radiographic imaging. Some skeletal injuries may not be apparent by clinical examination. A radiographic skeletal survey is part of the workup in infants and young children suspected of abuse (Photos 4.11 and 4.12). Across all ages, the rate of finding fractures on the skeletal survey is over 10% (Duffy et al. 2011; Lindberg et al. 2014), with the rate around 20% in infants (Barber et al. 2015; Lindberg et al. 2014).

A skeletal survey is a series of radiographs taken of the child's skeleton to look for indications of new or old injury. The skeletal survey is mandatory in cases of suspected physical abuse for all infants and children under 2 years of age (ACR Appropriateness Criteria: Suspected Physical Abuse-Child 2017; Christian and Committee on Child Abuse and Neglect 2015). It is not generally used in patients over 5 years of age. Clinical judgment is used to determine whether a screening survey is indicated for children between the ages of 2 and 5. In this age group, there are a few things to consider when deciding whether to obtain a skeletal survey. If a child is developmentally delayed, either not verbal enough to say if something hurts or not mobile enough to ambulate and move around normally, he or she may benefit from a skeletal survey. If there are distracting painful injuries such as burns, the child would benefit from a skeletal survey. In one study that looked at the frequency fractures were found on skeletal survey in children presenting with burns, nearly one-third of those with inflicted burns also had fractures identified on skeletal survey (Fagen et al. 2015). If the child's level of consciousness or ability to respond to pain on exam is altered due to ingestion or head trauma, a skeletal survey would be useful. In children 2–3 years old, the rate of additional fracture detection in those that receive a skeletal survey is over 10%, similar to children 1–2 years old; therefore, clinicians are encouraged to have a low threshold to obtain a skeletal survey in this age group (Lindberg et al. 2014).

The radiographs must include restricted views of the areas imaged in order to obtain proper quality and resolution of the bones (American College of Radiology 2016). A "babygram" (i.e., a single full body image) is not acceptable. Bilateral oblique views of the ribs (Photos 4.13 and 4.14) were added to the recommended skeletal survey protocol in 2011 by the American College of Radiology, which increases rib fracture detection (ACR Appropriateness Criteria: Suspected Physical Abuse-Child 2017; Maguire et al. 2013; Marine et al. 2014). The following films are included as part of the skeletal survey (ACR Appropriateness Criteria: Suspected Physical Abuse-Child 2017):

1. Anteroposterior view of the arms, forearms, hands, femurs, lower legs, and feet on separate exposures. Some institutions add lateral views to improve the sensitivity for classic metaphyseal fractures. Lateral views can always be obtained if there is a need to further clarify a finding.

Photo 4.13 This 2-month-old female presented with chest wall crepitus and was found to have multiple acute rib fractures. The anterior-posterior chest is notable for a displaced rib fracture posteriorly on the left seventh rib

Photo 4.14 The oblique view for the infant more clearly demonstrates acute displaced fractures of left posterior 5th–8th ribs

2. Lateral and anterior views of the axial skeleton to evaluate for vertebral, sternal, and pelvic fractures
3. Bilateral oblique views of the ribs to add sensitivity to detecting rib fractures
4. Anteroposterior and lateral views of the skull to evaluate for skull fractures

The American Academy of Pediatrics recommends obtaining screening skeletal surveys in siblings less than 2 years of age in cases of suspected abuse (Christian and CoCAN 2015). Siblings and children who share the same care environment in which the abuse occurred are also at risk for having been abused. These children may also have occult skeletal injuries. In one study, nearly 12% of the siblings/household contacts less than 2 years old had occult fractures (without physical exam findings) detected on the screening skeletal survey (Lindberg et al. 2012).

Even when the skeletal survey is performed correctly, it may fail to reveal acute rib fractures and classic metaphyseal lesions. It is recommended that the initial skeletal survey be repeated in approximately 2 weeks to diagnose those fractures that were acute at the time of the first skeletal survey once healing changes have made them easier to detect (ACR Appropriateness Criteria: Suspected Physical Abuse-Child 2017; Christian and CoCAN 2015). The repeat skeletal survey is also useful in clarifying questionable findings on the initial skeletal survey (Harper et al., 2013) and in dating information (Christian and CoCAN 2015). In children with a negative initial skeletal survey, one study found that over 8% had forensically significant findings on the repeat skeletal survey (Bennett et al. 2011). To limit radiation exposure with the repeat skeletal survey, the pelvis, spine, and skull radiographs can be omitted unless further clarification of an injury is needed (ACR Appropriateness Criteria: Suspected Physical Abuse-Child 2017; Hansen et al. 2014; Sonik et al. 2010).

Radionuclide Bone Scan

The radionuclide bone scan is a sensitive test for detecting rib fractures, subtle diaphyseal fractures, and early periosteal elevation. It is sometimes used as an adjunct to plain films. Most fractures can be identified by bone scan within the first 48 h after an injury. Bone scan is not sensitive for the detection of skull fractures or classic metaphyseal fractures and does not allow for the dating of injuries; therefore, it is not used as a substitute for the skeletal survey (Drubach et al. 2010). It is most often used in cases of suspected abuse of infants and young children in which the skeletal survey is negative and a more sensitive (but less specific) test is needed (see Chap. 2). A radionuclide bone scan may be useful when there are questionable findings on a skeletal survey, excluding skull or classic metaphyseal fractures, in the context of time-sensitive decision-making, such as whether protective placement is needed (Bainbridge et al. 2015).

Computed Tomography

Computed tomography (CT) has been traditionally utilized in imaging the head, chest, abdomen, and pelvis for traumatic injuries. With the arrival of multidetector CT scanning (with 16, 32, and 64 slice technology), coronal and sagittal as well as 3D reconstructions can be performed in addition to standard axial imaging. CT reconstruction technology has been useful in the delineation and identification of metaphyseal fractures, rib fractures (Kleinman and Schlesinger 1997; Wootton-Gorges et al. 2008), complex skull fractures, and skull variants in cases of head injury (Culotta et al. 2017; Parisi et al. 2015) (Photos 4.15, 4.16, 4.17, and 4.18). If 3D reconstructions of the skull are being used, plain films of the skull can be omitted from the skeletal survey (Culotta et al. 2017).

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is not the best imaging modality to visualize ossified bones. However, there are portions of young children's bones that are not yet ossified. MRI can be helpful for injuries of these unossified portions of bone, such as the epiphysis and/or growth plate (Supakul et al. 2015).
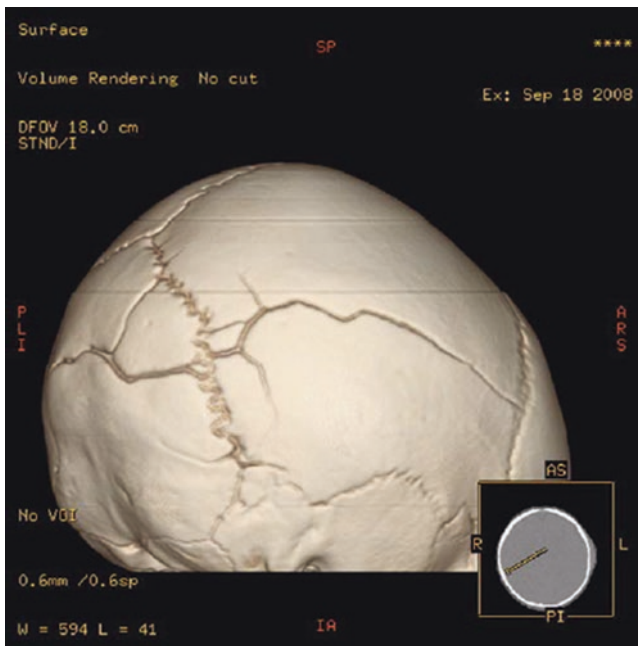
Photo 4.15 A 10-month-old male has a scalp swelling noted at bath time. Only history of trauma is a single fall from a bed. The skeletal imaging and 3D reconstruction of the CT scan is notable for multiple fractures. Photo 4.17 demonstrates a right parietal-occipital complex skull fracture
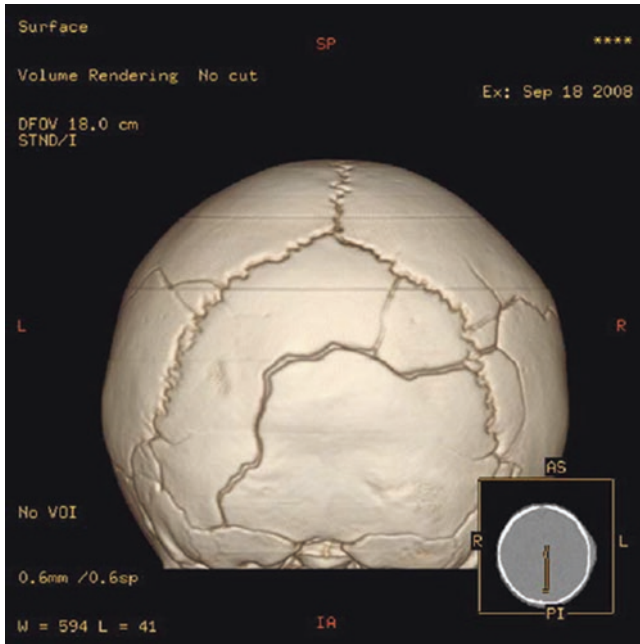
Photo 4.16 Same child with skull fracture crossing into the occipital bone
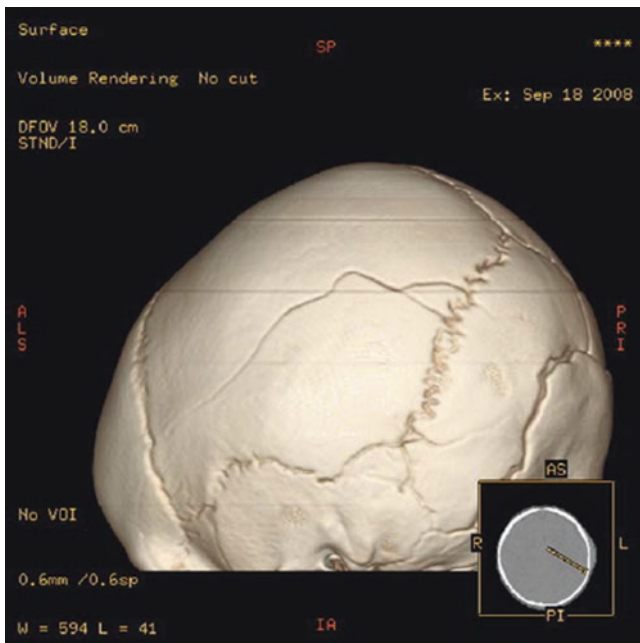
Photo 4.17 Same child with left linear parietal skull fracture as well. Extensive history of violence in the home

Photo 4.18 The 3D CT reconstruction of the infant shows acute fractures of left posterior 5th–9th ribs as well as the right 8th posterior. Additional fractures were identified on repeat skeletal imaging at 2 weeks. The child's father reported squeezing the child around the rib cage until the child stopped crying on three occasions

Stages of Fracture Healing

The radiographic appearance of bone healing has been divided into stages. These stages are not discrete and exist on more of a continuum, as they vary between individuals depending on age, disease, repeated trauma, immobilization, and surgical fixation. A number of fractures, such as metaphyseal and skull fractures, do not follow these stages and are difficult to date. A retrospective study found that incomplete long bone fractures in infants under 12 months were difficult to date outside of the appearance of periosteal reaction; however, complete long bone fractures had a predictable healing pattern (Warner et al. 2017). The presence of soft tissue swelling on the scalp may help differentiate recent from older fractures. However, the absence of soft tissue swelling does not preclude a recent injury (Ibrahim et al. 2012).

