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Skeletal imaging of child abuse (non-accidental injury)

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Abstract In recent years there has been a worldwide increased awareness that children are physically abused by their carers. Radiologists play a vital role in the detection of inflicted injuries. This article reviews the skeletal imaging findings seen in child abuse.

Keywords Skeleton · Child abuse · Radiography

Introduction

As discussed by Hobbs and Bilo [1], physical abuse of young children is a serious health problem. Diagnostic imaging plays an important role in the early diagnosis of abuse. The radiologist's task is to detect findings that are suggestive of abuse, to distinguish abuse from other pathologies and normal variants, and to provide reasonable estimates of fracture age and mechanism of injury. Additionally, a radiologist with specialized knowledge in the field of paediatric radiology may provide expert medical opinions to child protection and law enforcement agencies.

In this article we review the important skeletal imaging findings of abuse. A review paper on neuroimaging in abuse has recently been published, and this topic will not be addressed here [2]. It is, however, worth mentioning that the current controversy in the USA and UK regarding the 'shaken baby syndrome' has increased the importance of a detailed evaluation of the skeleton in cases of suspected inflicted neurotrauma (Fig. 1) [2, 3].

Imaging techniques

Fractures are the second most common finding in child abuse after cutaneous findings such as bruises and contusions. The skeletal survey is the cornerstone radiological examination in suspected physical abuse [4]. Although other imaging modalities may be applied, in most cases radiography alone can detect inflicted osseous injuries [5]. The follow-up skeletal survey has been shown to increase the sensitivity of initial radiographic imaging and should be considered in all cases where abuse is strongly suspected (Figs. 2 and 3) [6–9].

Bone scintigraphy is sometimes used to complement the skeletal survey [10]. Kemp et al. [10] reviewed five studies where bone scintigraphy had greater sensitivity than the skeletal survey [11–15] and two studies where the skeletal survey had a higher sensitivity [16, 17]. Kemp et al. [10] concluded that neither modality alone detected all fractures. Reportedly, bone scintigraphy has a lower sensitivity for the classic metaphyseal lesion (CML) and for skull fractures, but a higher sensitivity for rib fractures [11–16]. The American College of Radiology (ACR) appropriateness criteria state that bone scintigraphy is '... indicated when clinical suspicion of abuse remains high and documentation is still necessary' [18].

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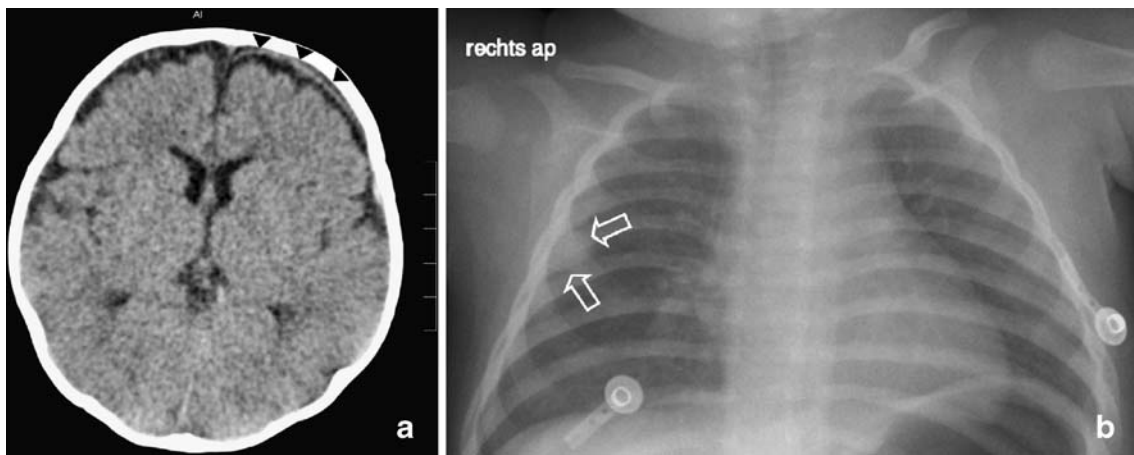


Fig. 1 A 4-month-old abused girl. **a** Axial CT image shows a left frontal subdural haematoma (*arrowheads*) **b** AP view of the chest reveals a healing posterolateral fracture of the right 6th rib (*arrows*)

CT, US and MRI may be of value in selected cases, but currently cannot replace the radiographic skeletal survey [19–22]. The use of fluorine-18 NaF PET imaging in the detection of occult inflicted fractures has recently been described in a single case; however, its clinical utility in suspected physical abuse requires further research [23].

Imaging protocol

A skeletal survey should be performed in cases of suspected child abuse. The ACR defines the skeletal survey as ‘a systematically performed series of radiographic images that encompasses the entire skeleton’ [24]. The ACR (Table 1) as well as the British Society of Paediatric Radiology (BSPR) (Table 2) [25, 26] have published guidelines for the skeletal survey protocol. The ACR and BSPR guidelines are nearly identical. One difference between the guidelines is the acquisition of oblique radio-

graphs of the ribs. This addition is supported by the findings of Ingram et al. [27] who, in a randomized controlled trial, found that oblique views of the chest increased the sensitivity for the detection of rib fractures by 17% and the specificity by 7%. Hansen et al. [28] compared the conventional two-view chest series to the four-view chest series in 21 abused children. The four-view chest series increased the diagnostic yield, both by including new fractures and by excluding fractures suspected on the two-view series. However, each case had at least one rib fracture visible on the two-view series and there were no cases in which the four-view series excluded all rib fractures seen on the two-view series (Fig. 4).

