The Extremities

5

5.1 Introduction

In his original publication from 1962 on 'The battered child syndrome', Kempe calls the child's arms and legs the handles used to inflict trauma [1]. This may lead to fractures, in particular of the long bones. However, in mobile children fractures of arms and legs are also frequently caused by accidents. Depending on the force of the impact, specific fractures will occur in specific parts of the long bones. Sometimes their location is an indicator for child abuse. In other cases, the anamnesis and the level of development of the child will make it possible to differentiate between accidental and non-accidental injuries.

5.2 Anatomy and Physiology

The bones of the human skeleton can be categorised according to their shape:

- Long and short long bones
  - Long: Femur, tibia, humerus, radius and ulna
  - Short: Phalanges of hands and feet, such as the metacarpals and metatarsals
- Short and irregular bones, such as the carpals and tarsals

Irrespective of their anatomical location, the long as well as the short long bones are all constructed in the same manner (Figs. 5.1 and 5.2a–c), i.e.:

- Diaphysis: the medulla-containing middle part (the shaft) of a long bone.
- Epiphysis: the end part of a long bone.
- Metaphysis: the area of the long bone between the diaphysis and the epiphysis. This part contains the growth plate.

Longitudinal growth of the long bones takes place in the growth plate, whereas growth in width originates in the periosteum. The epiphyses determine the size and form of the joint ends.

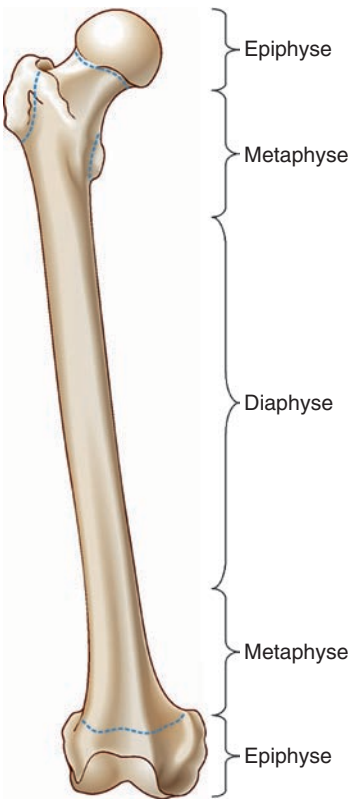

Fig. 5.1 Schematic representation of the anatomy of the long bones

R. A. C. Bilo et al., *Forensic Aspects of Pediatric Fractures,*
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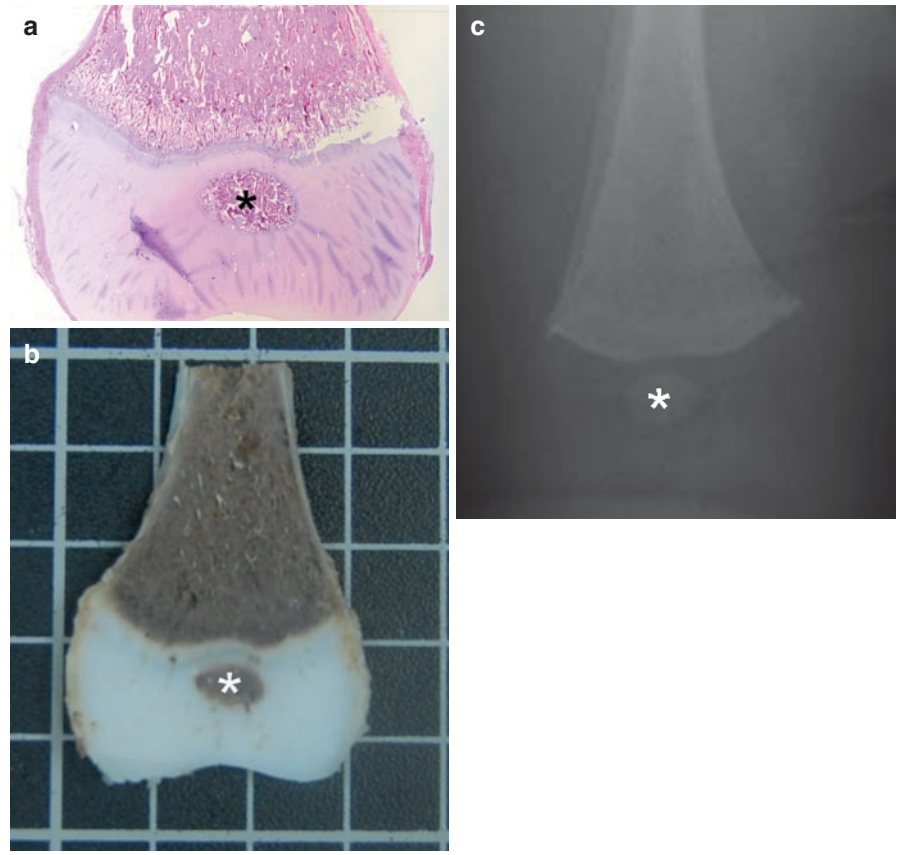


Fig. 5.2 (**a**) Histological section of the distal femur of a 3-month-old neonate, which shows ossification of the distal epiphysis of the femur (asterisk). (**b**) Corresponding specimen photo of the distal femur, showing ossification of the epiphysis of the distal femur. (**c**) Corresponding radiograph of the distal femur, showing ossification of the epiphysis of the distal femur

5.3 Shaft Fractures

5.3.1 General Aspects of Shaft Fractures

Many authors maintain that a spiral fracture of the shaft of one of the long bones, in particular of the femur, is proof for physical violence; however, this is incorrect. The only conclusion one can make with any certainty when confronted with such a fracture is that this fracture is based on torque, a rotating motion along the long axis of the bone. Torque is often seen in accidents, for example, slipping while running [2–4]. The fracture may also occur in a fall in which knee and hip remain stationary and the patient rotates in relation to the stationary joints. This happens regularly, not just in the femur, but also in the tibia. Consequently, such a fracture can only be evaluated when the context of its origin is also taken into consideration. However, when such a fracture is encountered in a child that does not yet walk, child abuse is very likely.

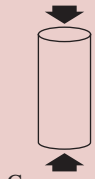
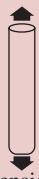
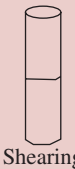
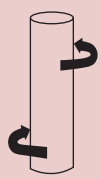
5.3.2 Biomechanical Aspects

In the analysis of what bone is exposed to in either daily life or under the impact of force, a number of aspects should be considered, such as [5]:

- The force or combination of forces exerted on the bone in day-to-day use and when under the impact of force: the load bearing of the bone (‘load’).
- The force of the bone to resist this load: tension (‘stress’).
- The changes in shape or size of tissue in reaction to this stress: stretch (‘strain’). In strain, three pure forms can be distinguished: compression, tension and shearing. Furthermore, various combinations may be seen, such as bowing and torque.

When a fracture is sustained, the three pure forms (load, stress, strain) seldom occur just by themselves, but nearly always a combination of the three is seen (Table 5.1).

Table 5.1 Biomechanical aspects of shaft fractures (a.o. 6)

Force/combination of forces	Fracture type	
 Compression	 Compression	• Oblique fracture
	 Compression and bowing	• Transverse fracture, possibly with loose fragments on the compression side • Greenstick fracture • Torus fracture • 'Bowing' fracture
 Tension	Tension  Shearing	• Transverse fracture, possibly with zigzag pattern
 Shearing		• Metaphyseal corner fracture
 Bowing	 Bowing	• Transverse fracture, possibly with loose fragments on the compression side • Greenstick fracture • Torus fracture • 'Bowing' fracture
	 Compression and bowing	
 Torsion	 Torsion	• Spiral fracture

5.3.2.1 Pressure – Compression

Compression is defined as a perpendicular force that affects a surface in such a manner that it compresses the object. Bone has great resistance to this kind of force. When a fracture is caused by compression, it is usually because the compression is not quite along the central axis of the bone [6]. In such cases, compression will cause the bone to bow, which results in tension on one side, which ultimately determines the nature of the fracture.

5.3.2.2 Stress – Tension

Tension is defined as a perpendicular force that affects a surface in such a manner that it pulls an object apart. Bone is less resistant to tension than to compression. In tension the bone is stretched out like a spring: it becomes longer and thinner.

Tension exerted on a bone for a limited period of time does not necessarily lead to a fracture. In normal cases it will fully recover; however, as soon as the limit of the elasticity of the bone is exceeded, damage is inflicted. This damage is not necessarily visible on radiographs. Only in cases with prolonged or stronger tension, a fracture will become visible. The fracture line will follow the contours of the weakest areas of the bone, which sometimes causes the fracture to have a zigzag line.

5.3.2.3 Shearing

With regard to force, shearing is physically equal to compression and tension, but the force is exerted in such a manner that the tissue is distorted and deformed. Bone is not very resistant to shearing.

5.3.2.4 Bowing

Bowing is caused by a force that causes tension on one side (the convex side) and compression on the opposite side (the concave side). In bowing, the cortex on the tension side will usually be damaged first. When this happens, and the loading stops, it will result in a so-called 'greenstick fracture' (Fig. 5.3). When the loading does not stop, the fracture will spread. The most classical expression of this type of loading is the transverse fracture. Depending on the type of bone and the additional forces exerted, other types of fractures may occur.

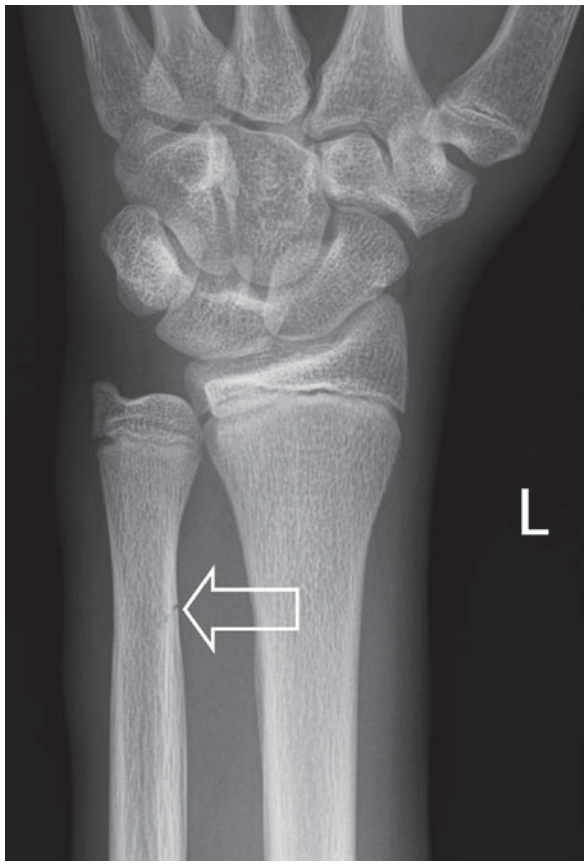


Fig. 5.3 Sixteen-year-old boy who had a painful wrist after romping around with his brother. The lateral side of the distal ulna shows a greenstick fracture (*open arrow*)

In immature bone, the bone may also yield on the compression side first, which may lead to a buckle fracture (torus fracture) of the compression side (Fig. 5.4).