Stage 1: Induction

The radiologic appearance of fractured long bones corresponds to the anatomic and histologic changes that occur with bone healing. Radiographically, soft tissue swelling around the injured bone represents the initial change and may be the only

Photo 4.19 At 3 weeks the 3-month-old has three clearly healing rib fractures with callus and fracture line definition

indication of the fracture. An injury to a bone and the soft tissues around the bone results in immediate hemorrhage and subsequent inflammation. This is clinically represented by swelling and tenderness. The majority of broken bones are not accompanied by associated external bruising or injury (Mathew et al. 1998; Peters et al. 2008; Worlock et al. 1986). The presence of soft tissue swelling is consistent with a fracture less than a week old (Prosser et al. 2012). Soft tissue injuries that do not involve the bone or cartilage are generally limited and resolve within a few days; therefore, if there is swelling that is more extensive or longer in duration than expected, it may suggest an occult skeletal injury (Kleinman 2015). An initial widening of the gap and softening of the fracture margins occurs as the osteoclasts respond to the necrotic ends of the bone with bone resorption (Photo 4.19). This becomes apparent radiographically around 2–3 weeks after injury (Chapman 1992; Islam et al. 2000).

Stage 2: Callus Formation

Callus formation begins with the laying down of periosteal new bone. Hemorrhage and inflammation occurring at the site of injury are osteo-inductive as the periosteum is rich in precursor cells and osteoblasts. Periosteal new bone is not specific for fractures and is laid down in response to a number of different injuries, including infection, inflammation, and nutritional and metabolic conditions (Kleinman 2015).

Periosteal new bone formation occurs approximately 1–4 weeks after an injury and may be earlier in young infants (Islam et al. 2000; Prosser et al. 2005). It starts as single-layered and becomes multi-layered (Walters et al. 2014). The absence of periosteal new bone correlates with a fracture less than a week old (Warner et al. 2017). The presence of periosteal new bone formation without callus formation is consistent with a fracture 5 days to 2 weeks old (Prosser et al. 2012). The initial callus consists of new blood vessels, fibrous tissue, cartilage, and new bone. Calcium deposition begins within a few days of healing, but does not peak for several weeks. The radiographic appearance of callus formation is the result of both the laying of periosteal new bone and the calcification of new cartilage (Kleinman 2015). The presence of periosteal bone formation and soft callus is consistent with a fracture that is 2–3 weeks old (Prosser et al. 2012). In studies of the healing patterns of clavicular fractures caused by birth—which are not immobilized for treatment, making them more similar to abusive fractures not discovered until they are already healing—callus formation is highly unlikely before 9 days and is usually present by 15 days (Fadell et al. 2017; Walters et al. 2014) (Photos 4.20 and 4.21). This is consistent with another retrospective study on long bone fracture healing patterns (Warner et al. 2017).

There is considerable variability in the timing, appearance, and quantity of new bone and callus formation as a result of repetitive injury and/or the degree of immobilization of the injured bone (Kleinman 2015). Femoral fractures in patients with head injuries have an average healing time that is shorter than that of control subjects (Perkins and Skirving 1987). The studies on the dating process of periosteal new bone and callus formation largely involve subjects with immobilized fractures. There is limited published data on the healing process of young infants and children with fractures. In addition, many non-accidental fractures are occult with late presentations for care and continued repetitive injury (Kleinman 2015; Prosser et al. 2005). Callus thickness decreases as the age of the fracture increases as it changes from soft to hard (Walters et al. 2014).

Photo 4.20 Abundant callus formation is seen of the 4-month-old's humerus on imaging performed 3 weeks after injury

Photo 4.21 Left humerus spiral fracture at 20 days with callus formation

The stage of soft callus ends with the bridging of bony fragments. The hard callus stage is characterized by lamellar bone formation with bridging of the fracture line. Hard callus or bridging of the fracture line is consistent with a fracture greater than 2–3 weeks old (Prosser et al. 2012; Warner et al. 2017). However, the timeline of the fracture line appearance may be affected by additional trauma to the fracture site, especially when the fracture is not immobilized (Kleinman 2015). Radiographically, the fracture line resolves, and periosteal new bone becomes incorporated into the adjacent cortex.

Stage 3: Remodeling

During remodeling (Photo 4.22), the original configuration of the bone is restored as the callus is smoothed circumferentially. Long bone fractures in infants can be remodeled by 3 months, but remodeling in fractures in children outside of infancy is highly variable (Kleinman 2015). Some pediatric fractures are unrecognizable by radiograph within months after they occur. The ability to detect an old fracture depends on multiple factors, including the bone injured, the type and extent of the injury, and the care (or lack of care) the child received (Photo 4.12).

Photo 4.22 Left humerus spiral fracture at 4 months with remodeling

Dating of Skeletal Injuries

The dating of fractures estimates the age of injury and can identify multiple episodes of trauma. It is based on the constellation of radiologic findings including the presence or absence of soft tissue swelling as well as the appearance of periosteum, widening of fracture margins, callus formation, periosteal new bone incorporation, and remodeling. There is little published evidence on the dating of fractures in children, especially in the context of potential repetitive injury from lack of immobilization. Recent fractures can be clearly delineated from older fractures. Estimates of the age of older fractures can often be made in weeks rather than days. From the literature that has been published on pediatric fracture healing patterns, there are general rules of thumb for healing (average): subperiosteal new bone formation 10–14 days, fracture line indistinct 14–21 days, soft callus 14–21 days, hard callus 21–42 days, and remodeling (up to 1 year) (Kleinman 2015; Prosser et al. 2012; Walters et al. 2014).

Other factors that affect the healing process need to be considered when dating fractures, including the severity of injury, degree of fracture displacement, degree of immobilization of the injured body part, metabolic bone diseases that influence the healing process, and repetitive trauma. Repetitive trauma to the fracture site cannot be ruled out in fractures that have not had medical care. Certain fracture sites, such as skull fractures or classic metaphyseal lesions, are difficult to date due to their

healing patterns. The follow-up skeletal survey performed approximately 2 weeks after the initial survey is quite useful as it assists in dating and in the identification of occult injury, skeletal dysplasias, and metabolic disease.

Long Bone Fractures

Fractures of the bones of the arms and legs are common childhood injuries (Rivara et al. 1986). Accidental trauma accounts for the majority of long bone fractures and abuse accounts for only a minority. The likelihood that a long bone fracture is due to abuse is greatest in infants. The type of fracture sustained depends on the mechanical forces applied to the bone during the trauma (Table 4.3).

Due to the decreased amount of mineral content in a child's bones (as compared to an adult's bones), there is greater elasticity. The child's bone will tolerate more stress before a fracture occurs (Pierce et al. 2005). Correlating the history with the fracture type is often useful in identifying cases of non-accidental injury. However, it is important to realize that accidental fractures may be unwitnessed in ambulatory children, and therefore the exact mechanism of trauma may not be recounted. Each case requires careful evaluation that includes developmental ability to determine if an injury is suspicious for abuse. For example, meta-analyses of current literature have found that femur and humerus fractures in children under 18 months are significantly more likely to be abusive than in children 12–48 months (Maguire et al. 2013). Careful evaluation is needed to uncover indicators of abuse for each case (Photos 4.3 and 4.11).

Diaphyseal Fractures

Diaphyseal fractures are injuries to the midshaft of the long bones. They are generally described by the bone injured (femur, humerus, ulna, radius, tibia, fibula), the location of the fracture within the bone (distal, proximal, midshaft), and the type of fracture as defined by radiography (transverse, spiral, torus, etc.) (Photos 4.3, 4.7, and 4.10). In young infants, a diaphyseal fracture of the femur (while often due to abuse) should raise the question of birth-related injury (both in vaginal and cesarean deliveries) (Morris et al. 2002). In birth-related fractures, metabolic bone disease with osteopenia should also be considered as a contributing cause. Toddler fractures (oblique or spiral tibial fractures) have been described and attributed to the mechanics of toddlers' balance and walking skills (John et al. 1997; Mellick et al. 1999).

