Are There Hallmarks of Child Abuse? I. Osseous Injuries

Alfredo Walker, Charis Kepron, Christopher M. Milroy

ABSTRACT

Fractures are commonly found in cases regarded as child abuse. The most commonly encountered fractures are to the ribs and the metaphyses. This paper examines the specificity of the classical metaphyseal lesion (CML) and rib fractures as hallmarks of child abuse. Recently, vitamin D deficiency (rickets) has been proposed as an alternative cause for the appearances typically described in CML. The literature in this area is examined. Rib fractures have also been highly associated with child abuse, particularly posterior rib fractures. As well as metabolic bone disease, resuscitation has been examined as a cause of rib fractures in young children. The current literature remains strongly supportive of rib fractures and metaphyseal fractures being indicators of child abuse. *Acad Forensic Pathol.* 2016 6(4): 568-590

AUTHORS

Alfredo Walker MB.BS FRCPath DMJ (Path) MFFLM MCSFS, University of Ottawa - Forensic Pathology

Roles: Project conception and/or design, data acquisition, analysis and/or interpretation, manuscript creation and/or revision, approved final version for publication, accountable for all aspects of the work, writing assistance and/or technical editing.

Charis Kepron MD MSc FRCPC, Ontario Forensic Pathology Service - Eastern Ontario Regional Forensic Pathology Unit and University of Ottawa - Pathology and Laboratory Medicine

Roles: Project conception and/or design, manuscript creation and/or revision, approved final version for publication, accountable for all aspects of the work.

Christopher M. Milroy MBChB MD LLB BA LLM FRCPath FFFLM FRCPC DMJ, The Ottawa Hospital - Anatomical Pathology

Roles: Project conception and/or design, data acquisition, analysis and/or interpretation, manuscript creation and/or revision, approved final version for publication, accountable for all aspects of the work, general supervision, writing assistance and/or technical editing.

CORRESPONDENCE

Christopher M. Milroy MD, 501 Smyth Road, Ottawa ON Canada K1H 8L6, c.milroy@btopenworld.com

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INTRODUCTION

Bony lesions are important findings in suspected child abuse. Both rib fractures and metaphyseal fractures have been highly associated with inflicted injury. This paper examines the literature on how specific for child abuse these entities are.

Physical child abuse can manifest in many ways; however, some of the injuries are regarded as indicative or highly suggestive of nonaccidental or inflicted injury (1). These injuries include rib fracture and metaphyseal fractures. When determining the likelihood of an injury being intentionally inflicted, there needs to be careful consideration of the associated history, the developmental capabilities of the child, and the nature of the injuries (1).

Skeletal injuries are the most common manifestation of inflicted trauma when soft tissue injuries are excluded (1). Virtually every type and location of fracture has been documented in abused children. The prevalence of fractures varies with the population studied but ranges from 11-55% in physically abused children (2-4). A large series of abuse-related fractures in all pediatric age groups reported that 76% occurred in the long bones, 8% in the skull, and 8% in the rib cage (5). Fractures that are considered highly specific for abuse are rib fractures (especially posterior fractures), classic metaphyseal lesions (CMLs), scapular fractures, spinous process fractures, and sternal fractures. Rib fractures constitute 35-60% of all fractures in infants and are more common than long bone fractures in this age group (6, 7). Postmortem radiographs of excised bones identified by a skeletal survey significantly increase the detection rate of rib fractures (6).

The immature skeletons of children younger than 18 months of age and the unique mechanisms by which they can be injured predispose them to developing unique injuries. The detection of metaphyseal and rib fractures in the younger age groups is considered highly specific for abuse. However, it is rare for older children to exhibit metaphyseal and rib fractures in the context of abuse-inflicted injury. But just how diagnostic are classic metaphyseal lesions and rib fractures for abuse?

DISCUSSION

Classic Metaphyseal Lesions: How Diagnostic are they for Child Abuse?

The most vulnerable part of the bone to injury in an infant is the distal metaphysis (also known as the primary spongiosa) where there are no chondrocytes. Fewer organized cells and less calcification make it weaker than the more proximal part of the metaphysis or the rest of the bone. The growth plates are the weakest areas in the growing skeleton and do not exhibit the same resistance to injury as do tendons and ligaments.