5.3.2.5 Torque

Torque is the result of forces rotating an object along the longitudinal axis, when the other side is stationary or turned in the opposite direction. When the torque forces are directed to the left, it will cause a spiral fracture that turns to the right, and the other way around.

5.4 Injuries to Metaphysis and Epiphysis

The anatomy and biomechanics of the joints near the growth plates will determine the differences between the types of fracture in growing children and adults.

Fig. 5.4 Three-year-old boy with a torus fracture of metatarsal I of the right foot after taking a jump (*open arrow*)

Growth plates are the weakest areas in the growing skeleton. In trauma, they do not have the same resistance to injury as do tendons and ligaments.

5.4.1 Salter-Harris Classification

Trauma during childhood may result in typical fractures around the growth plates, the so-called Salter-Harris fractures (Table 5.2). These fractures often result from accidental trauma in childhood (they are seen in 30% of all trauma-related fractures) and in mobile children are primarily not suspect for child abuse [7]. The Salter-Harris type II fractures are the most prevalent (Fig. 5.5 and Table 5.2) [8].

5.4.2 The Metaphyseal Corner Fracture

The classical metaphyseal corner fracture (classical metaphyseal lesion – CML) is, besides rib fractures, the most specific fracture seen in child abuse. Caffey was the first to describe this lesion [9]. Kleinman introduced the term 'classical metaphyseal lesion' [10]. When no plausible reason is offered, this type of fracture is seen by many as highly specific for inflicted injury [9, 11].

CMLs can be found in 39–50% of children under the age of 18 months of whom a skeletal survey was made because of suspected child abuse. They are almost exclusively seen in children of less than 2 years of age, bilateral as well as unilateral. The lesion may also be seen in just one bone or around one joint. Hereby should be mentioned that in a CML of the proximal tibial metaphysis there is often an associated avulsion fracture of the femur (distal metaphysis). CMLs are most frequently found in the distal femur, the proximal and distal tibia (Fig. 5.6a) and the proximal humerus (Fig. 5.6b), the tibial metaphysis being the most prevalent location for avulsion fractures in young abused children [12]. However, lesions to the elbow and wrist have also been reported (Fig. 5.6c) [10, 13–18]. The long-term consequences of CMLs appear to be minimal or even absent [19].

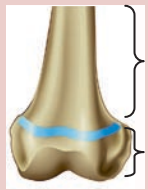
Hymel and Spivak maintain that the violent shaking of a child may lead to simultaneous avulsion fractures of the distal femur and the proximal and distal tibia accompanied by fractures of the posterior ribs and inflicted skull/brain injuries ('abusive head trauma', Fig. 5.7a–g) [18].

5.4.2.1 Radiological Aspects

A CML is composed of a series of micro-fractures right through the metaphysis. The lesion runs parallel to the growth plate, but does not necessarily extent over the full circumference of the bone [10]. When the micro-fractures are present over the full circumference of the bone, the radiographs will show a growth plate that is disconnected from the shaft, with a broad and flat centre and a wider edge (a so-called 'bucket-handle fracture', Fig. 5.8a).

Sometimes the radiographs only show the wider edge (a so-called 'corner fracture'; Fig. 5.8b). This

Table 5.2 Classification of meta-epiphyseal fractures according to Salter-Harris

Type		
		Metaphysis Growth plate Epiphysis
I		In type I the fracture line 'follows' the growth plate, separating epiphysis and metaphysis. The growth plate is still attached to the epiphysis. Usually there is no damage to the growth plate. Type I is seen in particular in young children The mechanism involved is shearing (see Sect. 5.3.2). Dislocation is only seen when the periosteum has been damaged. The healing process is quick (usually within 2–3 weeks) An uncommon type I is a fracture of the proximal femur called slipped capital femoral epiphysis (SCFE)
II		Type II is the most common, generally in children >10 years old. The fracture runs through the metaphysis and the growth plate As seen in type I, the mechanism involved is a shearing force or avulsion due to an angular force. This type of fracture usually heals quickly
III		Type III is rarely seen, and then mostly to the lower legs. The fracture runs through the epiphysis and the growth plate. Although the growth zone has been damaged, hardly any growth disturbance is seen after a type III fracture
IV		In type IV the fracture runs across the epiphysis, growth plate and metaphysis. In the long run this fracture may lead to deformation of the joint as a result of the bony bridging of the growth plate which may impede local growth
V		Type V is a compression fracture of the growth plate due to axial loading. This type is commonly seen in the knee and ankle

type of fracture usually shows no periosteal reaction. Callus formation is limited or lacking. The lesions ('corner fracture' and 'bucket-handle fracture') are different radiographic projections of the same lesion.

5.4.2.2 Biomechanical Aspects

The direction of the lesion is perpendicular to the axis of the bone. This shows clearly that a shearing force has been exerted on the end of the bone. The calcium-

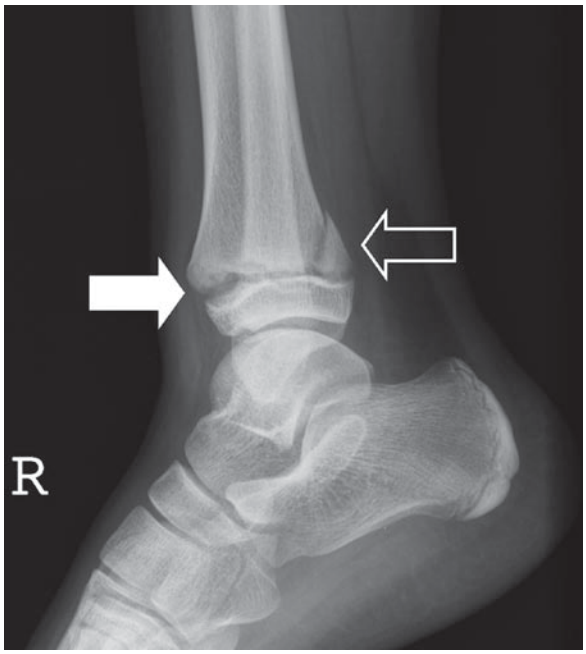


Fig. 5.5 Twelve-year-old girl (with unknown trauma) with a Salter-Harris type II fracture of the distal tibia (*open arrow*). The fracture through the growth plate can be identified by the anterior diastasis (*arrow*)

containing areas of the metaphysis tear away from the adjacent cartilaginous part of the growth plate. This type of force is the result of horizontal movement right through the metaphysis, which is not present in a fall or blunt trauma [20, 21]. However, such movement does occur when shaking a child while holding on to the hands or feet, or shaking a child who is held around the chest while the extremities hang down freely and move from back to front with great speed [10]. Consequently, this is seen mainly in children under 2 years of age: they are small enough to be shaken violently and unable to control or compensate for the resulting movements [21, 22].

5.4.2.3 Metaphyseal Corner Fracture: Differential Diagnosis

CMLs have been described in the treatment of clubfeet in children [23]. In this publication of Grayev et al., 7 children were considered not to be victims of child

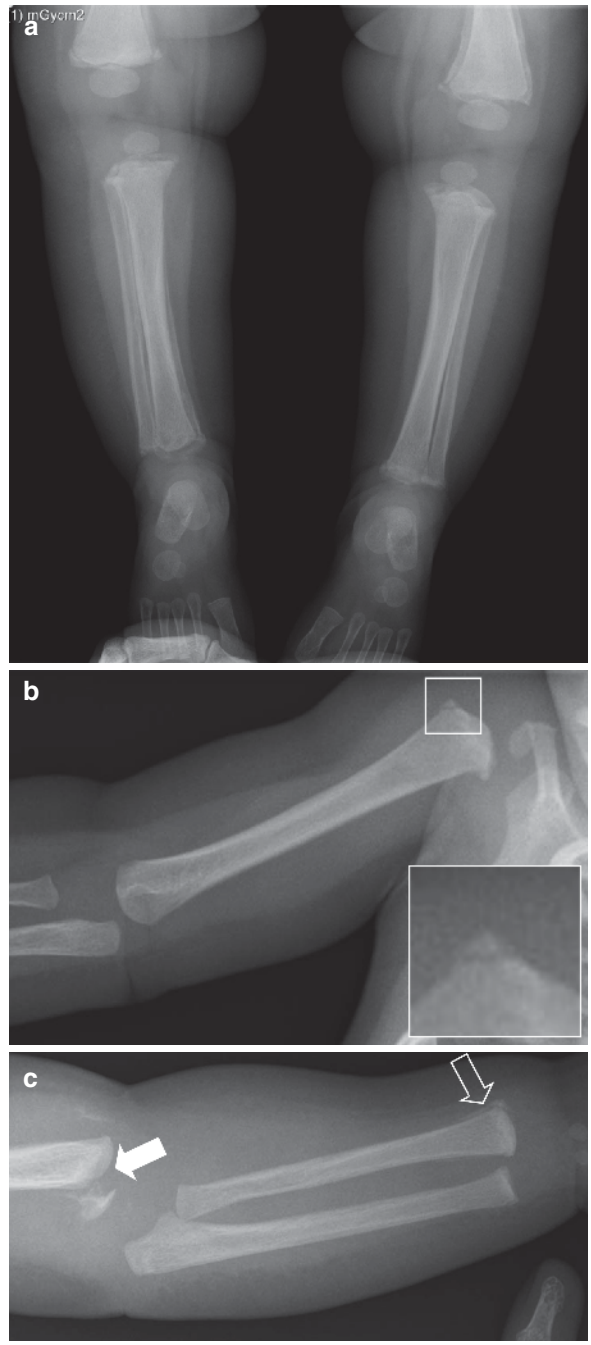


Fig. 5.6 (**a**) Severely abused 4-month-old girl. The skeletal survey shows healing metaphyseal corner fractures of the distal femurs and the proximal and distal tibias. Reactive sub-periosteal new-bone formation is visible along the greater part of the right tibia shaft. (**b**) Metaphyseal corner fracture of the right proximal humerus (see inset). (**c**) Metaphyseal corner fracture of the left distal radius (*open arrow*) and a distal metaphyseal humerus fracture (*arrow*)