It requires substantial force to break the femur (although precise forces needed have not been elucidated), and healthy, non-ambulatory infants do not take part in activities that generate the forces needed to sustain these fractures (Photo 4.3). A systematic review found a high prevalence of abuse in children who had femur fractures under 12 months of age (Wood et al. 2014b). Another study found that most

Table 4.3 Common types of diaphyseal fractures seen in childhood

Type	Characteristics	Causes
Transverse	Fracture line perpendicular to long axis of the bone Force applied to bone is perpendicular to length of the bone	Direct trauma Associated with accidental and inflicted injury
Spiral	An oblique fracture where fracture line encircles a portion of the bone	Indirect torsional forces to the bone Often associated with abusive injuries Seen with accidental injury (in ambulatory children) and child abuse (primarily in infants and young toddlers)
Oblique	Fracture line angled across long axis of the bone (from approximately 30–45 degrees)	Often the result of combination loading (torsional, tensile, and compressive) Seen in accidental and abusive injury
Toddler's fracture	A nondisplaced spiral fracture of the tibia Manifested by limp. There may be a delay in seeking medical care because the injury does not initially appear to be significant. May be occult: nondisplaced, little swelling, initial radiographs may fail to identify the fracture Diagnosed by bone scan at time of presentation or plain films repeated in approximately 2 weeks if clinical scenario indicates toddler's fracture but there is no fracture identified on initial radiographs	Common accidental injury in children between the ages of 1 and 3 Often occurs with routine play activities May result from running and slipping, jumping and falling, and even sliding with a difficult landing Uncommonly results from abuse History of trauma given may seem incomplete or insignificant
Greenstick fracture	An incomplete fracture Compressed side of bone is bowed, but not completely fractured	Occurs secondary to plasticity of a child's bone Commonly accidental and not commonly reported in the abused child
Torus (buckle) fracture	Localized buckling of the cortex of the bone Injuries located toward metaphysis of the bone Due to anatomy of the developing bone	Results from forces applied parallel to long axis of the bone
Impacted fracture	Involves entire bone	Both commonly accidental and not common in child abuse

Note: No type of diaphyseal fracture is diagnostic of abuse.

femur fractures in healthy, mobile children ages 1–5 years old were accidental due to falls (from standing or a height), stumbling, fall while running, or an object falling on the child (Capra et al. 2013). Yet another study found that transverse femur fractures are more predictive of abuse than spiral or oblique fractures in children 3 years and under (Murphy et al. 2015). These findings underlie the need for an

objective, thorough evaluation of femur fractures in infants that includes a detailed history and assessment of developmental ability. Risk factors for abuse suggested for infants include the following: non-ambulatory status, suspicious history (absent, unwitnessed, or inconsistent with the child's developmental ability or pattern of injury), and the presence of additional injuries (Wood et al. 2014a). The history is the most important factor in determining whether a femur fracture is inflicted or accidental (Capra et al. 2013).

Stair falls are often attributed as the cause of fractures. In general, serious injuries with stair falls are uncommon (Pierce et al. 2005). In a study of stair falls, spiral fractures of the femur were more commonly seen in children over 12 months, and buckle fractures were seen in the group under the age of 12 months. The likelihood of more serious injury was increased if the fall occurred with an adult. Buckle fractures of the femur appear to be associated with compressive injury occurring with the striking of the knee onto a surface (Photos 4.1 and 4.2). A torsional injury can occur with a leg being twisted under the child during a fall. Pierce found that the linear momentum associated with transverse femur fractures was almost 10 times greater than that seen with spiral or buckle fractures (Pierce et al. 2005).

Like with femur fractures, abusive humerus fractures are more often found in younger infants versus older children (Maguire et al. 2013). Overall, the majority of humeral fractures are accidental and occur in older children (Caviglia et al. 2005). Fracture patterns described include transverse or oblique occurring with force to the shoulder or outstretched arm and spiral or oblique fractures due to rotational (torsional) movement of the body onto an outstretched (weighted) arm (Photos 4.7 and 4.10). Supracondylar fractures of the humerus occur when children fall on the elbow or outstretched hand (with the elbow in full extension). Likely due to these mechanisms, distal humerus fractures are much more likely to be accidental when compared to proximal and humeral shaft fractures (Pandya et al. 2010). As seen with femur fractures, the type of fracture (transverse, spiral, etc.) does not necessarily predict whether an injury is due to abuse or accident. However, spiral and oblique fractures of the humerus are the most common fracture type from abuse (Kemp et al. 2008). As with many other abusive injuries, having greater than 1 fracture was also associated with abuse in humerus fractures (Pandya et al. 2010).

Forearm diaphyseal fractures often occur secondary to sports activities or falls (Ryznar et al. 2015). These fractures are common in the pediatric population, representing 42% of all pediatric fractures (Rodríguez-Merchán 2005). The injury often occurs with a fall onto an outstretched hand. In a retrospective study of forearm fractures in children less than 18 months, younger age (mean age 7 months) was associated with abuse versus a mean age of 12 months in those with accidental forearm fractures. Children with abusive forearm fractures were also more likely to have no explanation or a changing fracture history (Ryznar et al. 2015).

Treatment of diaphyseal fractures depends on patient age, fracture age when identified, and the type and location of the fracture. In general, diaphyseal fractures impede the normal functioning of the involved bone. Treatment requires immobilization and limitation of weight bearing for lower extremity fractures.

Metaphyseal Fractures

Metaphyseal fractures of the long bones are strongly predictive of abuse and are highly specific for inflicted injuries in children under 1 year of age (Kleinman and Marks Jr. 1998; Kleinman et al. 2011) (Photos 4.23, 4.24, and 4.25). In children over the age of 1 year, similar lesions should be viewed with caution as there are nonspecific Salter-Harris II fractures and developmental variants (Kleinman 2008). Until recently, metaphyseal fractures were thought to represent "chip fractures" of the metaphyses (Caffey 1957). Caffey (1957) postulated that these lesions were due to small avulsions of the metaphyseal cartilage and bone at the point of insertion of the periosteum. Recent findings in which histologic correlations to radiographic findings were performed document that metaphyseal fractures represent fracture through the most immature portion of the metaphysis creating a planar type injury (Kleinman et al. 1986). Depending on the radiologic projection, metaphyseal fractures may appear as linear lucencies or densities across the metaphysis, "bucket-handle" fractures, or corner fractures (Photo 4.23). All of these lesions are subtle and may be recognized on a skeletal survey or incidental radiograph.

Metaphyseal fractures are injuries generally found in infants and young toddlers. The mechanism of injury is related to either acceleration–deceleration forces associated with the abusive head trauma or torsional and tractional forces applied to the bone when an infant is twisted, jerked, or pulled by an extremity (Kleinman et al.

Photo 4.23 This 5-month-old female presented with swelling and pain with movement of her right lower leg. There was no known trauma reported other than the child caught her leg during a feeding. Multiple classic metaphyseal lesions were found including bilateral distal femurs, bilateral proximal, and distal tibias

Photo 4.24 Additional views of the 5-month-old female's left lower extremity and classic metaphyseal lesions

Photo 4.25 This demonstrates the 5-month-old female's right proximal humeral classic metaphyseal lesion. The left upper extremity has no fractures and normal metaphyses

1986) (Photos 4.4, 4.5, and 4.6). Metaphyseal fractures are often multiple and bilateral. Common sites for metaphyseal fractures include the proximal humerus, distal femur, proximal tibia, and distal tibia and fibula (Kleinman and Marks Jr. 1996a, b, c, 1998). The number of bones involved varies from case to case, and fractures isolated to one or only a few bones are not uncommon. Metaphyseal fractures do not typically result in significant soft tissue swelling or external bruising. Injuries are not usually identified clinically by either a parent or the physician during the physical examination. In addition, most of these fractures heal without specific treatment or the need for immobilization.

The differential diagnosis should include metabolic bone disease (particularly in a premature infant), a history of rickets with excessive range of motion exercise (Helfer et al. 1984; Kleinman and Marks Jr. 1998), bone dysplasias (Bronicki

et al. 2015), treatment for club foot (forced eversion and inversion) (Grayev et al. 2001), iatrogenic injury associated with neuromuscular disorders (Uddenfeldt Wort et al. 2013), birth-related injuries (both vaginal and cesarean deliveries) (O'Connell and Donoghue 2007), external cephalic version (Lysack and Soboleski 2003), and normal variants such as step-offs, beaks, and collars (Kleinman et al. 1991). In infants and toddlers with significant genu varum, classic metaphyseal-like lesions may be seen. With time these lesions do not show evidence of healing (Photos 4.19, 4.26, and 4.27).

The metaphysis is an area of rapid bone turnover due to normal growth of the infant skeleton. Because metaphyseal fractures are subtle and usually clinically silent, the skeletal survey remains the identification method of choice. A pediatrician or radiologist familiar with the skeletal manifestations of child abuse is often required to identify metaphyseal fractures. A bone scan, which identifies areas of rapid bone turnover, is not helpful in identifying metaphyseal fractures because the metaphysis is normally an area of bone growth and turnover (Drubach et al. 2010).

Metaphyseal fractures are difficult to detect or date radiographically due to an absence of periosteal elevation and hemorrhage. As a result, the fracture may not show signs of periosteal reaction, or the reaction may be only modest. Metaphyseal lesions may or may not heal with subperiosteal new bone formation. The clinician needs to differentiate this from physiologic new bone formation. However, physiologic new bone formation is largely diaphyseal in location. There may be sclerotic lines or loss of fracture line during the healing process. Another change that may

Photo 4.26 The 3-month-old infant in Photo 4.30 had multiple rib fractures in addition to her skull fractures and subdural hemorrhages. The stepfather reported squeezing her around the rib cage until she would "pass out." Healing rib fractures are seen in multiple locations including the right posterior 4th–9th, left posterior 3rd–10th, and left lateral 3rd–7th

Photo 4.27 This
3-month-old infant had
crepitus on examination
and posterior arc fractures
seen only on the oblique
view of the skeletal survey
at the left 6th–8th ribs

assist in identifying a healing fracture is local extension of the physeal lucency into
the metaphysis (caused by cartilaginous hypertrophy) (Kleinman 2015). Most classic metaphyseal lesions will be healed by 4 weeks (Kleinman 2008). Massive periosteal reaction usually indicates a displaced fracture or a shearing injury to the
periosteum itself (Photo 4.6) (Kleinman and Marks Jr. 1998). Metaphyseal fractures
also may be dated by evaluating the sharpness of the fracture margins. As the injury
heals, the margin becomes more poorly defined. Unfortunately, this is a subjective
measure and one that has not been studied systematically. It is thought that future
studies using MRI may help to date metaphyseal injuries more precisely (Perez-Rossello et al. 2010).

Growth Arrest Lines

Growth arrest lines are radiopaque transverse lines across the metaphyses seen
occasionally in abused or neglected children. They are not specific for maltreatment
and may occur in children with illness, injury, starvation, or other stresses that affect
growth (Zapala et al. 2016). Growth arrest lines represent periods of slowed growth
and are most evident in bones that normally grow rapidly. They form because the
usual orientation of the trabeculae of fast-growing bones is longitudinal (parallel to
the long axis of the bone), as opposed to transverse (seen in the trabeculae of normally slow-growing bones) (Ogden 1990). During periods of slow growth, the

trabeculae become oriented transversely, causing a thicker appearance to the affected bone. When the stress is removed and the bone begins to grow at a normal rate, the normal longitudinal orientation of the bone resumes, and the thickened area appears as a discrete transverse line. Many children have evidence of multiple growth arrest lines in a single bone, representing prolonged periods of physiological stress. With time, the transverse orientation of the bone resolves, and growth arrest lines break down so that they are no longer visible. One study compared the skeletal surveys in infants at high risk of abuse versus infants at low risk of abuse and found that growth arrest lines were more commonly found in the high-risk infants (Zapala et al. 2016). However, growth arrest lines are a nonspecific finding, as they can result from many types of physiologic stressors.