Childhood injury may result in the typical Salter-Harris fractures (meta-epiphyseal fractures), which often occur in an accidental manner and can be seen in 30% of all trauma-related injury. Salter-Harris type II fractures are the most prevalent (8). In mobile children, these fractures are not primarily suspicious for abuse (9).

No injury is considered more specific for child abuse than the metaphyseal fracture. Pediatric radiologist John Caffey first described this lesion in 1957 (10), which is considered virtually pathognomonic of abuse (11), but it is Kleinman and colleagues who coined the term, "classic metaphyseal lesion" (CML) in 1986 (6, 12-15).

The CML is a series of planar microfractures across the metaphysis of a long bone with the fracture line parallel to, but not involving, the physis. The fracture may not traverse the entire width of the bone (11). CMLs most commonly occur in the distal femur, proximal tibia, distal tibia, and proximal humerus (7, 11-15). They are believed to occur from repeated torsional and shearing forces (11).

The orientation of this fracture perpendicular to the long axis of the long bone infers that the precipitant force is a shearing injury that acts across the end of the bone. In this context, shearing injury is a peculiar injury for a long bone to sustain since it is the result of differential motion across the metaphysis that is not encountered in falls or blunt trauma (16, 17). The re-

quired force is believed to be typically generated by forceful manual “to-and-fro” manipulation of the extremities in a flailing manner as can occur with holding an infant around the chest and shaking it such that the limbs whiplash back and forth with generation of the required horizontal shear forces (11). As such, only children who are small enough to be violently shaken in this manner and who are unable to protect their extremities sustain this type of injury, making it almost exclusive to those under the age of two years (17, 18).

Histologically, the CML is defined as a series of microfractures in the subepiphyseal region of a long bone, the primary spongiosa, which is the most immature area of the mineralized matrix of the growing metaphysis (11) (**Figure 1**). It is this immature mineralized bone and not the adjacent cartilaginous physis that becomes disrupted to cause the lesion. The series of microfractures extend across the metaphysis to variable degrees—partially or completely. When complete, the fractured fragment can be considered as a disc or wafer of primary spongiosa that became sep-

arated from the shaft by the series of microfractures of the metaphysis. The lesion is usually thicker at the periphery and thinner centrally. As such, in its complete form, the CML is a disc of bone with a broad, thin center and a thicker circumferential rim (**Images 1 through 3**).

The orientation of the lesion is perpendicular to the long axis of the bone, which indicates that a shearing force has been exerted on the end of the bone. The calcium-containing area of the metaphysis tears away from the adjacent cartilaginous part of the growth plate. This type of injury is the result of the application of a horizontal force across the metaphysis, which does not occur in a fall or blunt trauma (16, 17). Such movement is stated to occur in shaking a child held around the chest with great speed (with flailing of the upper and lower limbs) or shaking a child whilst holding onto the hands or feet.

The acute CML is therefore a manifestation of the disruption of the bony trabeculae in the primary spongio-

Figure 1: Proposed mechanism of metaphyseal injury from shaking with diagrammatic illustration of site of fracture. Created under contract by professional medical illustrator Diana Kryski.

sa with disruption of the columns of calcified cartilage that normally extends into the metaphysis. It has been reported that it is extremely rare that concomitant disruption of the periosteum and extension into the physis occurs (11). As such, the healing of CMLs are not usually associated with periosteal reactions or callus formation and this has resulted in its postulated trau-

matic origin being questioned. The “corner fracture” usually does not show a periosteal reaction and callus formation is either lacking or limited. The long-term sequelae appear to be minimal (19). Kleinman et al. opined that it was reasonable to assume that the fundamental lesion commonly observed with metaphyseal injuries is bony and not cartilaginous (11).

Image 1: Specimen radiograph of metaphyseal fracture (arrow)

Radiologically, CMLs are referred to as “corner fractures” and “bucket handle fractures.” The concept of a corner fracture denotes a discrete, localized triangular fragment of bone that arises at the metaphyseal margin, but the term is only relevant to a two-dimensional image. There are no corners to the metaphysis in three dimensions. In three dimensions, the metaphysis exhibits a continuous rounded or ovoid contour. The corner fracture is a metaphyseal lesion that looks like the corner of the bone is fractured.