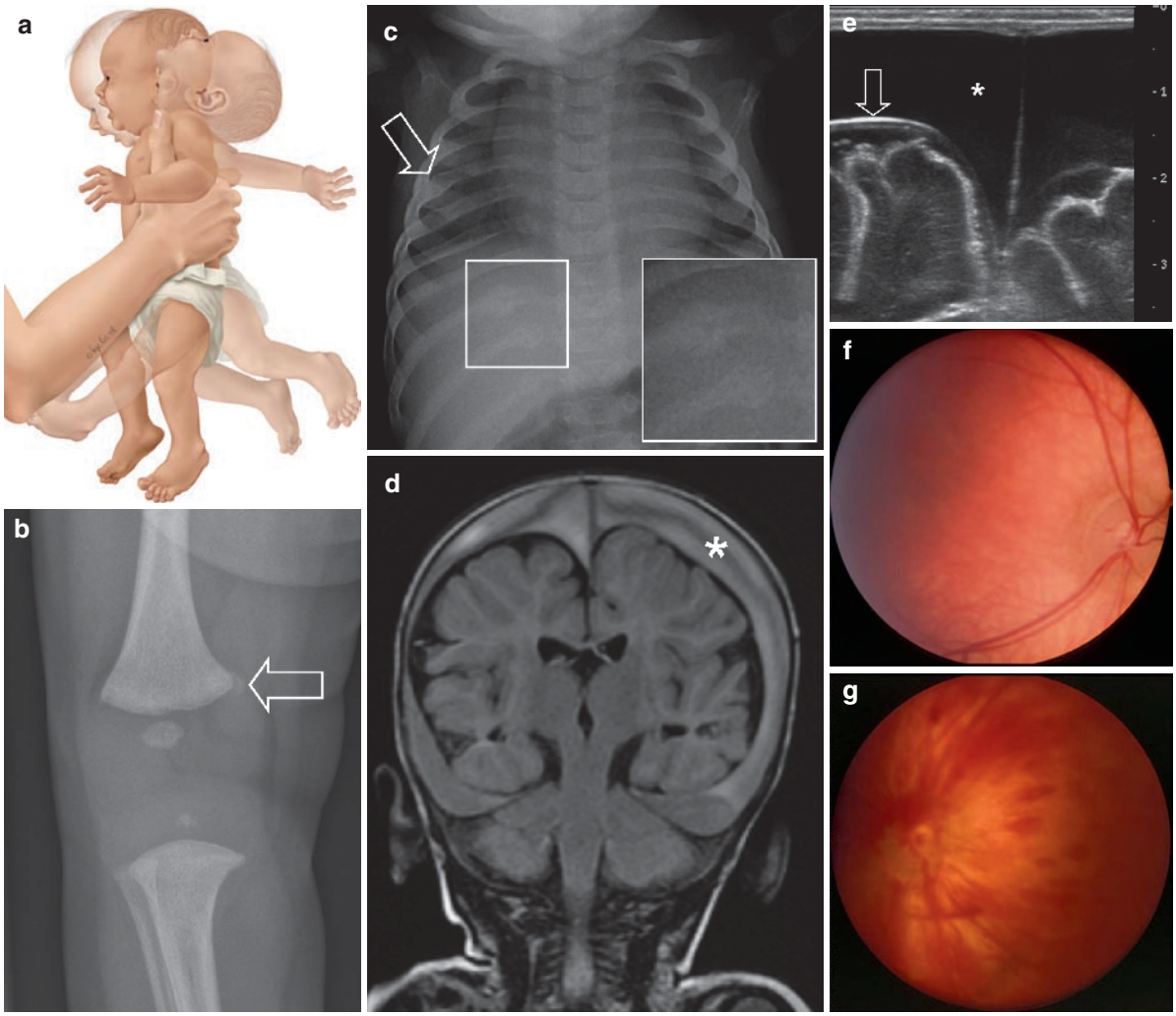


Fig. 5.7 (**a**) Graphic representation of a shaking incident. (**b**) Two-month-old boy with inflicted traumatic brain injury. The radiograph of the skeletal survey shows a metaphyseal corner fracture of the right distal femur (*open arrow*). (**c**) Four-month-old girl with inflicted traumatic brain injury. The skeletal survey shows a healing posterior fracture of the 9th right rib (see inset) Furthermore, there is an already healed rib fracture visible of the 5th right rib (*open arrow*). (**d**) MRI (T2 FLAIR) of this girl (**c**) shows a bilateral subdural haematoma (asterisk). (**e**) Cranial ultrasonography of this girl (**c**) shows the bilateral subdural haematoma (asterisk). Displacement of the arachnoid membrane (*open arrow*) is distinctly visible. (**f**) Normal view of the retina of a normal right eye at fundoscopy. (**g**) Diffuse retinal bleed in a left eye at fundoscopy resulting from inflicted skull/brain injury

abuse. One child was abused, in this case the skeletal survey also showed 24 rib fractures.

CMLs have also been reported after delivery (Fig. 5.9a and b). Lysack and Soboleski report a CML of the proximal tibia and distal femur in a healthy neonate; in this case, due to a breech presentation, it had been decided to turn the foetus externally. This did not turn out successfully and resulted in an emergency Caesarean section [24]. In a retrospective analysis over a period of 22 years, O' Connell and Donohue mention three cases of CML of the distal femur after Caesarean section [25].

Buonuomo et al. describe a neonate with multiple fractures, among which a metaphyseal fracture of the femur, ultimately resulting in the diagnosis infantile myofibromatosis [26].

Lesions similar to CML can also be found in diseases such as rickets, osteomyelitis, spondylometaphyseal dysplasia 'corner fracture type' and Jeune's disease (see Chap. 7).

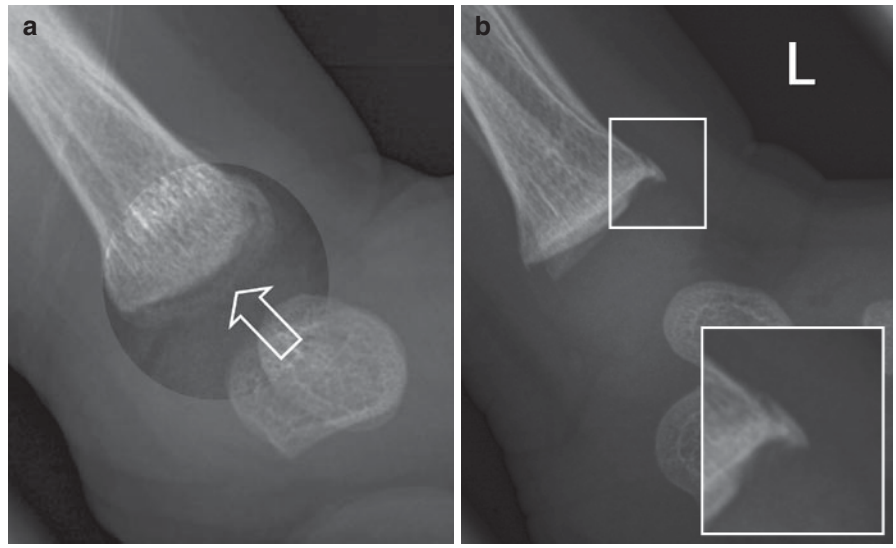


Fig. 5.8 (**a**) Two-month-old girl who died when 'co-sleeping'. Radiological examination within the scope of the Dutch cot-death protocol shows a bucket-handle fracture of the distal left tibia (*open arrow*). (**b**) Radiograph of the same tibia from a different angle shows a corner fracture (see inset)

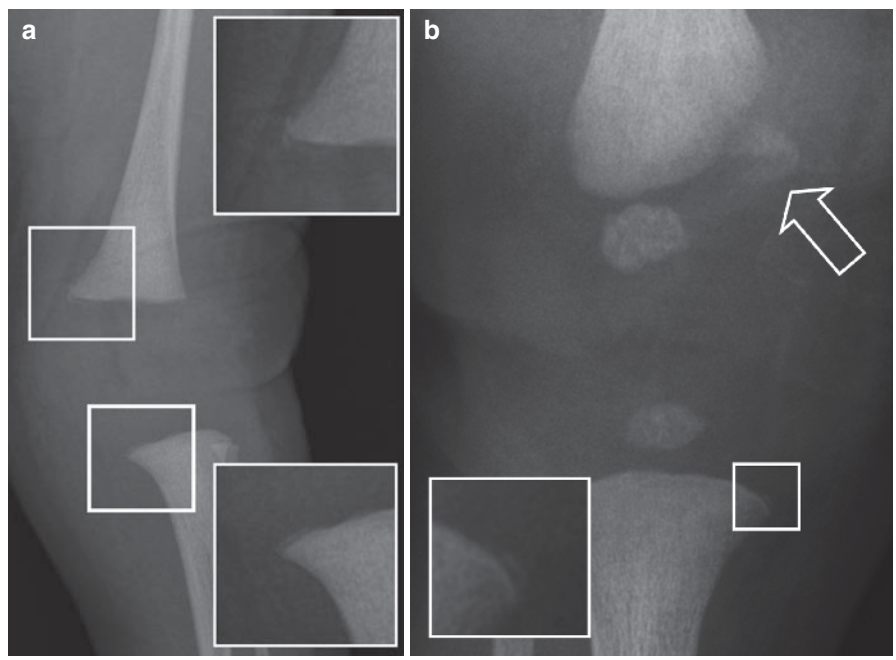


Fig. 5.9 (**a**) Term neonate, born at 39 weeks. Physical examination shows abnormal alignment of the left knee after uncomplicated delivery. A radiograph of the knee shows a metaphyseal corner fracture of the distal femur and the proximal tibia (see inset). (b) Term neonate shows post partum a swollen right knee after a complicated breech delivery. A radiograph of the knee shows a metaphyseal corner fracture of the proximal tibia (see inset) and a Salter-Harris type II fracture of the distal femur

5.5 Humerus

5.5.1 General Aspects of Humerus Fractures

Of all fractures in children, less than 10% are fractures of the humerus shaft. Of all fractures found in children of less than 16 years of age, 3–5% consists of fractures of the proximal humerus. Supracondylar fractures are thought to occur in <3% of children [27–31].

Humerus fractures are most frequently seen in children of <3 years and >12 years old. According to Caviglia et al., one should be aware that each age group has its own differential diagnosis. In neonates, humerus fractures are seen mainly within the scope of birth trauma in macrosomal children (Fig. 5.10). In children <3 years of age, child abuse should always be considered. In

Fig. 5.10 Birth-related humerus fracture after a complicated delivery due to shoulder dystocia

children >10 years, humerus fractures are often the result of direct or indirect trauma (Fig. 5.11) [32].