Physeal and Epiphyseal Fractures

Physeal and epiphyseal fractures in young children and infants are very rare. Most of physeal and epiphyseal injuries occur in school-age children. Since they are not ossified in young children, these types of fractures can be easily missed on radiographs, including skeletal surveys. Ultrasound or MRI can be useful to confirm a suspected epiphyseal separation or injury (Supakul et al. 2015). These fractures are important to confirm when suspected, as they sometimes require surgical intervention and long-term follow-up to monitor bone growth. These fractures can result from birth trauma, abuse, or accidental trauma in children under 3 years old (Supakul et al. 2015; Tharakan et al. 2016). More research is needed on these rare fractures.

Skull Fractures

Skull Anatomy

The skull consists of cranial and facial bones. The eight intramembranous cranial bones—frontal, occipital, sphenoid, ethmoid, and left and right parietal, and temporal bones—develop directly within a membrane and not from cartilage, as with the long bones. The cranium is composed of a number of separate bones joined by strips of connective tissue called sutures. The main sutures include the sagittal, coronal, and lambdoid. Lesser known sutures include the squamosal, metopic, and mendosal. The mendosal sutures extend medially from the lambdoid sutures into the occipital bone. In the sutures are larger areas of connective tissue known as the fontanelles. In addition to the anterior, posterior, and anterolateral fontanelles, there can also be small accessory fontanelles within the sutures, especially the sagittal suture. Islands of bone (ossification) found within the posterior sagittal and lambdoid sutures, if large enough, are referred to as "wormian bones." There is another

variant of the occipital bone referred to as the interparietal (Inca) bone at the vertex of the lambdoid sutures. The Inca bone can be bipartite divided by a superior median fissure (Quigley and Stafrace 2014).

Both accessory sutures and fissures are common in the parietal and occipital bones. These fissures can be mistaken for skull fractures (Choudhary et al. 2010; Quigley and Stafrace 2014). The occipital bone has several sutural variants including superior median, midline, and lateral occipital fissures; transverse occipital sutures; and innominate synchondrosis (Choudhary et al. 2010). The parietal bone may be partially or completely bisected by a fissure running parallel to the sagittal suture (Stokes and Cremin 1974). The presence of these fissures and sutural variants is largely the result of multiple ossification centers within the developing bones of the skull. The skull of the newborn is quite thin and does not achieve the adult "three-layer" diploe configuration for 3–4 years (Holck 2005). The parietal bone is quite thin, monolayer, and particularly susceptible to fracture. In studies of infant cadavers with falls (head-first with parieto-occipital impact) onto differing surfaces from 0.82 m, fractures occurred almost exclusively in the parietal bone (Weber 1984, 1985, 1987). The growth and repair of the skull bones are distinct from that of the long bones, making dating of skull fractures more difficult. Additionally, bone scans do not identify skull fractures with any sensitivity. Three-dimensional CT reconstruction does enable a detailed view of the skull, sutures, fissures, and fractures (Photos 4.15, 4.16, and 4.17) (Choudhary et al. 2010; Culotta et al. 2017; Parisi et al. 2015). CT of the head is also useful for differentiating between vascular channels that may be confused with fractures (George et al. 2017). With so many normal variants of the infant and young child's skull, working with a pediatric radiologist is highly recommended.

Skull Fractures and Abuse

Skull fractures are due to a direct impact of the head with a solid object. A description of the fracture includes the location identifying the skull bone involved and the type of fracture. Skull fractures related to child abuse generally refer to the cranial bones, although facial fractures occur (see Chap. 8). Table 4.4 describes common types of skull fractures.

Skull fractures are the perhaps the most common fracture in hospitalized children. However, only 17% of these were attributable to abuse in children under 12 months of age (Leventhal et al. 2008). Skull fractures are more commonly reported after accidental head injuries (Kemp et al. 2008). Simple linear parietal skull fractures are just as commonly found in accidental as in abusive head injuries (Billmire and Myers 1985; Leventhal et al. 1993; Meservy et al. 1987) (Photo 4.28). In young children, accidental linear fractures may occur from falls of less than 4 ft (such as off a bed, couch, or changing table), falls of greater distances (down stairs), or walker injuries (Coats and Margulies 2008; Duhaime et al. 1992). Likewise, linear fractures may result from abuse and are indicative of a direct impact to the

Table 4.4 Common types of skull fractures

Type	Characteristics
Basilar	Fracture of base of skull
	Difficult to identify radiologically
	CT scan is a more sensitive test than plain films
	Usually diagnosed by clinical criteria: CSF otorrhea, rhinorrhea, raccoon eyes (periorbital blood), or Battle's sign (ecchymoses over the mastoid area)
Comminuted	Complex fracture results in separate piece(s) of bone
Complex	Comprised of more than one line
	May be branched or stellate, or consist of more than one distinct fracture
Depressed	Occurs when bony fragment is displaced inward toward the brain
	Often a comminuted fracture and may be associated with neurologic deficits, usually due to underlying brain involvement
Diastatic	Fracture margins significantly separated
	Injuries to the sutures can result in diastasis, either in association with a fracture or as an isolated injury
	Diastasis of multiple sutures may occur with increased intracranial pressure or occasionally with rapid brain growth
Linear	A single, unbranched line that can be straight, curved, or angled
Ping-pong	Bone indented, but without a distinct fracture
Stellate	A type of complex fracture
	Fracture lines radiate from central point

Photo 4.28 A 1-month-old female with linear parietal skull fracture after a fall from parent's arms

head (Photo 4.29). Some report complex skull fractures, depressed fractures, and diastatic fractures as characteristic of inflicted injury (Hobbs 1984). Other studies report no real difference in the incidence of complex skull fractures (Leventhal et al. 1993; Meservy et al. 1987) but strong associations with multiple fractures, bilateral fractures, and fractures crossing sutures (Meservy et al. 1987) (Photos 4.15, 4.16, 4.17, 4.29, and 4.30). Bilateral skull fractures may result from crushing injuries (Hiss and Kahana 1995), but they can also occur from a single midline cranial impact (Arnholz et al. 1998). Young infants may sustain linear, depressed, and ping-pong fractures from simple falls because of the relative ease with which the

Photo 4.29 This 3-month-old female presented with poor feeding and lethargy and no history of trauma. Skeletal survey notable for bilateral skull fractures with diastasis on the left. The infant had multiple other injuries including subdural hemorrhages, bruises, and rib fractures

Photo 4.30 A 5-month-old female with multiple extremity fractures is found to have a complex, comminuted skull fracture on skeletal survey. Caregiver reported only a single fall from a bouncer chair

skull can be deformed at this young age and its thin, monolayer construction (Weber 1985). Although no fracture type is pathognomonic for abuse, abuse is suspected when no history of trauma is provided, the history is inconsistent or changes, the history is developmentally implausible, or a history of minor injury results in complex or multiple fractures.

In nonverbal children with a seemingly isolated skull fracture, it is controversial whether to complete the skeletal survey to screen for occult injuries or not. In recent studies, there is a small subset of young children who present with an apparently isolated skull fracture but are then found to have occult skeletal injuries on skeletal survey (Deye et al. 2013; Laskey et al. 2013). Laskey et al. (2013) recommend considering a skeletal survey in any child less than 2 years old who presents with a skull fracture and emphasizes the importance of a skeletal survey in infants less than 6 months old. Similarly, a multispecialty panel of experts deemed skeletal surveys "necessary" in infants 0–11 months old, with an exception for those infants 7–11 months who presented with a reported fall and a unilateral linear skull fracture (Wood et al. 2014b).

The presence or absence of cutaneous injury and/or skull fracture does not predict intracranial injury. In one study of the association between bruising and fractures, 43% of patients had bruising or subgaleal hematoma at the site of skull fracture. Of those patients with skull fractures, almost half had evidence of intracranial injury. Skull fractures were present in 75% of those with abusive head trauma (Peters et al. 2008). In Duhaime's study of head injury in young children, 37% of children with abusive head trauma had skull fractures (Duhaime et al. 1992). Much of the variability lies in study design. Controversy regarding the exact mechanism and biomechanics of abusive head trauma relates to whether impact is required to produce intracranial injury. Multiple and diastatic skull fractures, from direct impacts such as from falls from significant height or blows, do occur without life-threatening intracranial injury. Yet many children without skull fracture have intracranial injury so severe as to result in death. Infants whose injuries are credited to acceleration–deceleration injury may have a skull fracture documented by skull films. As indicated by the fracture, these children have sustained direct impact to the head in addition to acceleration–deceleration injury (see Chap. 6).

Dating Skull Fractures

Skull fractures are more difficult to date than long bone fractures, both clinically and radiographically. Soft tissue swelling may not be apparent clinically in the acute period and may become noticeable only after the associated scalp hematoma begins to degrade and liquefy. This can lead to a delay in seeking medical care by the child's caregiver as well. Soft tissue swelling in the first 24 h after a skull fracture should be evident on CT scan. Kleinman and Spevak (1992) evaluated soft tissue swelling associated with acute (less than 24 h old) accidental skull fractures in children. All fractures were associated with soft tissue swelling overlying the fracture

of at least 4 mm, as seen by CT scan (Kleinman and Spevak 1992). However, another study identified an absence of facial or scalp soft tissue swelling in 11% at the time of presentation with an acute head injury (Ibrahim et al. 2012). Skull fractures do not heal with exuberant callus formation. Recognition of older injuries rests on the subjective determination of fracture line definition and is therefore imprecise. Like those in other types of fractures, infant skull fractures heal relatively rapidly compared with older children and adults. In most cases, isolated skull fractures require no specific therapy. "Growing fracture" or "leptomeningeal cyst" is a known but rare complication of diastatic skull fractures in approximately 1–2% of children under 3 years of age. Clinical examination is recommended in 6–8 weeks after injury with consideration for follow-up radiography (Ersahin et al. 2000).