Equivocal fractures at all sites should be evaluated with additional projections. Ideally a radiologist should supervise the skeletal survey, and only once it has been reviewed and approved should the examination be considered complete. Because the skeletal survey may become part of legal proceedings, the radiology technologists are identified

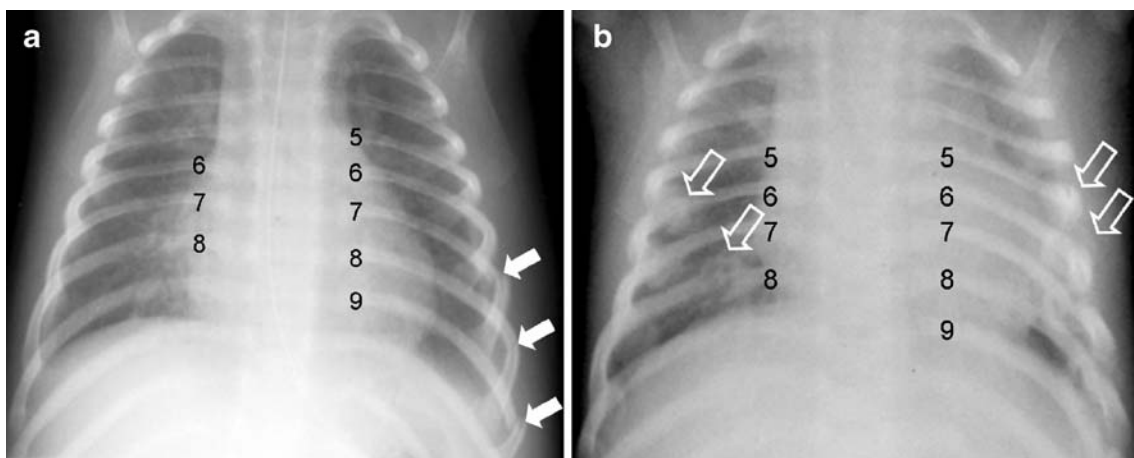


Fig. 2 An abused child of unknown age and sex. **a** Initial AP view of the chest shows three acute left lateral rib fractures (*arrows*). **b** Follow-up radiograph 6 weeks later shows four additional rib fractures not previously seen (*arrows*)

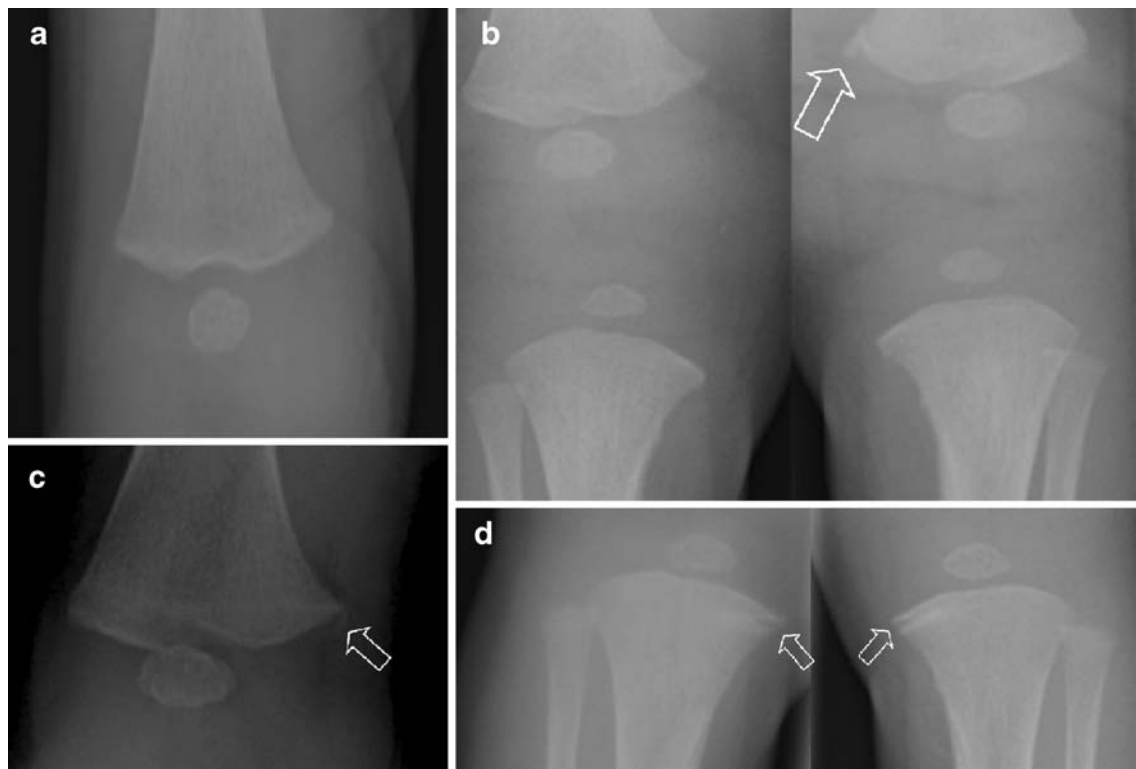


Fig. 3 A 3-week-old abused girl brought to the emergency room after an apnoeic episode. **a, b** Initial images of the lower extremity show **(a)** no abnormality of the right distal femur, and **(b)** a left distal femur CML (*arrow*) and no abnormality in the proximal right and left tibiae.

c, d Follow-up radiographs 2 weeks later reveal **(c)** a healing right distal femur CML (*arrow*) and **(d)** bilateral proximal tibia CMLs (*arrows*)

on the radiographs – either by their initials, or by preallocated codes.