5.5.2 Humerus Fractures in Child Abuse

Some authors maintain that humerus fractures (including fractures at locations other than the shaft) are the most frequently seen fractures in abused children [33, 34]. Others report that most humerus fractures (46–81%, five different studies) in children outside the neonatal period

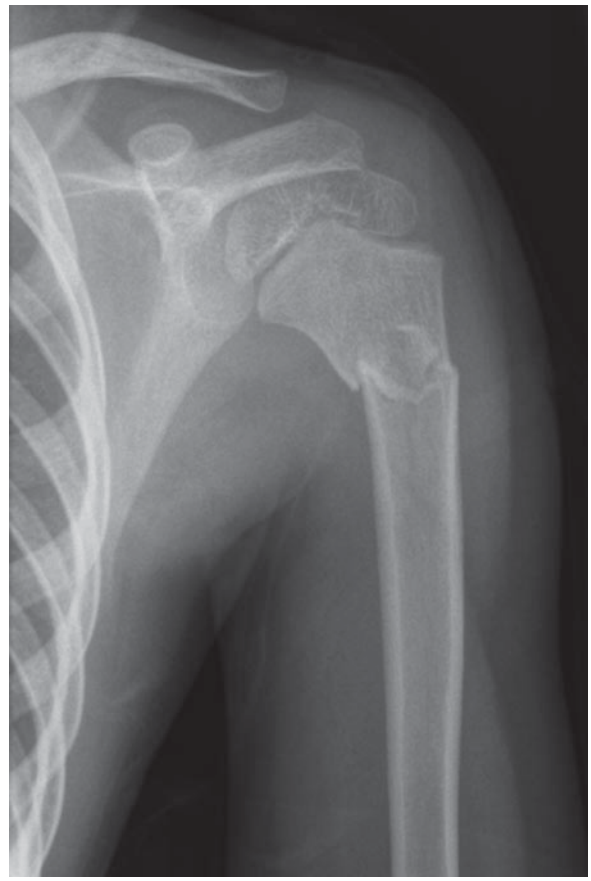


Fig. 5.11 Subcapital humerus fracture in a 4-year-old girl who fell from a swing

and <3 years old result from child abuse. In children <15 months old, the reported percentage ranges from 67% to 100% [3, 4, 35–37].

The most frequently seen locations are mid-shaft and metaphyseal [33, 34]. Transverse fractures are caused by direct-impact force (Fig. 5.11), spiral/oblique fractures result from torque and twisting (Fig. 5.12).

Williams and Hardcastle published a 'best evidence topic report' on the relation between humerus-shaft fractures and non-accidental injuries in children [38]. Their study comprised 44 articles, of which two were able to provide an indication regarding the formulated query: "What is the specificity of an isolated proximal humerus fracture in children who are suspected of being abused" [34, 39]. Their analysis provided the following 'clinical bottom line': although a humerus fracture cannot be seen as pathognomonic for child abuse, such a fracture in a young child should always be followed up with a closer look into its origin

Fig. 5.12 One-month-old infant girl who, according to the parents, had fallen from a bed. The spiral fracture of the humerus does not correspond with the trauma description

(Fig. 5.13). Williams and Hardcastle maintain that both included studies tried to define the specificity of the various types of humerus fracture in relation to child abuse, but that in both studies there is no 'golden standard'. Consequently, it is well feasible that in both studies children have been overlooked or that it was falsely concluded that child abuse was involved. Yet, it appears that the incidence of child abuse in this type of fracture is high. In particular in children <3 years old, spiral and oblique fractures are more often the result of violence than of anything else.

Shaw et al. carried out a retrospective study in 34 children of <3 years old that had sustained a humerus shaft fracture [39]. They excluded children with a humerus fracture at a different place (supracondylar, epicondylar, condylar, proximal epiphyseal and metaphyseal). From a revision of the clinical data and data from the society for the protection of children they established whether or not the child had been the victim of child abuse. They did not use any standard criteria. However, they did arrive at six factors essential in establishing whether child abuse was the most likely cause:

- The presence of simultaneous or older injuries (Fig. 5.14).
- Delay in seeking medical treatment.
- Differences in or contradicting stories regarding the incident.
- The child is accompanied by a person other than the one present at the incident.
- The lack of metabolic or genetic bone diseases.
- The parent shows lack of involvement or unusual behaviour.

Shaw et al. concluded that most humeral-shaft fractures are accidental. Before a report of child abuse is made, a full evaluation must take place. In general, it could be argued that a strong notion of child abuse is justified in children <15 months old, and that it should lead to a full skeletal survey. Salter-Harris fractures of the humerus are seen less frequently than fractures of the distal humerus (see Sect. 5.4.1). In general it is assumed that it takes greater force to sustain this type of fracture than a distal humerus fracture [40, 41].

5.5.3 Humerus Fractures: Differential Diagnosis

5.5.3.1 Fractures of the Proximal Humerus

Accidental fractures of the humerus can originate from birth trauma, directly or indirectly inflicted force, or as a complication of underlying diseases.

In a birth trauma the fracture results from hyperextension or rotation of the arm during passage through the birth canal [42–44]. The risk of fractures of the proximal humerus is highest in large infants during a vaginal delivery (although fractures have also been reported in smaller infants) or during a breech presentation (irrespective of the size of the child) [45, 46].

In older children the most frequent cause is accidental trauma. This may be either direct-impact blunt force

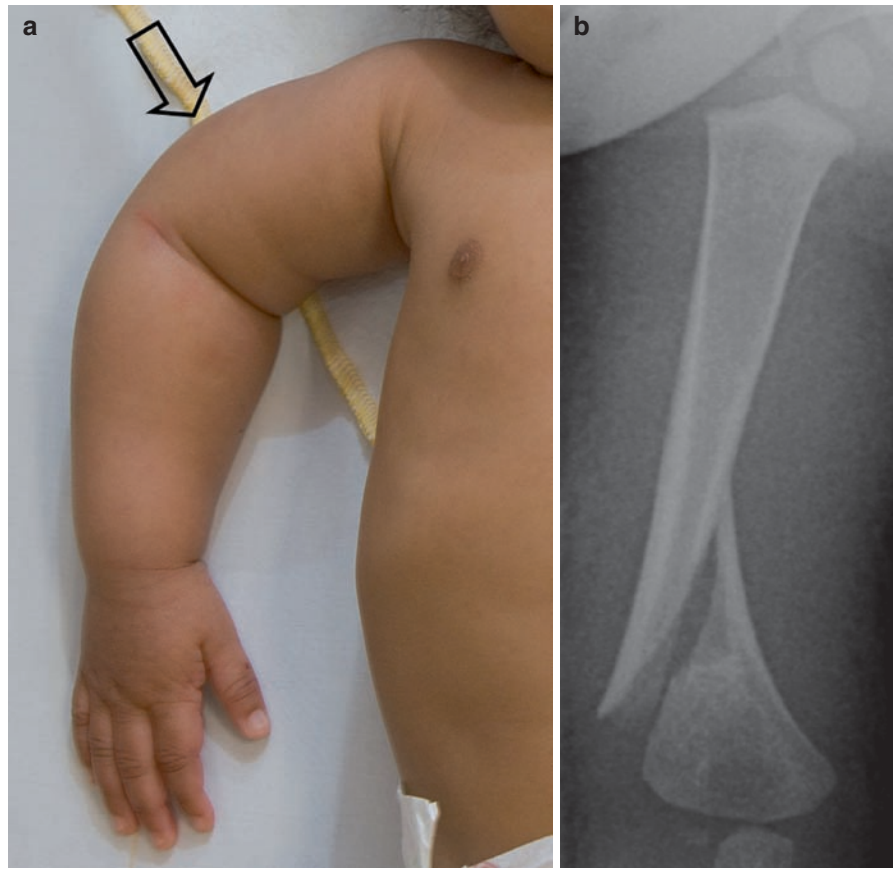


Fig. 5.13 (**a**) Seven-month-old girl suspected of being abused. Slightly abnormal alignment of the upper arm is visible (*open arrow*). (**b**) Radiograph shows a distal oblique humerus fracture

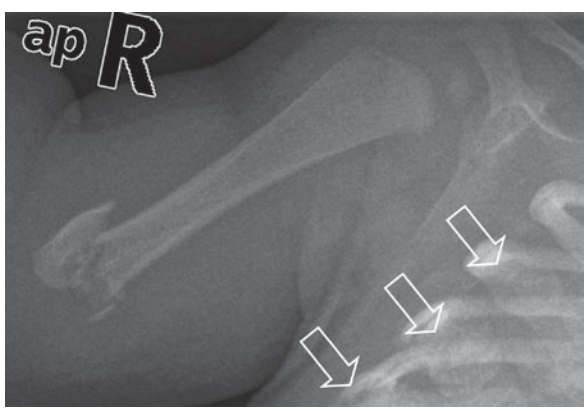


Fig. 5.14 Right distal metaphyseal humerus fracture in a 3-month-old boy. The mid-axillar rib fractures on the right are clearly visible in this view (*open arrows*), see also Fig. 3.9

against the shoulder or a fall on the posterolateral part of the shoulder. Indirect forces may also be involved, such as a fall (backwards) on the extended arm (hand in dorsiflexion and elbow in hyperextension). There fractures often occur during traffic accidents, sports (contact sports, horse riding, gymnastics) and during play (Fig. 5.11) [28, 47].

Proximal humerus fractures may result from complications of underlying diseases such as tumours, metabolic diseases and secondary neuropathies [28, 48–50].

5.5.3.2 Fractures of the Humerus Shaft

Accidental humerus-shaft fractures may result from birth trauma (Fig. 5.10), direct-impact force on the shaft or indirect force from a fall on the extended arm. Shaft fractures are often seen as birth trauma in infants that had a breech birth [51].