Rib Fractures

Rib fractures are unusual pediatric injuries that commonly result from major trauma (such as motor vehicle crashes [MVCs] or child abuse). An evaluation for child abuse is performed when an infant or young child presents with unexplained rib fractures. Rib fractures are the most common fracture found in association with other non-accidental injuries (Day et al. 2006; Kleinman et al. 1995; Worlock et al. 1986). Many studies have confirmed the association between child abuse and rib fractures (Darling et al. 2014; Paine et al. 2016). A large retrospective study of trauma patients with rib fractures calculated a 95% positive predictive value for non-accidental trauma in children less than 3 years of age with rib fractures (Barsness et al. 2003). A systematic review of the literature found rib fractures to have the highest probability for abuse at 0.71 (as compared to other skeletal injuries) (Kemp et al. 2008). Another more recent systematic review of the literature found that the prevalence of abuse in children under 12 months was 91% after excluding MVCs and bone pathology (Paine et al. 2016). Rib fractures from abuse are found in multiple locations including posterior (most common), posterolateral (mid-posterior), lateral, and anterior (Barsness et al. 2003; Bulloch et al. 2000; Kleinman et al. 1996) (Photos 4.23 and 4.24). Barsness et al. (2003) found a statistically significant association between the posterior location and non-accidental trauma. It should be noted that despite posterior rib fractures being highly specific for abuse, multiple posterior rib fractures have also been found in the case of high-impact blunt-force trauma of an infant in a stroller bring stuck by a car (Bixby et al. 2011). However, in this case the mechanism of injury was not in question.

Direct blows to the chest can result in rib fractures and probably represent the mechanism of injury in older children. Kleinman et al. (1992) studied postmortem changes of fractured ribs in infants who died of abuse. The location (near the costo-transverse process articulation) and the healing patterns (on the ventral or internal surface of the rib) of the fractures suggested that rib fractures occur as the rib is levered over the transverse process of the adjacent vertebral body during violent manual anterior-posterior compression of the chest (Kleinman et al. 1992). CT was utilized by Kleinman and Schlesinger (1997) to assess physical factors associated

with manual compression and rib fractures in rabbits. With digital chest compression on a firm surface simulating cardiopulmonary resuscitation, no rib fractures occurred. With manual compression with hands around the chest (until palpable/audible popping heard), levering of the ribs was seen as the vertebral body migrated dorsally. A total of 13 fractures occurred in 3 rabbits (Kleinman and Schlesinger 1997). Rib fractures in non-accidental trauma usually involve multiple ribs (Barsness et al. 2003) and are often bilateral. Children with accidental rib fractures from trauma often have blunt impact and/or thoracic compression. These children are struck or run over by motor vehicles or become unrestrained projectiles striking firm surfaces with anterior-posterior compression of the chest (Bulloch et al. 2000; Kleinman and Schlesinger 1997).

Cardiopulmonary Resuscitation and Rib Fractures

In adults, rib fractures frequently occur in association with cardiopulmonary resuscitation (CPR) (Krischer et al. 1987). Prior to 2005, when the recommended method of infant CPR was "one-handed CPR" (two fingers pressing on the sternum), rib fractures did not appear to be a clinically significant complication of CPR in infants and young children as the thorax is less rigid and has more elasticity. In a systematic review of the literature on the relationship between one-handed CPR and rib fractures, a total of three children had rib fractures as a consequence of CPR out of a documented 923 cases. Two children were less than 6 months of age and one child was 5 years of age. All rib fractures were multiple and anterior. Two of the cases had mid-clavicular fractures, and one case had bilateral fractures at the sterno-chondral junction. No cases were identified with posterior rib fractures. Five of the six studies meeting inclusion criteria were postmortem (Maguire et al. 2006).

In 2005, the American Heart Association changed their infant CPR recommendations to a "two-handed" method (both hands encircling the chest of an infant with thumbs compressing over the sternum). Since then, a case series of five infants found that this two-handed CPR may be associated with more rib fractures than the prior one-handed method; however, posterior rib fractures were not demonstrated (Matshes and Lew 2010).

Radiographic Findings of Rib Fractures

Rib fractures due to abuse are almost always occult and not recognized either by an unsuspecting caregiver or during routine physical examination. Occasionally, healing fractures with exuberant callus can be palpated, but this usually occurs only after the fractures have been diagnosed radiographically. Acute (new) rib fractures are difficult to identify by plain radiograph. Posterior rib fractures have little displacement or angulation or disruption of the periosteum (Kleinman et al. 1988). Fractures are generally recognized only after callus formation and

Photo 4.31 A 5-week-old infant with multiple skull fractures and cutaneous trauma. Initial chest radiograph appeared reassuring

periosteal reaction are evident. The addition of oblique views to the skeletal survey has been helpful in identifying fractures (Hansen et al. 2008; Marine et al. 2014) (Photos 4.31 and 4.32).

Bone scan is more sensitive for the identification of acute rib fractures (less than 7–10 days old) than plain films (Bainbridge et al. 2015; Drubach et al. 2010). Likewise, a study comparing CT with chest radiograph found CT more sensitive in identifying rib fractures at all locations except lateral (Photos 4.13, 4.14, and 4.18). However, the study did not utilize oblique views of the chest, and CT requires higher doses of radiation (Wootton-Gorges et al. 2008). Chest CT does have the additional benefit in children with multisystem trauma in identifying additional injuries including hemothorax and pulmonary contusion.

In suspected abuse with an initial negative skeletal survey, a bone scan may identify acute fractures, including those of the ribs. An infant who presents without a history of trauma but with intracranial injury should have a skeletal survey with oblique views of the chest performed as part of the initial evaluation. Repeat skeletal survey in 2 weeks, as outlined in the imaging section, is crucial in the identification of occult rib fractures (Photos 4.31 and 4.32).

In the majority of cases, rib fractures are not associated with clinical pulmonary or liver injuries and do not interfere with normal respiration. These fractures typically heal rapidly and without specific therapy. In studies of children with thoracic trauma, the likelihood of intrathoracic injury and multisystem trauma increased in children with multiple rib fractures or posterior rib fractures (Garcia et al. 1990). However, a recent retrospective study noted that although abuse cases were found to

Photo 4.32 The infant had a repeat skeletal survey now demonstrating healed left posterior rib fractures of ribs 7 and 8

have more rib fractures than the accidental cases, abuse cases were less likely to have intrathoracic injury. This is thought to be from the slower loading forces in child abuse versus the high-energy blunt force impacts in the accidental cases, which included MVCs and motor-pedestrian collisions (Darling et al. 2014).

Other Fractures Associated with Child Abuse

Child abuse can result in injury to virtually any bone in the body, although the most common injuries are fractures of the extremities, ribs, and skull. Many fractures are clinically unrecognized, which emphasizes the need for careful radiologic assessment of all bones. The following sections review injuries occasionally seen in the abused child, although none is pathognomonic for maltreatment.

Vertebral Fractures

Spinal fractures in infants and toddlers are relatively rare injuries from child abuse but probably occur more frequently than they are recognized (Kleinman 2015). The injury to the vertebral bodies and spinous processes are subtle and require lateral

views of the spine. Most vertebral injuries are occult, although a few children present with spinal cord compression. Lateral views of the spine may reveal vertebral body compression fractures or anterior vertebral end-plate injury. MRI may be used to further assess significant vertebral and spinal cord injuries. These abusive compression vertebral fractures often result from severe hyperflexion of the torso and axial spinal loading (Kleinman and Marks 1992; Tran et al. 2007). Vertebral compression fractures in isolation do require further evaluation for osteogenesis imperfecta (Renaud et al. 2013). Vertebral injuries, if stable, do not require specific therapy. Children with cord compression, however, require surgical intervention and often have permanent neurologic disability.

Even rarer than compression vertebral fractures are distraction fractures of the vertebral column. These can be associated with vascular and spinal injury, and the mechanism of this type of injury is a high force applied over a fulcrum that causes rapid hyperextension (Brink et al. 2017).

A couple of studies have shown that perhaps spinal fractures are not as rare as previously thought. One study showed a spinal fracture prevalence of 1.9% in children 0–4 years old (Barber et al. 2013). The other study showed a prevalence of 2.7% in the skeletal surveys on children under 2 years (Kleinman et al. 2013).

Pelvic Fractures

Fractures of the pelvic bones are uncommon injuries in abused children (Bixby et al. 2014; Lindberg et al. 2013). Injuries to the pelvis that occur in infants and young children are often unrecognized prior to radiologic discovery. Most of the reported injuries are unilateral and occur in conjunction with other skeletal trauma. The ischiopubic ramus is most commonly fractured. Although the precise mechanism of inflicted pelvic trauma is not described in the literature, accidental pelvic injuries in children are due to direct trauma in association with falls, motor vehicle crashes, and crush injury (Quinby 1966). Although accidental pelvic injuries may be life threatening, inflicted pelvic fractures are generally stable injuries that do not require surgical intervention.

There are anatomic variants associated with the ossification centers in the superior pubic ramus. The ossification centers can be single or multiple, unilateral or bilateral, and can have associated sclerosis of the margins. Fractures are more likely to be oriented obliquely to the axis of the pubic ramus with displacement of fragments and callus formation. A vertical radiolucency with smooth margins, in the absence of other pelvic or skeletal trauma, should be considered an anatomic variant (Perez-Rossello et al. 2008).

Clavicle Fractures

Clavicle fractures are common accidental pediatric injuries and are occasionally associated with abuse (Ogden 1990). This fracture is the most common birth-related fracture and is often associated with infants who are large for gestational age. The fracture may go unnoticed, while the infant is in the newborn nursery. If the question is raised on birth-related versus post-hospital care, attempts to age the healing fracture should be used. If callus is not present by the time the child is 10–14 days of age, it is unlikely to be birth-related (Walters et al. 2014). Accidental injury, accounting for 75–80% of all clavicle fractures, generally occurs in the midshaft of the bone due to the thinness of the bone at this site as well as the lack of muscular and ligamentous supports (Pecci and Kreher 2008). Accidental fractures of the clavicle are associated with birth trauma, direct injury, or falling on an outstretched arm. Midshaft fractures are common with both accidental as well as inflicted injury. Clavicular fractures involving the acromioclavicular joint are associated with violent traction of the arms (Kogutt et al. 1974). Inflicted clavicular fractures are typically associated with other skeletal injuries and are an uncommon isolated finding (Merten et al. 1983). In teens where ossification of the growing centers is not complete, growth plate injury must be considered (Pecci and Kreher 2008). Clavicle fractures in older children are usually treated with a clavicle strap or figure-8 sling, primarily to ease discomfort. These injuries in young children and infants often heal well without immobilization.

Fractures of the Hands and Feet

Fractures of the hands and feet, while common in older children, are suspicious injuries in infants and young toddlers. These fractures are rare but may be the only indication of inflicted injury (Lindberg et al. 2013). Close attention should be paid to images of the hands and feet in the skeletal survey, ensuring that the fingers are not curled or obscured by intravenous equipment. Specific treatment depends on the extent and location of the fracture.