The ACR and SPR guidelines are available online, but are not widely implemented. Kleinman et al. [5] surveyed radiologists at paediatric health-care facilities in the USA and found that imaging protocols varied from the recommended guidelines. In 2007, Schmit et al. [29] queried members of the Asian & Oceanic Society for Paediatric Radiology, the European Society of Paediatric Radiology, the Latin American Society of Pediatric Radiology, and the Society for Pediatric Radiology about the guidelines. Respondents perceived the recommendations as open to interpretation, improvement and research. Both studies found a wide range of imaging practices in cases of suspected abuse. Offiah and Hall [30] and van Rijn et al.

[31] retrospectively examined skeletal surveys and found many differences in the number and quality of radiographs performed. They concluded that the available guidelines are generally not implemented in clinical practice. Efforts to improve the quality of skeletal surveys for suspected abuse should be encouraged and there is evidence that standards, at least in the UK, are improving [32].

What is the impact of digital imaging systems on the evaluation of suspected abuse? Generally, digital imaging (CR and DR) has several practical advantages over conventional film-screen radiography, including economic and ergonomic considerations [33]. Postprocessing functions when used optimally may improve visualization of pathology and bone and soft-tissue detail differentiation. Techniques commonly used are magnification, grey-scale,

Table 1 American College of Radiology skeletal survey [24].

Axial skeleton	Appendicular skeleton ^a
Thorax (AP and lateral), to include ribs ^b , thoracic and upper lumbar spine	Humeri (AP)
Pelvis (AP), to include the mid-lumbar spine	Forearms (AP)
Lumbosacral spine (lateral)	Hands (PA)
Cervical spine (AP and lateral)	Femora (AP)
Skull (frontal and lateral), additional views if needed – oblique or Towne view	Lower legs (AP)
	Feet (PA or AP)

^a Additional views if needed; views centred on joints or lateral views.

^b Oblique views recommended, but not routine

Table 2 British Society of Paediatric Radiology skeletal survey [26].

Axial skeleton	Appendicular skeleton ^a
Thorax (AP), right and left oblique views of the ribs	Humeri (AP)
Pelvis (AP)	Forearms (AP)
Lumbosacral spine (lateral)	Hands (PA)
Cervical spine (lateral)	Femora (AP)
Skull (frontal and lateral), Towne view if occipital injury suspected	Lower legs (AP)
	Feet (AP)

^aLateral coned views of the elbows, wrists, knees and ankles may demonstrate metaphyseal injuries in greater detail. The consultant radiologist should decide this, at the time of checking the films with the radiographers.

contrast, brightness, nonlinear grey-scale enhancement, nonlinear unsharp masking (edge enhancement), and single or dual exposure energy subtraction. Digital imaging requires particular attention to technical factors, because observed performance may vary with mAs, kVp and CR system resolution. Radiology departments should optimize their digital imaging techniques accordingly [34]. A study by Offiah et al. [35] suggested that neither postprocessing parameters (magnification and edge enhancement) nor method of digital image display (i.e. whether radiographs were printed or viewed from a monitor) affects the diagnostic accuracy of fracture identification in abuse cases. Regardless of the imaging system used and method of image display, emphasis should be placed on improving performance.

Under- and over-diagnosis of abuse may have detrimental effects on children and their carers. It is critical that the skeletal survey be performed according to a rigorous imaging protocol, with careful attention to technique

ensuring high-quality radiographs. The skeletal survey should be reviewed by a radiologist with substantial experience in paediatric imaging to ensure accurate interpretation of the findings.

Radiological findings

Rib fractures

Rib fractures are frequently seen in adolescents and adults after severe trauma. Younger children have higher plasticity of their ribcage; the ribs deform before they fracture. This explains the relative scarcity of rib fractures in this age group. Rib fractures in younger children are usually clinically occult and found incidentally [36]. The presence of rib fractures in infants (less than 1 year of age) is highly specific for abuse (Figs. 2, 4 and 5) [37]. One mechanism of rib fracture is anterior-posterior compression of the chest [38, 39]. Excessive leverage of the ribs over the transverse process leads to fractures of the rib head and neck (Fig. 6). Other forms of chest compression and blunt impact may be responsible for rib fractures at other sites.

Barsness et al. [40] assessed the positive predictive value (PPV) of rib fractures in relation to abuse. In 62 children, a total of 316 rib fractures were identified. In 51 children (82%) the fractures were due to abuse. In children less than 3 years of age the PPV of rib fractures for abuse was 95%. Fractures of the first rib appear to require even greater force than other rib fractures, and strongly suggest abuse [41].