Direct-impact forces to the shaft may cause transverse fractures. In older children these occur as the result of a direct blow to the upper arm; for example, in a traffic accident or a fall. In contact sports, there is also a possibility of impact force, directly (such as a karate blow) or indirectly (such as a fall during a judo throw). Accidental shaft fractures occur more

Fig. 5.15 Ten-year-old girl with a supracondylar humerus fracture after a fall

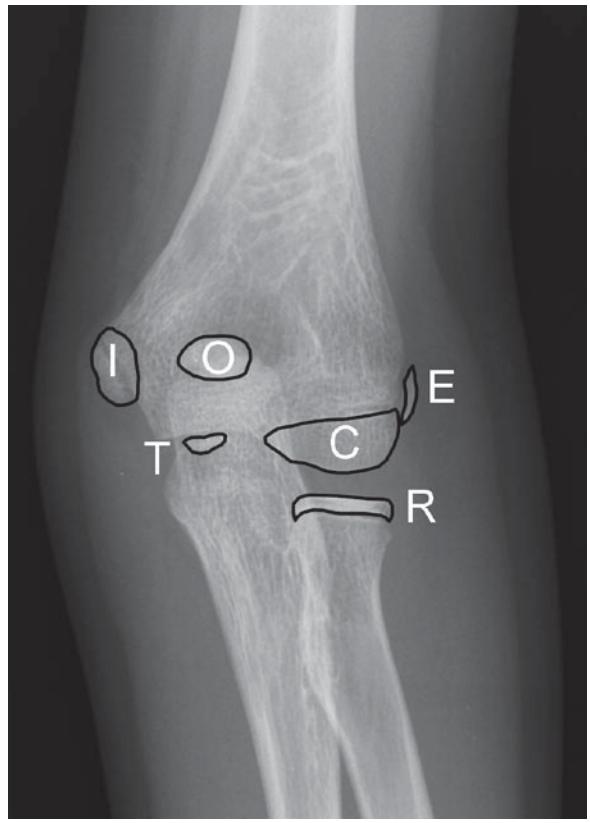


Fig. 5.16 Ossification of the elbow follows a set sequence that is described in the acronym CRITOE (see Table 5.3).

frequently in children that have been victims of a serious accident [52].

5.5.3.3 Supracondylar Fractures

Supracondylar fractures and dislocations are nearly always the result of an accident (Fig. 5.15) and rarely from child abuse [53]. The anamnesis usually shows that the (mobile) child fell on the extended arm (hand in dorsiflexion and elbow in hyperextension) or directly on the bend elbow [4, 53].

However, Strait et al. found in their study that in 20% of children of <15 months old, a supracondylar fracture resulted from child abuse. In these children the anamnesis and the moment that medical help was sought were conclusive [54].

5.5.3.4 Fractures of the Distal Humeral Epiphysis

When birth trauma can be excluded, fractures of the distal epiphysis in children are nearly always the result of child abuse. On plain radiographs, distal fractures may be confused with supracondylar fractures or dislocation of the elbow joint. When evaluating the distal humerus, the ossification of the growth centers should be taken into account. These growth centers ossify according to a set order (Fig. 5.16 and Table 5.3). Avulsion fractures of a growth centers have been found after accidental trauma (Fig. 5.17).

5.6 Radius and Ulna

5.6.1 General Aspects of Fractures of the Lower Arm

In children, fractures of the lower arm are the most prevalent fractures of the long bones (in total 40%, irrespective of type or location) [28, 53, 55]. Of all fractures in childhood, 3–6% are shaft fractures of the lower

Table 5.3 Ossification sequence of the elbow according to CRITOE

Structure	Age (years)
Capitulum	1
Radius head	3
Internal epicondyle	5
Trochlea	7
Olecranon	9
External epicondyle	11

arm. In mobile children, fractures of the radius and ulna are usually the result of accidental trauma [28, 29].

Accidental fractures of the shaft of the radius and ulna are sustained in a fall, as are most fractures of the arm, especially by the application of indirect forces to the lower arm, as the child tries to break his/her fall by out stretching the arm and hand. As soon as the child lands on the extended arm, the main deforming force is transferred to the radius. Consequently, a fracture in the lower arm may occur first in the radius, and then in the ulna. Often these are greenstick or torus fractures. Generally, this type of fracture is not suspect for child abuse. In minors, the distal part of the radius and ulna is the most prevalent location for fractures of the lower arm (Fig. 5.18) [28, 35, 56–58]. Although distally located fractures may occur at any age, they are predominantly seen during the growth spurt in puberty [59]. Mid-shaft fractures are more frequently seen in young children [60].

The metaphyseal corner fracture in the lower arm is also regularly seen in young children (see Sect. 5.4.2) [55]. Due to the strength of the cortical bone, it often takes greater force to cause a shaft fracture than a

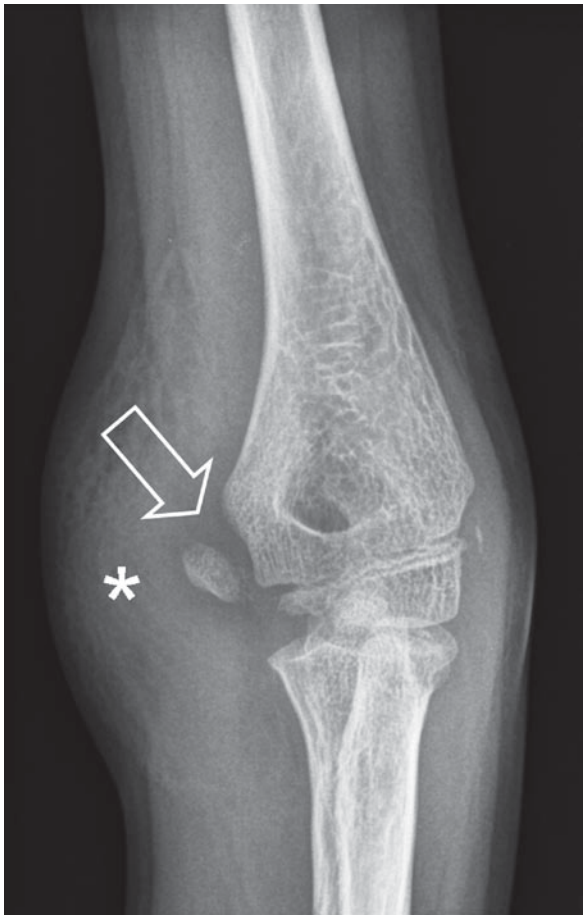


Fig. 5.17 Avulsion fracture of the medial epicondyle of the humerus (*open arrow*) in a 9-year-old girl who had fallen from a skateboard. There is considerable soft-tissue swelling present (arterisk)

Fig. 5.18 Distal fracture of the radius and ulna in a 6-year-old girl after a fall

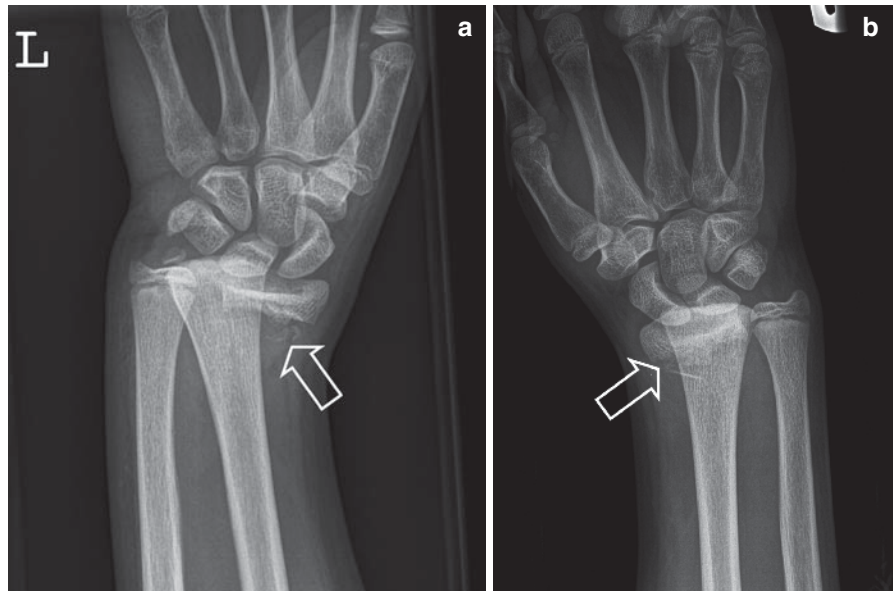


Fig. 5.19 Bilateral Salter-Harris type II fracture (**a** and **b**) of the distal radius in a 13-year-old boy after a fall while skating

metaphyseal fracture. Most metaphyseal/epiphyseal injuries of the distal radius and ulna present as metaphyseal fractures [61]. Fractures of the distal radial and ulnar growth plate are often Salter-Harris I or II fractures (Fig. 5.19a and b). Just like shaft fractures, these fractures may have an accidental or a non-accidental cause.

The clinical signs of a lower-arm fracture, and in particular a shaft fracture, are: pain, pain at pressure, swelling, crunching (crepitus), restricted movement in wrist and hand, and possibly an aberrant alignment or the arm. This is seen mainly in complete fractures. In 'bowing' fractures and minimal greenstick fractures an aberrant position is seen (may be minimal), there is sensitivity when touched and restricted movement of the lower arm. Pain and swelling may be minimal, while crepitus may not be present at all [62].

5.6.2 Fractures of the Radial and/or Ulnar Shaft in Child Abuse

Of all bone injuries due to child abuse, 10–20% are shaft fractures of the radius and ulna. Usually these are transverse fractures [61]. The manner in which age and level of development relate to the anamnesis are important indicators for determining the cause of the fractures. One could say: the younger the child, the more likely the fractures were caused by child abuse [60, 63].

Leventhal et al. concluded that fractures in children of <3 years old were usually caused by child abuse when the child showed a change in behaviour, the parents/carers did not report a fall or accident or just a moderate fall, and when the injury is more severe than one would expect from a moderate fall. They also concluded that fractures of the radius and/or ulna, tibia and/or fibula, femur and mid-shaft or metaphyseal fractures of the humerus in children of less than 1 year old are usually the result of child abuse [3].

In shaft fractures of the radius, one should be aware of a possible dislocation in the proximal radio-ulnar joint (Monteggia fracture, Fig. 5.20) or a dislocation of the distal radio-ulnar joint (Galeazzi fracture) [64–66]. Both fractures are relatively rare and have no predictive value for child abuse.

5.6.3 'Nursemaid's Elbow'

'Nursemaids elbow', or pulled elbow syndrome, is the popular name for a subluxation of the head of the radius. These subluxations are regularly seen in children; generally children in the age of 2–3 years old. An infant of 2 months is the youngest child with a subluxation known in the literature. Subluxations of the head of the radius are also seen in older children, although seldom in children over the age of 7 years [67].

Fig. 5.20 Monteggia fracture, with the characteristic mid-shaft fracture of the ulna and dislocation of the head of the radius (*open arrow*), in a 2-year-old child after a fall from the couch (Courtesy of J. Davis, fellow Chadwick Center for Children and Families, San Diego, CA, USA)

When someone pulls the child's arm with great force, and there is traction along the longitudinal axis of the arm while the lower arm is pronated, it may result in a subluxation. This arm-pulling may be part of the child abuse of the child. However, the majority of cases is caused by an accident. Recurrences may occur.