Foot fractures may occur from forces acting on the foot such as objects dropped onto the foot, falling from height, lawn mower injuries, or from using the foot to stop motion (biking, sledding, etc.). Likewise, indirect force (adduction, eversion, and inversion) may result in fractures. Due to the many small bones, growth centers, cartilaginous bones, and lack of displacement of fracture fragments, it may be difficult to identify a fracture in the foot. Radiographs, if inconclusive, may be repeated in 2–3 weeks (in the otherwise stable patient). Use of bone scans or MRI studies can be used in more concerning evaluations such as concern over talus fractures and the potential risk of avascular necrosis. Some conditions may be confused with foot fractures, including osteochondroses, tumors, inflammatory conditions, and infections.

Hand fractures are relatively common in children. Two peak ages have been identified with the first occurring at age 1–2 years (distal phalangeal fractures) and next at age 12 years (with proximal phalangeal and metacarpal) (Valencia et al. 2005). Sports injuries are more common in older pediatric patients (teenagers). Fractures of the fingers may present with swelling, whereas fractures to the metatarsals, metacarpals, and phalanges are frequently asymptomatic and only incidentally discovered by skeletal survey (Kleinman 1990). The fractures can be caused by direct impact, torsion, and twisting. Buckle fractures of the proximal phalanx may be the result of forced hyperextension of the fingers (Nimkin et al. 1997). Oblique views may be useful in the evaluation of buckle fractures (Nimkin et al. 1997). With Salter type I injuries, the initial radiographs may appear normal. Scaphoid fractures are unique since they may be difficult to identify acutely without the use of MRI or scaphoid views. If not identified and treated early, these fractures can result in avascular necrosis.

The Differential Diagnosis of Inflicted Fractures

Metabolic and physiological processes may lead to pathological fractures, or they may simulate fractures. Although some of these conditions are readily apparent and easily diagnosed, others can be confused with and misdiagnosed as abuse. The presence of a metabolic bone disease does not preclude abuse. The following sections describe some of the more common conditions included in the differential diagnosis of inflicted fractures.

Birth Trauma

Difficult or emergency deliveries, large infants, or breech presentations may cause diaphyseal or epiphyseal fractures of the clavicle, humerus, or femur. Multiple fractures in the newborn suggest an underlying neuromuscular or metabolic bone disease (Ogden 1990).

Clavicle fractures are most common and may not be recognized in the days after delivery. They are often asymptomatic and may be detected initially by a parent who palpates the callus when the infant is a few weeks old.

Diaphyseal femur and humerus fractures may be noted at the time of delivery. These injuries typically cause a pseudoparalysis (the infant does not move the extremity in order to avoid pain and discomfort; to the observer, it appears "paralyzed") or asymmetry in the use of the extremities. Treatment generally requires splinting of the involved extremity for a few weeks during rapid healing.

Epiphyseal fractures most commonly involve the proximal humerus and are associated with difficult deliveries. The diagnosis may be made clinically and may

be difficult to detect radiographically. A distal humerus epiphysis can also be from birth injury (Supakul et al. 2015).

Fractures of the distal extremities or ribs are extremely rare in association with birth trauma. A case series identified 13 cases of definitive birth-related posterior rib fractures (van Rijn et al. 2009). The majority of infants had large birth weights and difficult deliveries, over 50% with shoulder dystocia. In infants with an associated clavicular fracture, the rib fractures were ipsilateral. Van Rijn et al. (2009) reported in detail three definitive and one possible case of birth-related posterior rib fractures. In all four cases, the rib fractures were mid-posterior. The authors postulate that leverage over the pubic symphysis in the macrosomic infants applies forces similar to those seen with bimanual compression, without anterior displacement of the vertebrae (van Rijn et al. 2009). Fractures due to the birth process heal rapidly. By 2 weeks of age, they should all show radiographic signs of healing (Fadell et al. 2017; Walters et al. 2014). In most cases, birth trauma is easily distinguished from abuse, although the possibility that an injury was the result of birth trauma occasionally arises. Fractures that do not show the callus by 2 weeks of age are not consistent with birth trauma, and the injuries should be accounted for by another mechanism.

Caffey disease (infantile cortical hyperostosis) is a rare, benign condition that presents with a classic triad of fever, soft-tissue swelling, and irritability. The radiographic appearance is striking and notable for thickening or bony expansion, especially affecting the flat bones such as the mandible, clavicle, rib, scapula, skull, and ilium (Davis 2010). The underlying cause of Caffey disease remains unclear. It has characteristics of an inflammatory process that may be inherited, immunologic, or infectious in nature. It typically presents in early infancy, is self-limited, but it may have a protracted course over months. Owing to its dramatic presentation, it may be confused with child maltreatment (Davis 2010) (Photos 4.33 and 4.34).

Photo 4.33 A 1-week-old male with bony angulations noted at birth. Multiple lesions noted in the mandible, clavicles, humeri, and ribs. The child has Caffey disease or infantile cortical hyperostosis

Photo 4.34 The left upper extremity of the 1-week-old with Caffey disease demonstrates the periostitis and subsequent lamellar bone formation

Normal Variations Mistaken for Abuse

A number of normal variants of the developing skeleton may be mistaken for fractures and may sometimes suggest abuse. The most common of these variations is the subperiosteal new bone formation of the long bones seen commonly in young infants between 1 and 4 months of age (Kwon et al. 2002). The subperiosteal new bone formation is a normal physiologic pattern of rapid bone growth in infants who still undergo intramembranous ossification. The new bone formation is smooth, involves multiple bones, and is generally symmetric (although it can be unilateral). The infant is asymptomatic, in contrast to infants with congenital syphilis or other disorders. If the new bone formation occurs in older infants or appears thick, irregular, or extends to the end of the metaphysis, other etiologies, including trauma, should be explored (Glaser 1949; Kwon et al. 2002; Shopfner 1966).

Variations can also be seen in the newborn and infant skull in size, shape, and ossification. Suture variants and fissures can be mistaken for fractures. Common mimickers of trauma include the median occipital fissure, intraparietal (accessory) sutures, the interparietal bone, and accessory fontanelles in the sagittal suture (called the third fontanelle) (Quigley and Stafrace 2014). Wormian bones in the skull, which can be associated with osteogenesis imperfecta, are also present in children without any bone disease. One study of 605 CT scans of the brain found that 53% of children under 3 years of age had wormian bones and 10% had four or more wormian bones (Marti et al. 2013).

Congenital Syphilis

The osteochondritis, epiphysitis, and periostitis (inflammation of the periosteum) of congenital syphilis may mimic the metaphyseal fractures and periosteal new bone formation associated with child abuse (Fiser et al. 1972). Sixty to hundred percent

of pregnant women with primary or secondary syphilis will transmit the infection to the fetus, and the risk of transmission slowly lessens in the latent stages of mother's infection (Kimberlin et al. 2018). Bone involvement (most often involving the humerus or femur but may affect any bone of the skeletal system) is the most common sign of syphilis. The early findings in congenital syphilis are varied and unpredictable. There are limited studies available to follow the long-term effects. The presentation may be early (birth to 3 months) or late. Treatment with antibiotics for the mother (during the pregnancy) does not assure that infection will not occur in the fetus. Negative testing early in pregnancy does not rule out congenital syphilis in the infant.

Radiographic changes are often diagnostic and usually involve multiple symmetric bones. The lower extremities are involved more often than the upper extremities. Metaphyseal destruction and periosteal new bone formation are characteristic of the skeletal changes associated with syphilis. Epiphyseal changes are evident radiographically approximately 5 weeks after infection, whereas periosteal changes are first seen after 4–5 months of infection. Therefore, the radiographic manifestations of syphilis vary depending on the trimester in which the fetus was infected. Radiologic findings also include (1) Wegner's sign (serrated appearance of epiphyseal margin), (2) a zone of rarefaction at the metaphysis, (3) a moth-eaten appearance, (4) irregular periosteal thickening, (5) Wimberger's sign (demineralization and boney destruction in the upper medial tibial metaphysis), (6) saber shin (anterior bowing of tibia), (7) Higoumenakis' sign (periosteal reaction to the sternoclavicular portion of the clavicle), and (8) saddle nose deformity. Perforation of the hard palate has been suggested to be pathognomonic for congenital syphilis.

Clinical signs of skeletal involvement include pseudoparalysis of affected limbs (due to pain) and swelling and tenderness of the ends of involved bones. Affected infants may have other clinical manifestations of congenital syphilis, including hepatomegaly, splenomegaly, anemia, jaundice, rash, sniffles, and adenopathy. Often the first symptom is rhinitis. The rash is desquamative, diffuse, and maculopapular and is found on the palms, soles, mouth, and anus.

Diagnosis is based on serologic testing, which should be obtained in all high-risk infants.

Copper Deficiency and Scurvy

Copper deficiency is a rare cause of metabolic bone disease and pathologic fractures. Causes include both nutritional deficiencies in premature infants as well as diseases associated with intestinal copper transport. Radiologic features include severe osteopenia, symmetric cupping of the metaphyses, metaphyseal spurs, and subperiosteal new bone formation (Flaherty et al. 2014). The osteopenia develops after the fetal copper stores are utilized, which would be after 6 months in a term infant but sooner in a premature infant. Predisposing risk factors include prematurity, deficient nutrition, malnutrition, and malabsorption. Children with copper

deficiency will have associated laboratory changes including sideroblastic anemia resistant to iron, neutropenia, and low levels of copper and ceruloplasmin. Menke's syndrome (kinky hair syndrome) is notable for psychomotor retardation, hypotonia, seizures, failure to thrive, and hypopigmentation, with hair that is kinky, coarse, and lacking in pigment.

Scurvy, a deficiency of vitamin C (ascorbic acid) and ascorbic acid oxidase (copper dependent enzyme), has similar clinical and radiologic features to copper deficiency. It is also the consequence of malnutrition (not often seen before 6 months of age). Although this is a rare disease, it can be seen in infants and children with extremely restricted diets that are void of vitamin C, iron overload from multiple transfusions for sickle cell anemia or thalassemia, neurologic disorders, or chemotherapy from bone marrow transplants (Flaherty et al. 2014; Golriz et al. 2017). The "scurvy line" is a lucent band under the zone of provisional calcification (not usually present in copper deficiency). Features include pathologic fractures occurring through the metaphyses as well as subperiosteal and soft tissue hemorrhages. Diaphyseal fractures are not common (Kleinman 2015).