Although rib fractures have a high specificity for abuse, they have been described in other scenarios where similar strong forces may have occurred. Mid-posterior rib arc fractures have been reported after vaginal delivery [42–47].

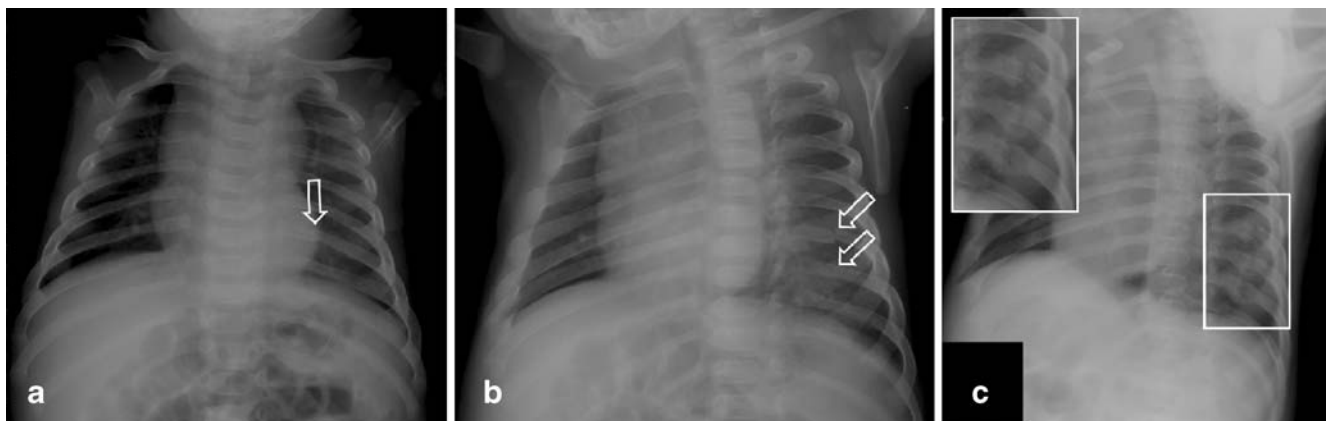


Fig. 4 A 3-month-old abused boy brought to the emergency room because of a ‘crack’ sound in the chest and irritability. **a** Initial chest radiograph shows an acute left 7th rib fracture (arrow). **b** Initial oblique images of the chest better demonstrate the left 7th rib fracture

and a possible left 8th rib fracture (arrows). **c** Follow-up oblique images of the chest obtained 2 weeks later show healing left 7th, 8th and 9th rib fractures

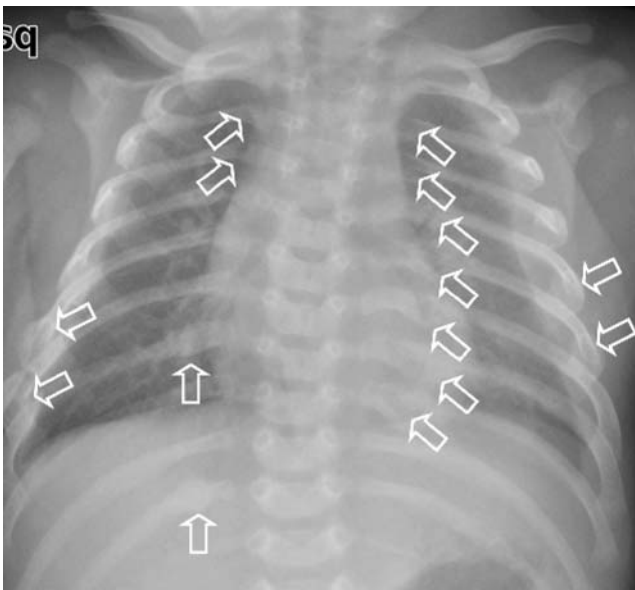


Fig. 5 A 3-month-old severely abused boy. AP radiograph of the chest reveals multiple bilateral acute and healing rib fractures (arrows). The child later succumbed as a result of the accompanying inflicted traumatic brain injury

In most cases the babies were large and the deliveries were difficult or assisted. When data of five studies on birth trauma were combined, yielding a total 115,756 live births, no single case of rib fractures was reported [48–52]. Until recently, cardiopulmonary resuscitation was not considered to cause rib fractures in normal infants. A post-mortem study of 91 infants found no rib fractures after resuscitation efforts [53]. The authors concluded that ‘when rib fractures are encountered in an otherwise normal infant, child abuse must be considered’. A recent development is the introduction of two-handed infant CPR with the hands encircling the chest [54]. This technique resembles the way perpetrators hold their children when they are reportedly shaken. Clouse and Lantz [55] reported four premature neonates (1 day to 3 months) who died after resuscitation. In all