The radiological examination, which is usually not required due to the obvious anamnesis, generally shows no dislocation. When the radiograph is taken, positioning of the arm by the radiographer will usually reduce the arm.

5.7 Femur

5.7.1 General Aspects of Femoral-Shaft Fractures

In children, less than 2% of all fractures are fractures of the femoral shaft, this includes subtrochanteric and supracondylar fractures (fractures of the upper and lower third of the shaft) [68]. Boys are more at risk than girls (2.6:1) [28, 69].

Two peak periods can be distinguished: in children of <4 years old (in particular around 2 years old) and in young children >12 years old [70]. Regional differences can also be seen: in the United States (Maryland) an incidence of 1:5,000 in minors [70], in Switzerland the incidence in minors is 1:2,000 [71].

5.7.2 Aetiology and Pathogenesis

Children can sustain a femoral-shaft fracture due to traffic accidents, falls and child abuse [72]. Furthermore, it appears that there is an increased risk for femoral-shaft fractures in diseases that negativitively influence bone formation. The aetiology of femoral-shaft fractures in children depends on age and level of development.

5.7.2.1 Spiral Fractures of the Femoral Shaft

It is often maintained that a spiral fracture of the shaft of one of the long bones, and in particular the femur, is evidence of child abuse. This is incorrect [3, 72, 73]. It is only possible to evaluate such a fracture when the context of the origin of the fracture is also considered [12].

The only conclusion that can be made with certainty when a spiral fracture of the femur is encountered is that the fracture is the result or applied torque (rotation along the longitudinal axis of the bone). Torque may occur in child abuse (Figs. 5.21 and 5.22). In particular in non-mobile children child abuse should be considered.

In mobile children torque can take place in accidents, such as slipping and falling while running, in which the foot takes a more or less stationary position [2–4, 12, 53, 74]. The fracture may also occur in a fall in which knee and hip are more or less stationary, and the child turns the lower leg in relation to the stationary joints. This happens regularly, not just to the femur but also to, for example, the tibia, as in the 'toddlers' fracture' (see Sect. 5.8.2).

5.7.2.2 Transverse and Oblique Fractures

In a transverse fracture, the fracture line is more or less perpendicular to the long axis of the bone. In an oblique fracture the fracture line is at an angle of 30–40 degrees to the long axis of the bone. Transverse and oblique

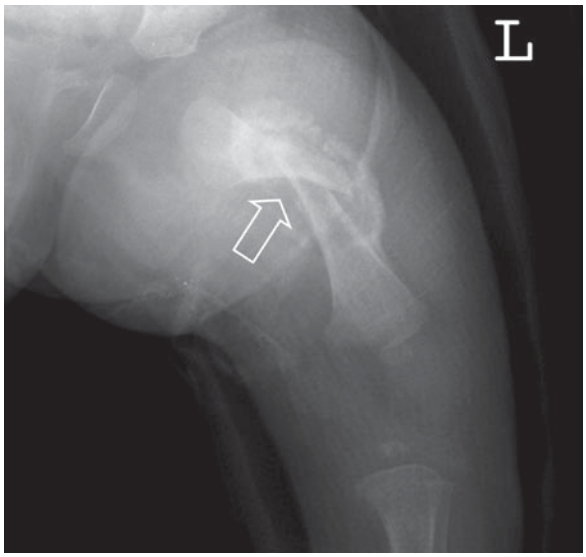


Fig. 5.21 Healing spiral fracture of the left femur (*open arrow*) in a 3-week-old infant who, according to the parents, had fallen from the couch. The fracture does not correspond with the described biomechanics

Fig. 5.22 Graphic representation of the possible origin of a non-accidental femur fracture

fractures may occur due to compression, tension, shearing and bowing, or a combination of the aforementioned (Table 5.1).

Transverse and oblique fractures are frequently seen in accidental and non-accidental situations [72]. In an accidental cause, such a fracture may occur as a result of direct-impact forces on the bone, for example when an object hits the bone directly (mostly based on bowing or shearing, Fig. 5.23), or by indirect impact, such as when a child falls from significant height and

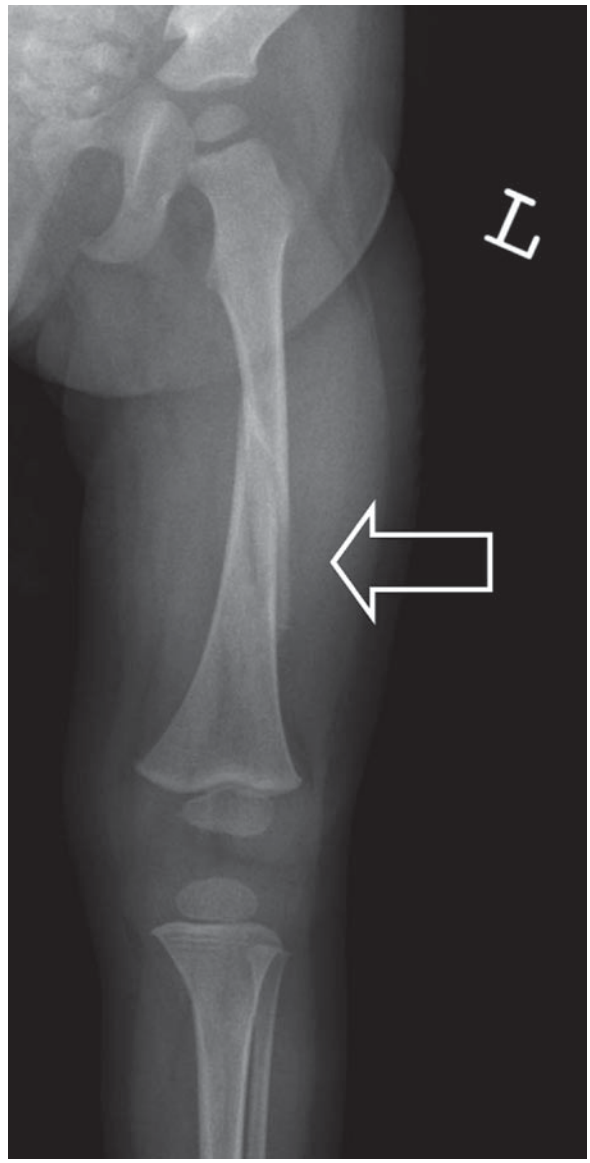


Fig. 5.23 Oblique femur fracture (*open arrow*) in a 3-year-old boy who had toppled a television (witnessed trauma)

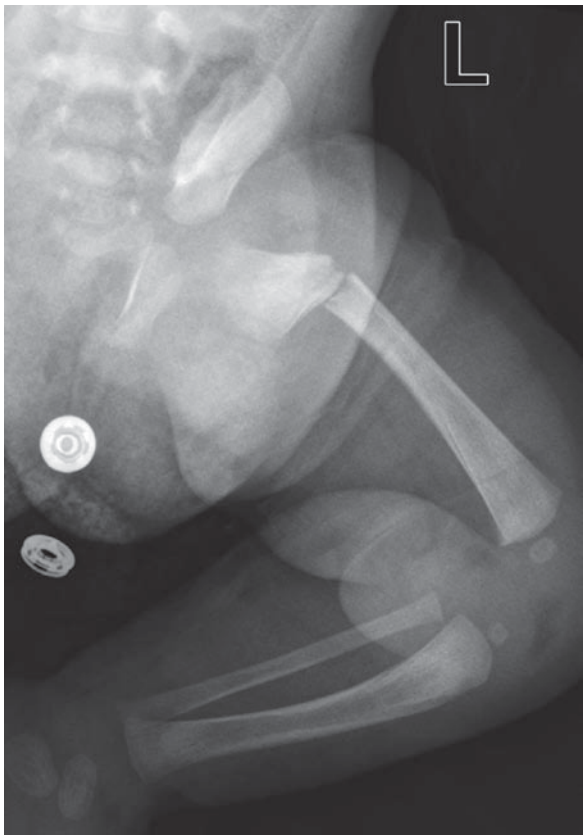


Fig. 5.24 Four-week-old girl who had sustained a proximal femur fracture after a fall from the arm of her mother who tripped over the family dog

lands on a knee (usually based on compression and/or bowing). It may also happen when a parent falls down the stairs while holding the child on an arm and the child lands on the femur (Fig. 5.24) [75]. This is often a high-energy trauma [75].

In child abuse, particularly bowing and shearing are involved. A child may have received a blow or a kick to the upper leg, and the bone bows past the point at which recovery is still possible without a fracture. In younger children, indirectly applied forces may also be involved; for example, when a person violently grabs and manipulates the leg, swings the child to and fro, or hits or throws the child against some object [12]. In such situations bowing and shearing can take place.

Oblique fractures are usually the result of a combination of various forms of loading, such as compression with some torque, or compression with bowing [75]. By using conventional radiology, it is not always possible to distinguish between an oblique fracture and a spiral fracture.

5.7.3 Differentiation Based on Age and Level of Development

Research has shown that age and level of development of the child are important factors when differentiating between accidental and non-accidental femoral-shaft fractures. In the literature, percentages up to 80% are found for child abuse being the cause in non-mobile children [2, 76, 77]. In children of <4 years old, percentages up to 30% are found [68]. Research by Thomas et al. has shown that 60% of femoral-shaft fractures in children <1 year old are due to physical violence. In children between 2 and 3 years old, this appeared to be the case in 20% [4, 33]. In mobile children the rule of thumb is that transverse or spiral fractures are the result of accidents, but only when a plausible explanation has been provided [4].

The study of Rex and Kay also shows that age is an important indication [78]. Thirteen of 14 children that had sustained a fracture due to child abuse appeared to be <1 year old. Rex and Kay compared the group abused children with a group of 33 children with an accidental femoral fracture. They found that accidental and non-accidental shaft fractures cannot be differentiated solely on basis of location [78].

In young children, an unusual accidental femur fracture may be sustained when a parent falls on the child while the child is carried on the hip of the parent. This can cause a greenstick fracture of the medial distal metaphysis of the femur (Fig. 5.25a and b) due to bowing of the thigh bone, which leads to compression damage to the medial cortex [68].