Both copper deficiency and scurvy have severe osteopenia, which can aid in the differentiation between these deficiencies and child abuse. Other clinical, laboratory, and radiologic features should be present if the copper deficiency is severe enough to cause fractures. Metabolic bone disease, such as copper deficiency, should affect the entire skeleton symmetrically.

Disuse Osteopenia

Any condition that severely impairs normal motor function to the point of inability to bear weight can cause a disuse osteopenia. One study that evaluated the bone mineral density in the femoral neck of children with spina bifida showed that wheelchair-bound children have lower bone mineral density compared to ambulatory children (Apkon et al. 2009). When disuse osteopenia is severe enough, it is possible that the bones may become fractured in the course of daily care. If the bones are affected to the degree that fracture risk increases, the bones should be clearly osteopenic on radiographs (Photo 4.35). Another study, which evaluated fractures in children with cerebral palsy, found that the risk of fracture increased only in the children with the least gross motor function, which was defined as children mostly or completely confined to a wheelchair or bed (Uddenfeldt Wort et al. 2013). The fracture risk was increased even more if the child did not use a standing device or if their growth was significantly stunted. The authors also noted multiple contributing factors in addition to disuse osteopenia including the following: use of antiepileptic drugs that negatively affect bone mineral density, potential malnutrition due to feeding difficulties, or frequent hospitalizations that result in even more immobilization than their usual daily routine (Uddenfeldt Wort et al. 2013).

Photo 4.35 This 2-year-old male presented with leg swelling and fussiness. He had a history of spastic quadriplegia after being struck by a car. His radiographs demonstrate disuse osteopenia with thin cortices. He has a distal transverse femur fracture with swelling noted after physical therapy

Osteopenia of Prematurity

It is estimated that 50% of infants less than 1000 g will develop osteopenia of prematurity (Moyer-Mileur et al. 1995) with fracture rates ranging from as low as 1.2% (Amir et al. 1988) to 27% (Dabezies and Warren 1997). There is tremendous variability between studies depending on the gestational age of the infant, weight, and other risk factors. In addition, many of the studies with the highest rates of fracture were performed in the 1980s to early 1990s. There is now significant improvement in nutritional management, immobilization, and ventilator times (Rauch and Schoenau 2002).

Decreased bone mineralization can occur as the result of insufficient matrix being deposited or as the result of insufficient mineral being incorporated into the matrix. Osteomalacia results from an accumulation of unmineralized bone matrix and can be seen clinically as "rickets." Osteopenia (scarcity of bone) is the result of decreased amounts of matrix or bone tissue whether through insufficient deposition or increased resorption. During the last trimester, 80% of calcium and phosphorous deposition occurs in fetal bone as well as two-thirds of the fetal weight gain. The full-term infant will develop "physiological osteoporosis of infancy" in the first few months of life as the marrow cavity size in the long bone increases faster than the cross-sectional area of the bone cortex. There is no bone fragility associated with "physiological osteoporosis of infancy" in the full-term infant. This also occurs in the premature infant albeit earlier than the term infant (Rauch and Schoenau 2002).

The preterm infant (<32 weeks gestation) has a bone mineral content (BMC) that is 40–50% less than the full-term infant at 40 weeks gestation (Congdon et al. 1990; Horsman et al. 1989a). In multiple prospective studies of premature infant bone accretion, there is rapid mineral deposition occurring between 40 and 60 weeks postconception (Congdon et al. 1990; Horsman et al. 1989b; McDevitt et al. 2007). Mineral accretion rates are often 5–10 times higher in preterm infants (Congdon et al. 1990) than in full-term infants, suggesting the presence of a "biostat" (McDevitt et al. 2007). The deficit noted at birth between preterm and full-term infants is largely resolved by 50 weeks postconception in preterm infants (Horsman et al. 1989c). Preterm infants increase their BMC by 30–60% of the mean value seen in full-term infants whereas full-term infants increase their BMC by only 11–45% (Horsman et al. 1989c).

Risk factors for mineralization issues in premature infants include prematurity <28 weeks gestational age, cholestatic jaundice, total parenteral nutrition (TPN) for greater than 3 weeks, bronchopulmonary dysplasia with prolonged use of steroids, and prolonged diuretic therapy (greater than 2 weeks) (Amir et al. 1988; Carroll et al. 2007). Premature infants who are ELBW (<1000 g) appear to be at greatest risk for osteopenia of prematurity at 6–12 weeks of age. Osteopenia of prematurity should be suspected when there is elevation in alkaline phosphatase and low phosphorous levels (Rauch and Schoenau 2002). Close attention to calcium and phosphorous content in TPN, as well as the use of supplemented breast milk and premature formulas, has decreased the incidence of bone disorders in premature infants. In a large study of fractures in 973 premature infants, only 1.2% of infants surviving more than 6 months had fractures (Amir et al. 1988).

Rickets

The radiographic appearance of rickets is identical regardless of its etiology and reflects the undermineralization of growing bones. There are multiple causes of rickets, including vitamin D deficiency, renal and hepatic disease, medications (antacids, anticonvulsants, furosemide), and other rare diseases. Children at risk for rickets include small, ill, premature infants (related to nutritional compromise, high growth rates, medication use); breastfed infants who do not receive vitamin D supplementation and have limited UV-B light exposure; children using sunscreen or in the practice of covering most of the skin with clothing; children and adolescents with restrictive diets or poor nutritional habits; and children with kidney or liver disease (Wharton and Bishop 2003).

Radiographic findings include fraying of the costochondral junctions and metaphyses, widening of the distance from the epiphysis to the mineralized portion of the metaphysis, flaring of the metaphyses, and cortical thinning (Photo 4.36). The changes that occur in the metaphyses and ribs are not usually confused with abuse (Perez-Rossello et al. 2015). These changes can develop rapidly, in contrast to

Photo 4.36 A 3.5-year-old female with renal rickets. Note the bowing of the long bones as well as the flaring and ragged metaphyses

osteomalacia. During healing, bony changes may mimic abuse because dense mineralization occurs adjacent to radiolucent bone, which may resemble metaphyseal fractures. Periosteal new bone formation may mimic trauma. The most common long bone sites are the proximal tibia and fibula and the distal end of the radius and ulna. Changes in the phalanges include subperiosteal erosions. In a retrospective study evaluating fractures in infants and toddlers with rickets, the vast majority of fractures were in mobile children with overt radiologic rickets (Chapman et al. 2010). The fractures that were found were from load-bearing failure, not easily mistaken for abuse (Chapman et al. 2010). Classic metaphyseal fractures and posterior-medial rib fractures were not found (Chapman et al. 2010).

The diagnosis of rickets is dependent on clinical suspicion, radiographic findings, and laboratory screening for rickets (Servaes et al. 2016). Clinically, affected children may appear apathetic and irritable and prefer to sit rather than stand and walk. The epiphyseal ends of long bones may be tender and swollen (big wrists). Other clinical findings include delayed eruption of teeth, enamel hypoplasia, rachitic rosary, frontal bossing, craniotabes, and genu varum (bowed legs) (Wharton and Bishop 2003). Laboratory findings in rickets include hypophosphatemia, elevated alkaline phosphatase, and elevated parathyroid hormone (PTH). Calcium levels are often variable (normal to low). The diagnosis of rickets requires a detailed evaluation of clinical, laboratory, and radiologic findings (Misra et al. 2008). Low levels of 25-hydroxy vitamin D can confirm the diagnosis, but are not diagnostic in isolation (Perez-Rossello et al. 2012; Schilling et al. 2011; Servaes et al. 2016).

There is a lack of agreement in the literature surrounding the definition of normal levels for 25-hydroxy vitamin D. Most experts agree that levels of 25-hydroxy vitamin D less than 20 ng/ml are deficient, with less than 8 ng/ml indicative of severe deficiency. Levels between 21 and 30 ng/ml are considered insufficient (Gordon et al. 2008; Holick 2009). A prospective study found that in children less than 2 years old vitamin D insufficiency (20–30 ng/ml) was not associated with the diagnosis of child abuse, multiple fractures, rib fractures, or classic metaphyseal lesions (Schilling et al. 2011). Vitamin D insufficiency was not more common in those with unexplained vs accidental fractures (Schilling et al. 2011). A vitamin D level in the insufficient range does not have a clinical correlation with bone health (Servaes et al. 2016).

There is increasing evidence that vitamin D deficiency is common among infants and toddlers (Holick 2007). In a prospective study of children ages 8–24 months, 40% had insufficient levels of vitamin D with 12% deficient (<20 ng/ml) and approximately 2% severely deficient (<8 ng/ml). Of those children found deficient in vitamin D, one-third appeared demineralized on plain radiograph and a few children (3 of 40) demonstrated rachitic changes (Gordon et al. 2008). In another prospective study, demineralization and rachitic changes were also found to be rare in 40 children 8–24 months with vitamin D deficiency (<20 ng/ml) who were otherwise healthy. Within this group, no fractures were discovered (Perez-Rossello et al. 2012). Vitamin D deficiency has certainly been associated with breastfeeding without vitamin supplementation and with inadequate milk consumption.

There are other metabolic causes of osteopenia, osteomalacia, and rickets. Metabolic bone disease should affect the entire skeleton symmetrically. Low levels of 25-hydroxy vitamin D are not diagnostic of metabolic bone disease in isolation and are a common finding in the population. A detailed evaluation including careful history taking, physical examination, and laboratory and radiologic testing should exclude these conditions. Treatment of rickets is guided by the primary cause.

Osteogenesis Imperfecta

Osteogenesis imperfecta (OI), also referred to as brittle bone disease, is a rare (6–7/100,000) (Van Dijk et al. 2013), inherited disorder of connective tissue that results from an abnormal quantity or quality of type I collagen. The clinical result is osteoporosis with increased bone fragility and decreased bone density. There are different variable expressions of the disease. Currently there are 13 types of OI. Types I–V are based on clinical phenotype and radiologic features, and type VI–XIII are phenotypically like type II, III, or IV but with different genetic mutations (Van Dijk et al. 2013). Over half the OI cases are types I and IV (Van Dijk et al. 2013). OI type V is very rare with only 47 cases reported to date (Forin 2010).

Most forms of this disease are easily distinguished from child abuse, but only the rare case may pose difficulties. In infants with OI, one study found that rib fractures and multiple fractures were not found in the time between the neonatal period and

becoming an active toddler (Greeley et al. 2013). They did note that rib fractures were found to result from both the birth process and being an active, mobile child (Greeley et al. 2013).