The radiological appearance of the CML correlates well with its histological appearance (**Images 1 through 5**). It is manifested as a lucent region within

the subphyseal metaphysis that extends completely or partially across the metaphysis, roughly perpendicular to the long axis of the affected bone. However, the lesion may be occult radiologically due to the rather thin nature of the central aspect of the fractured wafer of bone. The thicker peripheral rim is more readily visualized and can appear as a triangular fragment in profile, commonly referred to as a “corner fracture.” Separation of this fragment from the shaft or oblique angle viewing of it will give rise to a curvilinear appearance reminiscent of a bucket handle. The observed radiological appearance of the fracture is therefore dependent on how far across the metaphysis the fracture extends and the position of the X-ray beam (11).

Image 2: Normal metaphysis (H&E, x25).

It must be pointed out that the radiographic appearance of a discrete fragment is commonly an illusion that results from an orthograde projection of the dense periphery of the disc-like metaphyseal fragment (11). The “bucket handle” is also a function of the radiographic projection, with an oblique projection of the beam to the growth plate, resulting in its anterior and posterior margins appearing as separate radiolucencies projected over the epiphysis and shaft. A similar, non-orthograde view of the metaphyseal fragment will project one margin over the metaphysis and the other over the epiphysis to give the curvilinear bucket handle appearance. Actual displacement of a fragment with “tipping” of the fragment can result in a bucket handle appearance but displacement is not a prerequisite for the bucket handle appearance to occur.

Most bucket handle lesions are not associated with displaced fractures but rather are the result of non-orthograde radiographic projection (11). The bucket handle lesion is therefore a metaphyseal lesion that looks like a bucket handle. The appearance of a corner fracture or a bucket handle fracture depends on the angle of radiographic projection and they refer to the same fractured fragment, the classic metaphyseal lesion, which is in the shape of a disc (20). Classic metaphyseal lesions are seen in only 39-50% of abused children under 18 months of age (6, 7) but are considered highly specific for abuse. As previously stated, they are almost exclusively seen in this age group due to the unique mechanism of causation which is required (17, 18).

Image 3: Histology of acute metaphyseal fracture seen in radiograph in **Figure 2** (Trichrome, x25).

Image 4: Hemorrhage in acute metaphyseal fracture (Trichrome, x200).

Classic metaphyseal lesions have also been reported secondary to birth trauma and other iatrogenic causes (21-25). Lysack and Soboleski reported a CML of the proximal tibia and distal femur in a healthy neonate delivered by emergency C-section after a failed attempt at external turning due to breech presentation (21). O'Connell and Donohue reported three cases of CMLs of the distal femur following C-section in a retrospective analysis over a 22-year period (22). Buonuomo et al. described a neonate with multiple fractures inclusive of a metaphyseal fracture of the femur in which infantile myofibromatosis was ultimately diagnosed (26). In the case of Burrell and colleagues, a metaphyseal fracture was witnessed to be induced while putting an intravenous line into a 20-day-old

child and a "pop" was heard. Pre- and post-incident radiographs revealed a metaphyseal fracture had been inflicted during the procedure (25).

Classic metaphyseal lesion-like lesions have been described in rickets, osteomyelitis, spondylometaphyseal dysplasia "corner fracture type" and Jeune's disease (Jeune's asphyxiating thoracic dysplasia) (27). Spondylometaphyseal dysplasia "corner fracture type" is a rare skeletal dysplasia that is characterized by short stature and an aberrant waddling gait. The diagnosis is not usually made until two to three years of age when the increasingly abnormal gait is noticed. Radiologically, the most important anomalies are vertebral and metaphyseal in nature, the latter exhibiting irregular

Image 5: Acute metaphyseal fracture (H&E, x100).

margins. There may be triangular fragments that are misinterpreted as metaphyseal corner fractures by those unfamiliar with this dysplasia (28, 29).

Jeune's disease (Jeune's asphyxiating thoracic dysplasia) is associated with metaphyseal spurs, which can be misinterpreted (30). Metaphyseal chondroplasia Type Schmid is a rare autosomal dominant skeletal dysplasia characterized by irregular margins of the metaphysis. The metaphyseal defects are very similar to rickets and may be confused with metaphyseal corner fractures. Bowing and shortening of the extremities occur during growth (31, 32).