According to Schwend et al., femoral-shaft fractures in children under 4 years of age are seldom the result of child abuse [74]. However, their study also shows that in children besides age the level of motor development is an important indicator. The strongest indicator for child abuse appeared to be whether or not the child could walk. In their study it appeared that in 42% of non-walking children the fractures were the result of child abuse, whereas in the walking children it was 2.6%. In particular when oblique and spiral fractures are seen in non-mobile children, child abuse should always be excluded. In their opinion, child

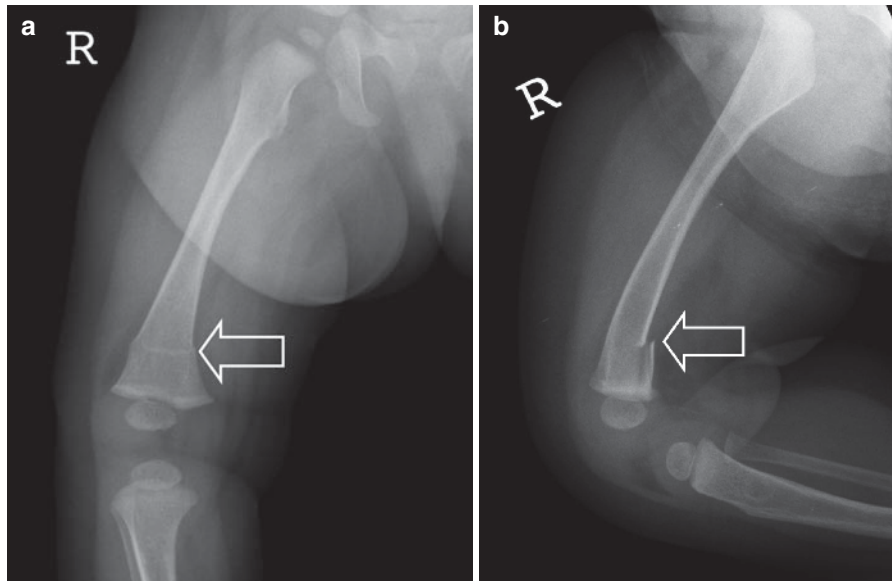


Fig. 5.25 (**a**) Five-month-old girl who had sustained a greenstick fracture of the distal femur (*open arrow*, A-P view). (**b**) Lateral view of the femur shows a cortical defect (*open arrow*)

abuse in mobile children is highly unlikely when there are no additional signs such as an inconsistent story, haematomas or other fractures. When a non-mobile child presents with a fracture of the femur, it is an important indication for child abuse.

Blake et al. evaluated 42 children in the age of 1–5 years that presented with a shaft fracture. Thirty-four of them had fallen [79]. In 14 children the anamnesis led to suspected child abuse, but only in one child there was proof. Yet, Blakemore et al. maintain that when a young child presents with a femoral-shaft fracture, child abuse should always be considered when the patient history mentions a fall and there are no eye-witnesses to confirm either the fall or its context. The distance of the fall may also provide an indication towards the cause. In case the anamnesis shows that the fracture is caused by a fall of less than 1 m in height, this is an unlikely statement [80]. The force required to cause a mid-shaft fracture is considerable and requires a substantial acceleration-deceleration trauma.

In children of 5 years and older and adolescents, a shaft fracture is hardly ever the result of child abuse. The most likely cause is a high-energy trauma, such as a traffic accident. In this age group, in 90% of cases the cause is a traffic accident [69, 81, 82]. In the United States, shot wounds are increasingly a cause for shaft fractures [68].

Only occasionally fractures are caused by sexual abuse. In 5% of a group of sexually abused children, Johnson et al. found fractures as a sign of child abuse. According to the authors, these fractures are seldom or never the result of sexual acts. In three children they did find fractures resulting from sexual acts. A 5-month-old girl sustained a femoral fracture without dislocation as the result of abuse [83].

5.7.3.1 Birth Trauma-Related Femoral-Shaft Fractures

A birth trauma may lead to femoral fractures (Fig. 5.26a and b). However, this happens rarely (see Chap. 6). Morris et al. recorded an incidence of 0.13 in 1,000 live births (seven neonates with in total eight fractures in 55,296 live births) [84]. Spiral fractures of the proximal part of the femur were most commonly seen and have been reported in breech birth, forceps births, twin births, premature births and Caesarean sections.

Not all fractures are immediately identified after birth. A study by Morris et al. even showed that in the majority of children there was a delay in diagnosis. In only two children the fracture was established immediately post partum. In the other children there was a delay of 2–21 days, even when hospitalised [84]. Such a delay may unjustly lead to suspected child abuse. Up to a certain extent it is possible to differentiate between birth and other trauma by evaluating the formation of callus. Cumming mentions that callus can be found as early as 7 days post partum [85]. When a fracture is found in an unusual location, or when there is no callus

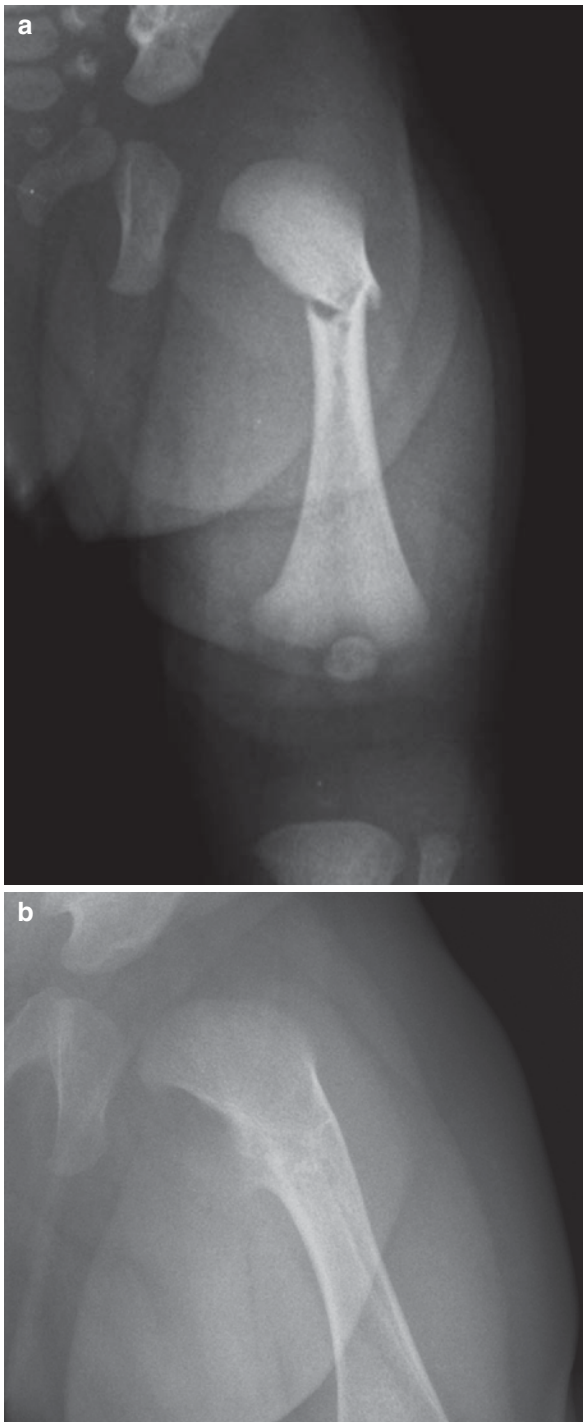


Fig. 5.26 (**a**) One-day-old neonate (birth weight 2,215 g) with a femur fracture after a complicated delivery with transverse presentation. (**b**) After 4 months the fracture has healed practically seamless

visible 11 days after birth, child abuse must be considered as possible cause.

5.7.3.2 Disease-Related Fractures

In differential diagnoses one should be aware of disease-related fractures, in particular when there is a 'blank' anamnesis. In children, pathological fractures are relatively rare, but may be seen in children with generalised osteopenia, such as osteoporosis imperfecta (OI). When a femur-shaft fracture is found in a child, and there are no signs of violence or significant trauma, OI must be considered [3]. Other causes of generalised osteopenia in which a minor trauma may cause a fracture of the femoral shaft are neurological diseases such as cerebral palsy or meningomyocele [86–89]. Pathological fractures may be seen in patients with neoplasms. Usually these are benign lesions such as eosinophylic granuloma and bone cysts. Pathological femur fractures are seldom seen in patients suffering from osteosarcoma or a Ewing sarcoma (see Chap. 7) [68].

5.8 Tibia and Fibula

5.8.1 General Aspects of Fractures of the Lower Leg

In young children, fractures of the tibial shaft are very suspect for child abuse. Direct-impact force on the shaft may lead to transverse or oblique fractures. Grabbing hold of the leg and turning with great force may lead to spiral and oblique fractures. The fracture lines are not always visible; however, a reaction of the periosteum with callus formation is regularly found.

Metaphyseal corner fractures of the tibia are a regular occurring phenomenon [33, 90]. In these cases the proximal growth plate is affected more often than the distal growth plate (see Sect. 5.4.2) [16]. Accidental spiral fractures or oblique fractures are often seen in mobile children of 3–4 years old [91, 92].

Fibula fractures are rarely seen in child abuse. When they do occur, they result from direct- impact

Fig. 5.27 Distal fracture of tibia and fibula in a 4-year-old boy after high-energy trauma, car vs pedestrian (radiograph was taken in a vacuum splint)

force to the shaft. Usually a simultaneous fracture of the tibia is seen.

Simultaneous fractures of the tibia and fibula are often seen in accidents (Fig. 5.27). Fractures of tibia and fibula may also occur when the child is seated on the backseat of a bike (usually a bike of one of the parents) and the foot gets caught between the frame and the spokes of the wheel (Figs. 5.28 and 5.29) [93, 94].

Fig. 5.28 Graphic representation of a spoke injury

These easily avoidable injuries are known as 'spokes' injuries and unfortunately, at least in the Netherlands with many cycling parents, these are seen on a regular basis.

5.8.2 Isolated (Spiral) Fracture of the Tibia

Mellick at al. pose that isolated spiral fractures of the tibia are often seen in children <8 years old, usually as the result of an accident. In their study, they found that 95% of all fractures were seen in the lower two thirds of the tibia. They seldom noticed alignment abnormalities based on the mutual dislocation of the ends of the fracture. They suggested that when these fractures are caused by an accident, they should no longer be called 'toddler's fracture', but accidental spiral fractures of the tibia (CAST – Childhood Accidental Spiral Tibia fractures, Fig. 5.30) [95].