The following sections describe the major features of each type of OI. Table 4.5 shows common characteristics of the five main OI phenotypes. An important piece of the diagnosis of OI is the emphasis on connective tissue defects including the dental, skin, bone, and sclera. Due to the range of severity expressed, patients may not always fall clearly into one category (Glorieux 2008).

Type I

The most common (and mildest form) of OI is type I, which accounts for 80% of all cases and has autosomal dominant inheritance. No recessive cases have been reported of the OI type I phenotype (Van Dijk et al. 2013). Although type I is a

Table 4.5 Common characteristics of osteogenesis imperfecta phenotypes

Phenotype	Major characteristics	Comments	Confused with abuse	Genetic defect
Type I	80% of all cases Bone fragility mild to moderately severe Fractures occasionally at birth Fractures common during preschool years Radiographic osteopenia Blue sclera Hearing impairment or family history of hearing impairment Wormian bones Easy bruising Normal stature Dentinogenesis imperfecta	Most common form No known recessive inheritance	Sometimes	*COL1A1*
Type II	Death by 1 month of age Severe skeletal deformities Blue sclerae Intrauterine growth retardation Multiple fractures at birth	Perinatal lethal form	Never	*COL1A1* *COL1A2*
Type III	Severe bone fragility Severe osteopenia Fractures at birth (2/3 cases) Extremely short stature Skeletal deformities Sclerae: normal but may be mild blue at birth Triangular facies (85% cases) Dentinogenesis imperfecta (50%) Ligamentous laxity (50%) Easy bruising (25%) Occasional hearing impairment	Most severe nonlethal form	Unlikely	*COL1A1* *COL1A2*

(continued)

Table 4.5 (continued)

Phenotype	Major characteristics	Comments	Confused with abuse	Genetic defect
Type IV	Bone fragility mild to moderate Birth fractures (>1/3 cases) Radiographic osteopenia Wormian bones Triangular facies may be present Short stature may be present Normal sclerae Dentinogenesis imperfecta may be present Hearing impairment uncommon Easy bruising uncommon	Rare	Sometimes	*COL1A1* *COL1A2*
Type V	Bone fragility moderate to severe May have fractures at birth Hyperplastic callus formation Calcification of interosseous membrane in forearm Normal sclerae No dentinogenesis imperfecta May have short stature May have scoliosis May have wormian bones	Rare	Unlikely	*IFITM5*

relatively mild form of OI, the bone fragility varies from mild to moderately severe. Fractures are occasionally present at birth but characteristically begin during preschool years (Sillence 1988). Children often have blue sclerae. Common findings include hearing impairment or a family history of hearing loss and easy bruising due to abnormal collagen in blood vessels. Associated findings such as joint hypermobility and dentinogenesis imperfecta may occur. Stature is usually not significantly impacted (Ablin et al. 1990; Kleinman 2015). Dentinogenesis imperfecta and eventual bowing of long bones are generally not helpful in distinguishing OI type I from abuse, as infants would not yet have these findings (Kleinman 2015).

Type II

Type II is the perinatal lethal form of the disease and is not confused with child abuse. Affected neonates all have severe skeletal deformities, blue sclerae, intrauterine growth retardation, short bowed legs and arms, and multiple fractures at birth. Affected children generally die in early infancy, although there are reports of infants surviving to 1 year of life.

Type III

Type III is the most severe form surviving beyond infancy and is also called "progressive deforming type." Mode of inheritance is usually autosomal dominant, by spontaneous mutation, or rarely autosomal recessive (Ablin et al. 1990). Bone fragility and osteopenia are more severe than in types I and IV, and fractures at birth are present in two-thirds of affected patients (Sillence et al. 1986). Growth deficiency (height achieved is that of a prepubertal child) and skeletal deformities such as scoliosis and bowed limbs are common, often resulting in patients requiring wheelchair use. Sclerae are typically normal but may be mildly blue or gray at birth. Eighty-five percent of patients eventually manifest triangular facies because of soft craniofacial bones and temporal bossing (Sillence 1988). This is usually not apparent in early childhood. Dentinogenesis imperfecta and ligamentous laxity occur in about half of the patients and easy bruising in 25%. Hearing impairment is found only occasionally (Photo 4.37).

Type IV

Type IV is a rare form of OI with autosomal dominant inheritance. This is the most variable form of OI from moderately severe to a mild form of OI (with the first clinical signs occurring at birth or later in school years). Type IV may be the most difficult to distinguish from abuse (Ablin et al. 1990). Bone fragility varies from mild to moderate, and fractures at birth are present in less than one-third of patients. The bones may be normal in radiologic appearance at the time of the first fracture. The

Photo 4.37 Left upper extremity of an infant with osteogenesis imperfecta type III
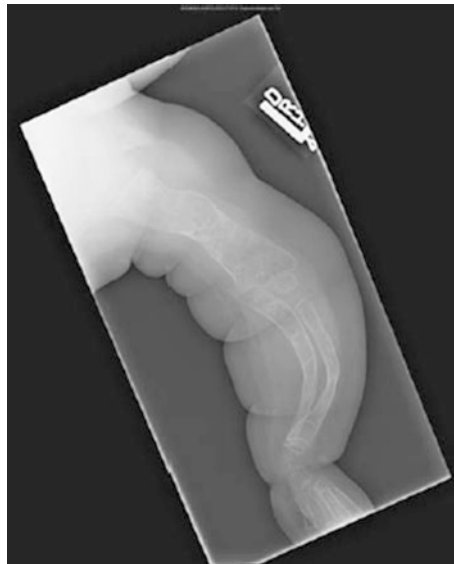
sclerae are typically normal. Hearing impairment and easy bruising are uncommon. Dentinogenesis imperfecta may be present.

Type V

Type V is similar to type IV due to its variable severity in bone fragility. In fact, type V was originally classified as type IV with negative *COL1* testing until 2000, when it was reclassified as a distinct type of OI (Marini and Blissett 2013). Features unique to type V are hyperplastic callus formation (beginning in later infancy), calcification of the interosseous membrane in the forearm (also beginning in later infancy), and unique histology. Dentinogenesis imperfecta and blue sclerae are not usually present. Type V is very rare.

Distinguishing Osteogenesis Imperfecta from Child Abuse

A number of clinical findings help identify children with OI. Blue sclerae, hearing impairment, dental abnormalities, hypermobility of joints, easy bruising, short stature, wormian skull bones, osteopenia, bowing tendency, angulation of healed fractures, and progressive scoliosis all suggest OI.

The fractures seen in OI are generally diaphyseal, although metaphyseal fractures resembling those seen in abuse are described (Astley 1979). Radiographic changes of generalized osteopenia, bowing, and remodeling deformities can be seen. Vertebral compression fractures may also be identified.

A few children with type IV OI have a normal physical examination, no obvious radiographic evidence of OI, and a negative family history. These children are at risk for an incorrect diagnosis of abuse. Children with OI usually have a history of minor trauma that accounts for the location but not the severity of the injury. Recurrent fractures often occur in different environments, helping to distinguish OI from abuse (Gahagan and Rimsza 1991).

Laboratory testing for bone studies are generally normal, except following a fracture when the alkaline phosphatase may be elevated. Teeth may look normal on gross examination but may show defects on radiograph (Glorieux 2008).

Most cases of OI can be diagnosed clinically; however, genetic testing is useful for prognostic value and for knowledge regarding risk of transmission to potential children (Van Dijk et al. 2013). Ninety percent of OI cases are caused by a mutation in *COL1A1* or *COL1A2* (Van Dijk et al. 2013). For those more recently discovered recessive forms of OI (types VI–XIII), genetic mutations are not found in *COL1* but in genes that produce proteins that act upon type I collagen (Marini and Blissett 2013). Many of these mutations are transmitted in an autosomal dominant pattern; however, many of the more recently discovered genetic mutations that can cause OI are autosomal recessive (Marini and Blissett 2013; Van Dijk et al. 2013). Many cases result from spontaneous mutation, so a negative family history of OI does not

rule out an autosomal dominant form of OI. Various genetic testing panels are available; however, it is reasonable to start by testing *COL1A1* and *COL1A2*.

Culture of skin fibroblasts from a skin biopsy used to be the mainstay of laboratory diagnosis of OI, prior to the widespread availability of genetic testing. However, this modality will also not catch every case of OI. Furthermore, when it does confirm the diagnosis of OI, it does not determine the genetic mutation, lacking prognostic information. If there is any question about the correct diagnosis, the child should be placed in a protective environment while awaiting test results. Finally, it is important to note that osteogenesis imperfecta and child abuse can coexist.

It is also important to note that outside of OI, there are other genetic conditions that can cause bone fragility. These disorders can be classified by the following features: decreased bone density, increased bone density, and slender bones (Bronicki et al. 2015). As these categories imply, there are clinical features that would point to an underlying disorder in these cases, as well as radiographic findings. The vast majority of these conditions cause distinctive craniofacial features that lead to clinical suspicion of the underlying disorder (Bronicki et al. 2015).

In Brief

- Fractures are a common manifestation of abuse, particularly in infants and young children.
- Diaphyseal fractures are the most common type of fracture associated with abuse, but are not specific for inflicted injury.
- The history of injury, development abilities of the child, morphologic type of fracture, and biomechanics are considered in determining the likelihood of abuse in children with diaphyseal fractures.
- Rib fractures and metaphyseal fractures are highly specific for child abuse.
- A skeletal survey should be done in all children less than 2 years of age who have injuries suspicious for abuse.
- The yield from the skeletal survey decreases with increasing age of the child and is not a useful test in children older than 5 years.
- Standards for performing skeletal surveys exist and should be followed (ACR Appropriateness Criteria: Suspected Physical Abuse-Child 2017).
- Radionuclide bone scan may identify infants and young children with subtle injuries that are not detected by skeletal survey.
- Bone scans are excellent in detecting rib injury, but are not useful in identifying skull fractures and do not consistently identify metaphyseal fractures.
- Skeletal surveys should be repeated in 2 weeks in all children under 2 years old undergoing workup for suspected physical abuse.
- A number of disease states predispose to fractures. Careful evaluation usually distinguishes children with pathologic fractures from those who are abused.
- Trauma is the leading cause of bony injury to otherwise healthy bones.
- A medical disease and child abuse can coexist and are not mutually exclusive.

Additional Recommended Reading

ACR appropriateness criteria: Suspected physical abuse-child. (2017). *Journal of the American College of Radiology, 14*(5S), S338–S349. doi:https://doi.org/10.1016/j.jacr.2017.01.036.

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