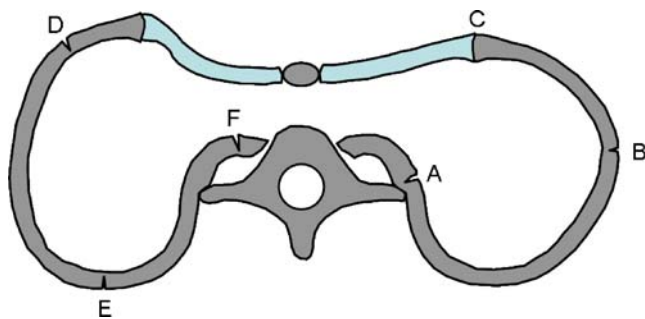


Fig. 6 Schematic representation of the chest during anterior-posterior compression. Compression can result in fractures at: *A* costotransverse process articulation, *B* lateral arc, *C* costochondral junction, *D* anterior arc, *E* posterior arc, and *F* rib head (adapted with permission from Kleinman [37])

cases abuse was excluded and autopsy showed posterior rib fractures. Rib fractures are well described in metabolic bone disease of prematurity [56]. Rib fractures can also be seen with metabolic disorders and skeletal dysplasias. In osteogenesis imperfecta, the fractures most commonly occur in the long bones, although rib fractures can be found (Fig. 7) [57].

Classic metaphyseal lesion

The CML is a highly specific finding for abuse [58, 59]. CMLs are most often found in the distal femur, proximal and distal tibia/fibula and proximal humerus (Figs. 3 and 8) [38]. CMLs are characteristically seen in infants, and above 1 year of age the finding is not specific. Caffey was the first to use the terms “corner fracture” and “bucket handle fracture” to describe the metaphyseal fracture patterns seen in abuse [60]. The radiographic appearance of the CML corner or bucket handle vary depending on the size of the fragment and the position of the extremity relative to the X-ray beam (Fig. 9) [58]. The mechanism of injury for the CML involves a shearing force; the resulting fracture line is nearly parallel to the physis centrally, but veers to undercut the subperiosteal bone collar peripherally [59]. In manual assaults, the extremities may undergo substantial torsional and tractional forces leading to these strong indicators of inflicted injury. Healing of CMLs is variable. Sclerosis may be present at the injury site (Fig. 3). If the CML is associated with significant displacement and periosteal stripping there

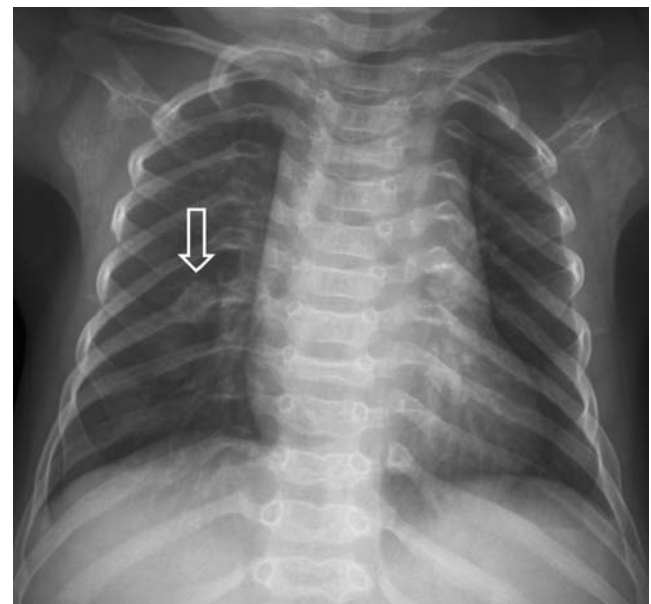


Fig. 7 A 1-year-old boy with osteogenesis imperfecta who sustained a witnessed fall from a counter. The AP chest radiograph shows a posterior rib fracture (arrow) and multiple vertebral compression fractures

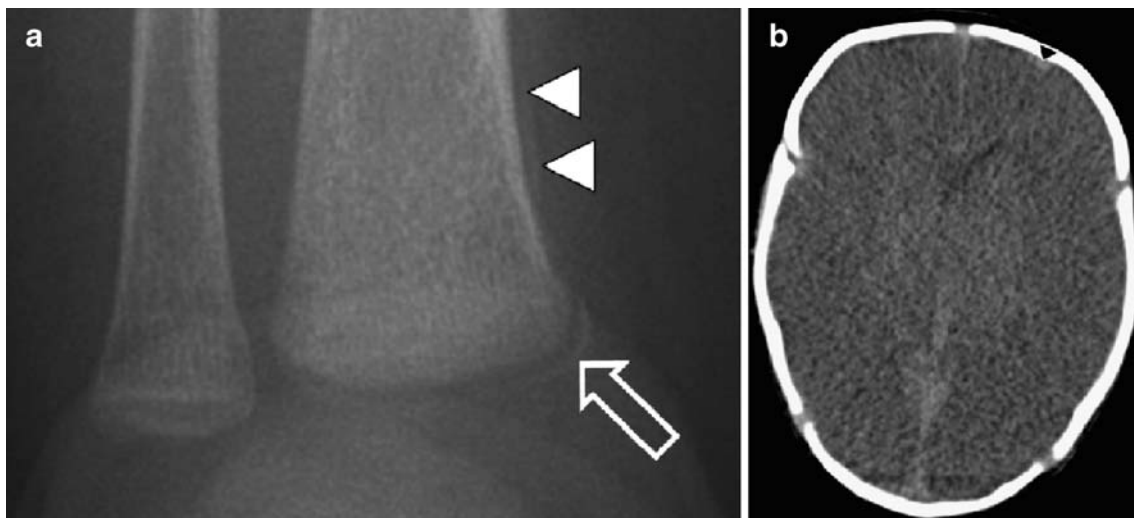


Fig. 8 A 2-month-old girl presenting with convulsions. **a** The skeletal survey reveals a right distal tibia CML (*arrow*) and subperiosteal new bone formation (*arrowheads*). **b** Axial CT image of the brain