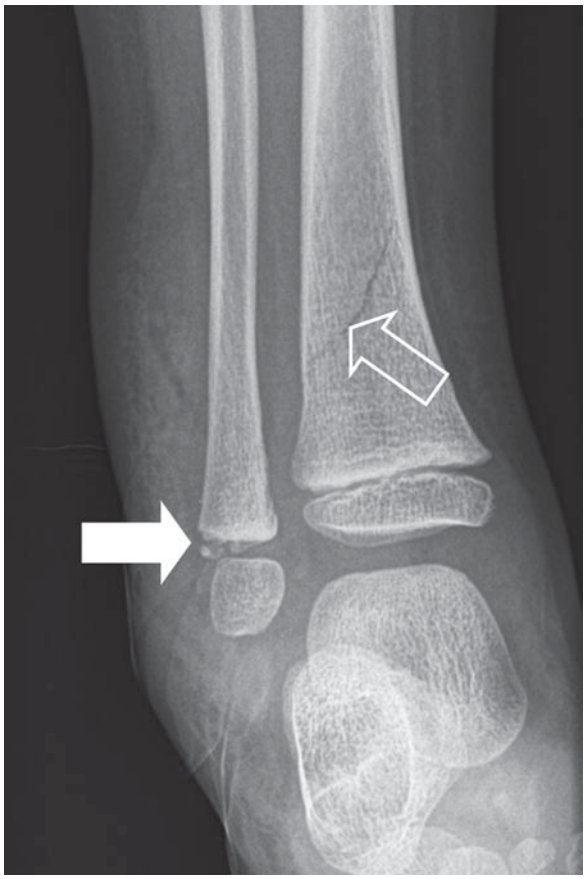


Fig. 5.29 Spoke injury in a 4-month-old girl who was seated at the back of her mother's bike. The trauma resulted in an oblique fracture of the tibia (*open arrow*) and a Salter-Harris type II fracture of the fibula (*arrow*)

Fig. 5.30 Childhood accidental spiral tibia fracture in a 22-month-old boy

5.9 Shaft Fractures of the Lower Extremities

In 2005, Coffey et al. published an article that supports the earlier-mentioned data on shaft fractures in the upper and lower leg [96]. In this study, fractures of the lower extremities and their possible relation to child abuse were retrospectively evaluated. The study comprised data of 5,497 trauma patients. Of this population, 4,942 children were >18 months old. One hundred and four (2%) children appeared to have been abused. In the group of 555 children of ≤18 months old, 175 children (32%) were found to have fallen victim to child abuse.

Looking at fractures in all extremities, it appeared that in children of >18 months old, injuries to the extremities ($n=1186$) were in 1% ($n=16$) of cases due to child abuse, whereas this was 67% ($n=44$) in children of <18 months old ($n=66$). When only the injuries of the lower extremities were considered, 41 (75%) of the 55 fractures in the younger group were the result of child abuse. In this group, 134 (27%) of 500 other injuries were also found to be the result of physical violence. In 22 cases a femur fracture was seen and in 14 cases a tibia fracture. Coffey et al. concluded:

- In children of >18 months old, child abuse is an unusual cause for injuries to the legs.
- In children of ≤18 months old, injuries to the legs, and in particular fractures, are an evident indication for child abuse: 'Clinicians must thoroughly

investigate lower extremity injuries in this age group'.

5.10 Hands and Feet

In child abuse, fractures of the hands and feet are unusual. In older children they are usually the result of accidents (Figs. 5.31 and 5.32a–c) [21]. When fractures due to child abuse are found in older children, they may be metaphyseal/epiphyseal and diaphyseal fractures, mostly located in the metacarpals (Fig. 5.33) or metatarsals. It often concerns multiple fingers and/or toes [61].

In children <1 year old, fractures of the hands and feet are suspect for child abuse (Fig. 5.34a and b). Nimkin et al. evaluated 11 fractures of hands and feet in infants of <10 months old. They found predominantly torus fractures, either of the metacarpals or the proximal phalanges of the hands, and comparable fractures of the first metatarsals of the feet. Only one child showed clinical symptoms [97].

The lesions are the result of direct-impact force, either by being hit with an object or by punching [61]. Fractures may also be caused by hyperflexion or hyperextension.

Fig. 5.31 Fracture of the proximal phalanx (*open arrow*) of a 4-year-old girl who had a television topple on her hand

5.11 Subperiosteal Haemorrhages/ Calcifications

Subperiosteal haemorrhages may be caused by friction trauma, in which the perpetrator makes a rotating movement while holding on to the upper arms, or from a blunt trauma. These haemorrhages are not immediately visible on a radiograph. A 2-week follow-up of the radiograph is indicated. When a subperiosteal haemorrhage is present, a double contour is seen due to 'lifting' of the periosteum.

Subperiosteal haemorrhages/calcifications must be distinguished from physiological periosteal thickening of the long bones (femur, tibia, humerus) in neonates and infants, and from skeletal lesions seen in vitamin-C deficiency, vitamin-A intoxication, infantile cortical hyperostosis, osteomyelitis, malignancies (such as leukaemia) and congenital syphilis (see Chap. 7).

5.12 Growth-Retardation Lines

5.12.1 General Aspects of Growth-Retardation Lines

Metaphyseal growth-retardation lines are formed in periods when growth is delayed or has ceased and may remain visible for months [98]. They are evidence of a disturbance in longitudinal growth, which takes place in the metaphyses. These lines have been reported in a multitude of childhood diseases in which a disturbance (a delay or even a temporary cessation) in growth is seen; causes of 'organic failure to thrive'. This phenomenon may occur in every disease with a severe course of illness.

Fig. 5.32 (**a**) Two-year-old girl who had a drawer fall on her hand while playing. Radiological examination revealed a fracture of the capitate bone (Reprinted from Obdeijn MC, van Vliet C, van Rijn RR. Capitate and hamate fracture in a child: the value of MRI imaging Emerg Radiol. 2009 May 26. [Epub ahead of print] DOI 10.1007/s10140-009-0815-9. With permission.) (**b**) Postero-anterior view of the hand shows the fracture of the capitate bone. (**c**) Coronal STIR-weighted MRI shows bone oedema at the location of earlier-mentioned capitate fracture (*open arrow*); however, also of the hamate bone (*arrow*)

The documented causes include: malnourishment [99], infections [99], hypothyroidism [100], parahypothyroidism [101], Cushing's syndrome [102], chronic diseases, chronic juvenile arthritis [103], and chemotherapy in children with malignancies and other medications (Fig. 5.35) [104–106]. The lines were also found in children that had been immobilised after orthopaedic surgery [107].

5.12.2 Growth-Retardation Lines and Non-organic Failure to Thrive

Growth disturbances are not just caused by diseases. In the Western world, the most common cause of growth and development retardation – in other words, the most common cause for 'failure to thrive' – is neglect and understimulation. In neglect, the child is

Fig. 5.33 Sclerotic aspect of the base of metacarpal 3 of the right hand (*open arrow*), suspect for a healed fracture

offered insufficient calories (malnourishment) and/or insufficient affective stimulation. As early as 1967, Patton and Gardner mentioned metaphyseal growth-retardation lines in their book on maternal deprivation [108]. Maternal deprivation stands for a serious disturbance in the relation between parent (mother) and child, and a lack of bonding between parent (mother) and child. The deprivation consists of neglect, rejection and isolation of the child. Maternal deprivation syndrome leads to serious growth retardation, delayed skeletal maturation and retarded motor and intellectual development [109]. This multitude of physical symptoms is nowadays summarised in the term 'non-organic failure to thrive'. Khadilkar et al. confirm the observation of Patton and Gardner that the origin of these lines may involve psychological factors [110].

Animal tests suggest that the lines are formed after an initial retardation or cessation in growth, followed by resumed growth [99, 107]. According to Khadilkar et al., in children they seem to occur in similar circumstances [110]. In case the process is cyclic (repeated periods of delayed growth interspersed with periods of resumed growth) a large number of lines may be found. These lines will always remain visible, up to and including puberty.

When multiple growth-retardation lines are found in a child, non-organic failure to thrive will be, after

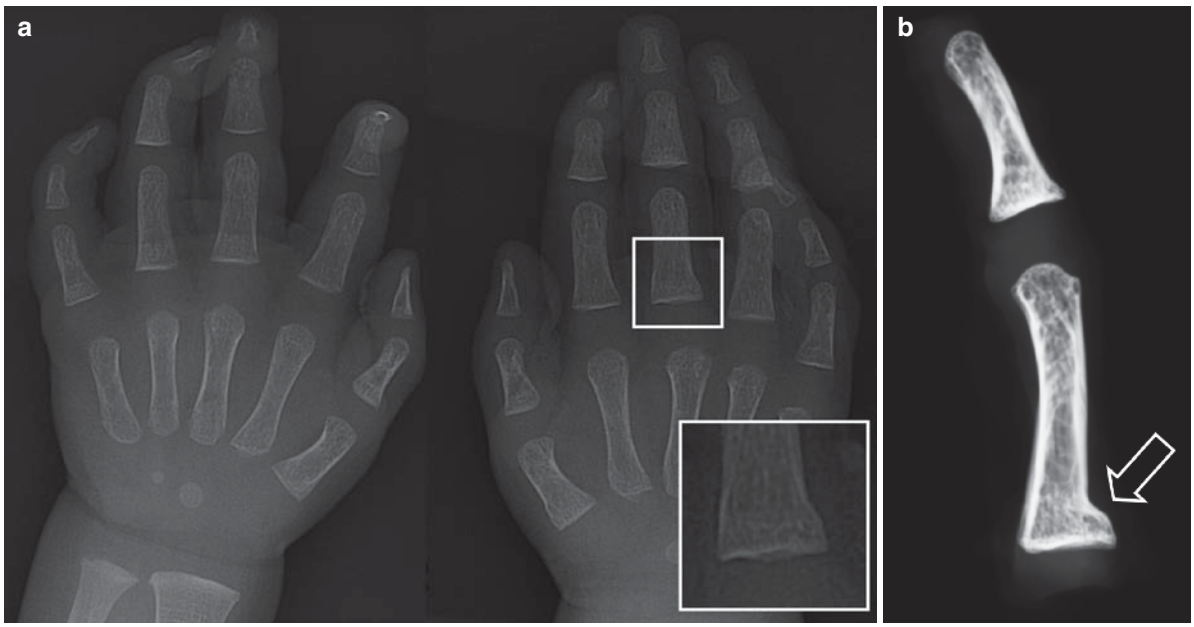


Fig. 5.34 (**a**) One and a half-month-old girl found dead in her crib. Radiological examination of the hands revealed a torus fracture at the base of the proximal phalanx of the third finger of the right hand (see inset). (**b**) Radiograph of the finger, sampled at autopsy. The radiograph has been taken with a mammography system, because of its high resolution

Fig. 5.35 Growth retardation lines in a 5-year-old girl after treatment with intravenous bisphosphates, due to fibrous dysplasia in the left maxillary sinus

exclusion of other (organic) causes, the most probable cause [110].

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