demonstrates absence of grey–white matter differentiation (consistent with severe hypoxia) and a small subdural haematoma (*arrowhead*)

may be conspicuous sclerosis and subperiosteal new bone formation (Fig. 10). Most CMLs heal without subperiosteal new bone formation. Kleinman et al. [61] described a metaphyseal lucency that grows away from the growth plate invaginating the metaphysis that may be used to determine chronicity.

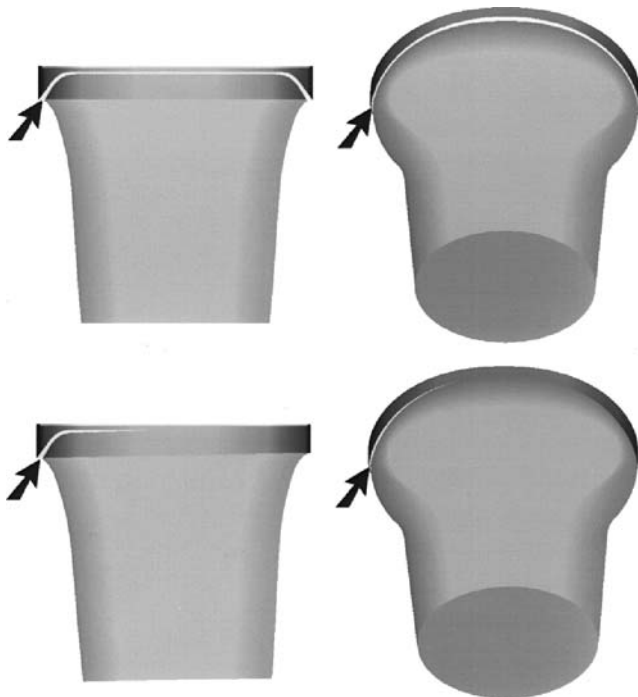


Fig. 9 Schematic representation of corner and bucket handle fractures. A tangential view results in a corner fracture pattern (*left images*). An angled view results in a bucket-handle pattern (*right images*). *Top images* show a diffuse bone injury, the *bottom images* a localized injury (reprinted with permission from Kleinman [58])

A radiographic pattern resembling the CML can be seen in other conditions. As early as 1957, Caffey noted that birth trauma can cause metaphyseal injuries [60]. In a retrospective analysis over a 22-year period, O’Connell and Donoghue [62] reported three neonates with metaphyseal fractures resembling CMLs after lower segment caesarian sections. Iatrogenic metaphyseal injuries have been seen after orthopaedic manipulation for treatment of clubfoot [63].

Metabolic bone diseases and bone dysplasias can have metaphyseal changes similar to the CML. For example, in rickets the characteristic findings of metaphyseal irregularity and physal widening may be accompanied by osseous fragments resembling the CML [58]. In most cases the diagnosis of rickets will be fairly straightforward and laboratory findings will generally differentiate between abuse and rickets. The Schmid-type metaphyseal chondrodysplasia (OMIM #156500) and the spondylometaphyseal dysplasia, corner fracture type (OMIM #184255) can have marginal metaphyseal fragments. In both dysplasias the lesions lack the typical healing pattern noted with the CML, and the skeletal survey will reveal other abnormalities associated with the given skeletal dysplasia.

Long-bone fractures

Paediatric long bone diaphyseal (shaft) fractures are a common finding in the emergency department and in general have a low specificity for abuse (Table 3). The older the child, the more likely a long-bone fracture occurred as a result of accidental trauma. Long-bone fractures in nonambulatory infants are concerning for abuse: ‘those who don’t cruise, don’t bruise’ [64] (Fig. 11). The mechanism for

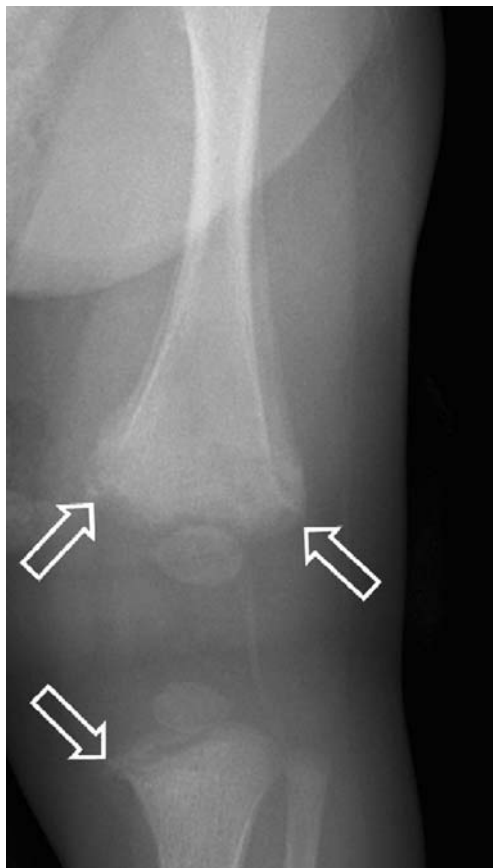


Fig. 10 A 2-month-old boy. Radiograph of the left femur shows healing with sclerosis of CMLs of the distal femur and proximal tibia (arrows). The periosteal reaction along the distal femoral shaft may be related to displacement of the fracture and periosteal stripping

the fractures in infants is usually an indirect force. The perpetrator grabs the infant by an extremity and applies a bending or rotational force that results in a transverse, oblique or spiral fracture.

Carty and Pierce [65] retrospectively studied a cohort of 467 children in whom abuse was suspected (proven in 93%); 77 children had isolated long-bone fractures. The most common sites were the humerus ($n=27$, 1 metaphyseal) and femur ($n=25$, two metaphyseal). In a post-mortem study of 31 infants by Kleinman et al. [66], of 165 fractures (skull excluded), 8 were diaphyseal fractures of the long bones.

Other fractures

A linear skull fractures can be seen after a fall from a height of 3–4 feet (about 1 m), and occasionally after a fall from a height less than this [67–69]. The younger the child presenting with a skull fracture the higher the likelihood of abuse, particularly in the absence of a history of trauma [70]. Complex and depressed skull fractures have a higher PPV for abuse than simple linear fractures [70, 71]. A relatively rare complication of skull fractures is the develop-

ment of a growing fracture (leptomeningeal cyst, traumatic meningocele, cerebrocranial erosion, cephalhydrocele; Fig. 12). When there is clinical concern for leptomeningeal cyst, a CT or MRI scan is indicated.

Pelvic fractures in young children are almost always seen following significant trauma such as motor vehicle accidents. However, there have been case reports of pelvic fractures due to abuse [72–75]. Most of these children were girls who were sexually abused. In infants, care should be taken to exclude normal developmental variants of the superior pubic ramus that may simulate a fracture [76].

A wide variety of other skeletal injuries have been described in abused children [37].

Dating fractures

O’Connor and Cohen outlined radiographic features that may be used to date fractures based on their personal experience (Table 4) [77]. Recently Prosser et al. [78] reported an analysis in which 1,556 publications were systematically reviewed. Three studies, with data on 189 children (only 56 children were younger than 5 years, the age group most vulnerable for abuse) met the authors’ inclusion criteria. The key findings of the review were quite similar to the table of O’Connor and Cohen. Prosser et al. [78] concluded that fracture dating in children is an inexact science, but that radiologists should be able to differentiate recent from old fractures.

Although estimation of fracture age should be approached with caution, experienced paediatric radiologists should be able to make informed judgements as to whether or not

Table 3 Specificity of fracture locations [77].

Specificity	Fracture
High	Classic metaphyseal lesions
	Rib fractures (especially posteromedial)
	Scapular fractures
	Spinous process fractures
	Sternal fractures
	Moderate
Low	Fractures of different ages
	Epiphyseal separations
	Vertebral body fractures and subluxations
	Digital fractures
	Complex skull fractures
	Subperiosteal new bone formation
	Clavicular fractures
	Long-bone shaft fractures
Linear skull fractures	

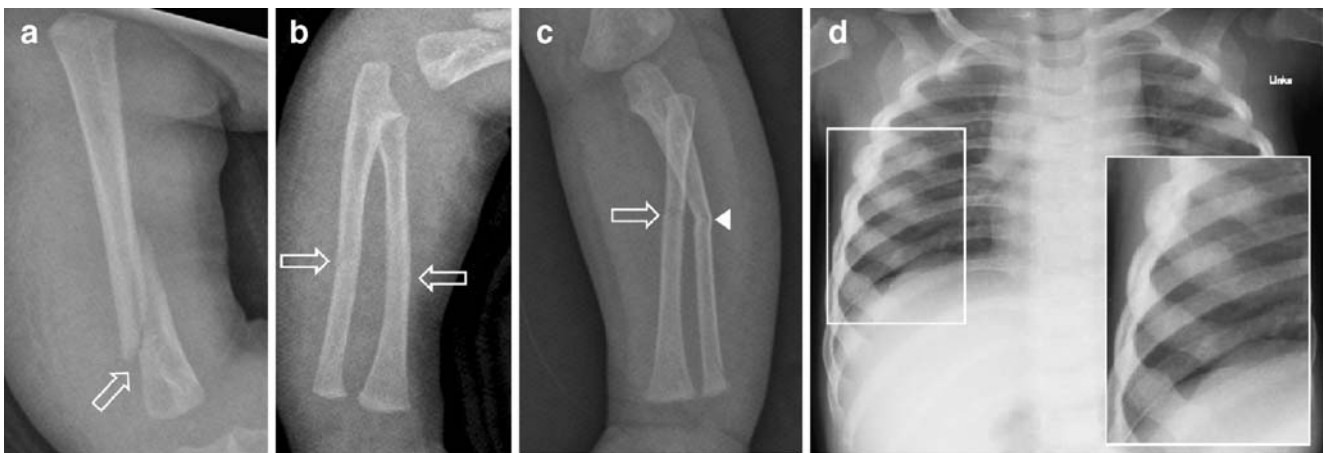


Fig. 11 A 7-month-old abused girl in whom a carer admitted to the physical abuse. **a** Radiograph of the right humerus shows an oblique diaphyseal fracture (*arrow*). **b** Radiograph of the forearm reveals transverse fractures of the mid-radius and ulna (*arrows*). **c** Radiograph

of the left arm shows a transverse fracture of the radius (*arrow*) and a buckle fracture of the ulna (*arrowhead*). **d** Chest radiograph shows multiple healing right anterior rib fractures (*see inset*)

fractures (excluding skull, spine fractures and some CMLs) are in a healing phase. Healing can usually be judged as early or mature, and when multiple fractures are present, it is often possible to state if the fractures are of similar or different ages.

Imaging plays an important role in the detection and documentation of abuse, and failure to make a correct diagnosis may have serious consequences. In a retrospective analysis Carty and Pierce [65] showed that out of 435 abuse cases, imaging initially missed 55. Of these 55 children, 6 (12%)

died and 10 (20%) survived with a handicap. Careful interpretation of skeletal surveys by radiologists with experience in paediatric imaging is mandatory in cases of suspected abuse. It is the radiologist's task to distinguish abuse from accidental trauma, normal variants, metabolic bone diseases and skeletal dysplasias. Medical professionals have demonstrated an increasing focus on the problem of child maltreatment. An encouraging sign is the recent establishment of certification of child abuse paediatrics by the American Board of Pediatrics [79]. Paediatric

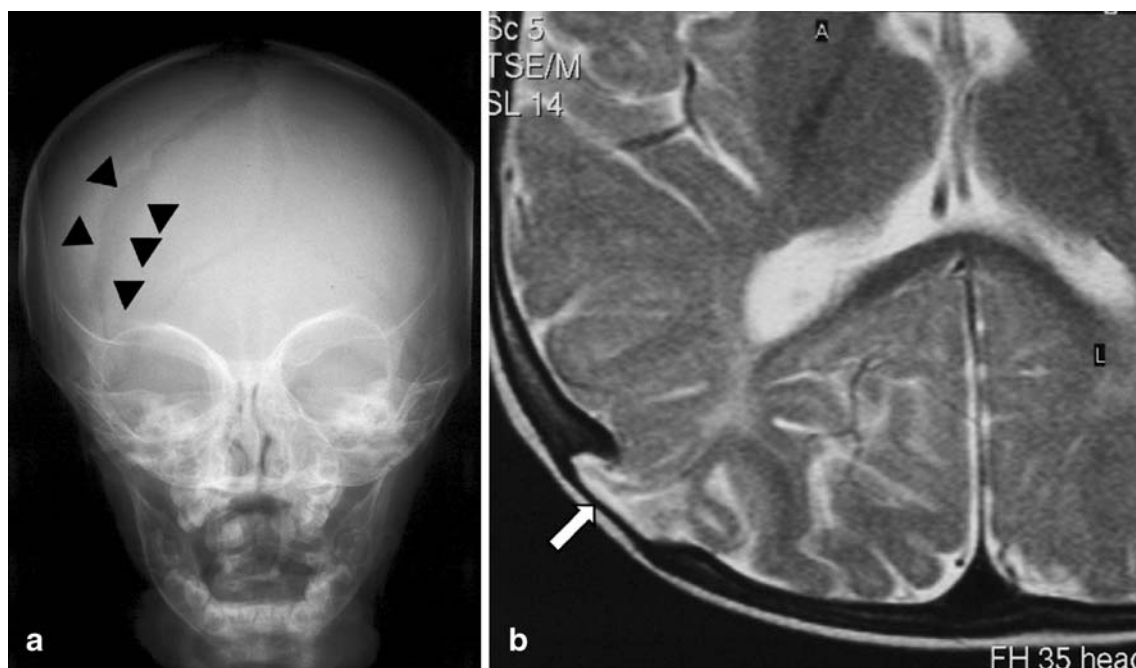


Fig. 12 A 1-year-old girl. **a** Radiograph of the skull shows a wide fracture (leptomeningeal cyst) with smooth margins (*arrowheads*). Previous radiographs showed a linear skull fracture. **b** Axial T2-W

MR image of the brain shows a dural tear and herniation of cerebrospinal fluid and brain tissue (*arrow*)

Table 4 Fracture dating on conventional radiographs^a.

Feature	Early	Peak	Delayed
Resolution of soft tissues	2–5 days	4–10 days	10–21 days
Subperiosteal new bone formation	4–10 days	10–14 days	14–21 days
Loss of fracture line definition	10–14 days	14–21 days	
Soft callus	10–14 days	14–21 days	
Hard callus	14–21 days	21–42 days	42–90 days
Remodelling	3 months	1 year	2 years to physeal closure

^a Confirmed exceptions for dating fractures on the basis of callus formation are fractures of the skull and CMLs.

radiologists are a vital resource to these clinicians and must be suitably trained and experienced in the imaging of child abuse and its imitators. An appropriate response to this critical public health concern of child abuse requires a multidisciplinary approach in which paediatric radiologists are active and important members of institutional child protection teams.

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