In osteomyelitis, metaphyseal abnormalities and periosteal reactions may be found (**Images 6 and 7**). They

can mimic metaphyseal and other fractures with an incorrect diagnosis of child abuse. Taylor et al. reported on a 7-month-old infant who had sustained a fracture of the proximal left humerus with no clear explanation. Child abuse was suspected but follow-up examinations revealed radiological findings that looked more like a pathological fracture and biopsy identified *Staphylococcus aureus* infection on culture (33).

Kleinman et al. investigated the radiological prevalence of the CML in infants at low risk for abuse versus those at high risk for abuse (34). They retrospectively studied 42 low-risk infants and 18 high-risk infants over a ten-year period using defined risk category criteria. Low-risk infants fulfilled the criteria of having a skull fracture without significant intracranial

Image 6: Osteomyelitis at metaphysis (HPS, x100).

injury on computed tomography (CT) and a history of a fall but no other social risk factor for abuse. The high-risk category fulfilled the criteria of significant intracranial injury, retinal hemorrhages, and skeletal injuries (excluding CMLs and skull fractures). The results were that no CMLs were identified in the low-risk group and at least one CML was identified in 50% of the high-risk group. Therefore, it was concluded that CMLs are commonly encountered in infants at high risk for abuse but are rare in cases of infants who sustained skull fractures from falls and did not have any other risk factors. That determination supported the view that the CML is a highly specific indicator of child abuse.

Although CMLs have been considered pathognomic of abuse, some radiologists believe that this lesion may be due to rickets. Although CMLs usually occur with violent shaking, any theory to explain those lesions presupposes that form of injury as causative. The predilection for metaphyseal involvement may reflect a susceptibility during a period of relative rapid growth (16) or possibly a characteristic response to the specific mechanism of injury that occurs in battered infants.

Recently, the multidisciplinary team of Ayoub et al. published a review of the publications on the histopathologic correlation of classic metaphyseal lesions,

Image 7: High power view of neutrophils in osteomyelitis (HPS, x400).

and selective studies of growth plate injury and rickets were also cross-referenced (35). This review was prompted by the results of an evaluation of 63 infants with unexplained fractures in which child abuse was alleged and in whom 67% was found to have classic metaphyseal-like lesions (36). From the clinical and radiological findings, Miller et al. concluded that most of the lesions were not of traumatic origin but likely related to underlying metabolic bone disease; namely, healing infantile rickets.

Nine studies on CMLs were identified by Ayoub et al. These studies had all been performed between 1986 and 1998 by the same principal investigator, Dr. Paul Kleinman, a pediatric radiologist at the University of Massachusetts. The largest CML series evaluated 31 infants (6), and it appeared that subsets of that study population had served as the basis for additional articles that evaluated regional CMLs. For their analysis, all nine publications collectively served as the core CML studies for Ayoub et al. It appeared that the principal investigator and colleagues were the only researchers who had reported on the histologic interpretation of radiologically determined CMLs in the literature, but their findings have yet to be independently replicated by others.

Ayoub et al. concluded that the hypothesis that CMLs were secondary to child abuse was poorly supported, as their histologic and radiologic features are similar to healing infantile rickets. They stated that until CMLs are experimentally replicated and independently validated, their traumatic origin remains unsubstantiated. This opinion was based on the fact that control subjects in the studies were inadequate, details of the determination of abuse were lacking, details about any exclusion of metabolic bone disease were lacking, and the involvement of a single radiology reviewer prevented the establishment of interobserver variability. It was also stated that the microscopy had been performed by two researchers who were not certified histopathologists and that it was not apparent that a credentialed pathologist had participated in any of the histologic analyses of CMLs. Classic metaphyseal lesions were not differentiated from tissue processing artifacts. Bleeding and callus were uncommon in spite

of the vascular nature of the metaphysis and that the conclusion that excessive hypertrophic chondrocytes secondary to vascular disruption were indicative of fracture healing contradicted the paucity of bleeding, callus, and periosteal reaction.

Ayoub and colleagues stated that several similarities exist between CMLs and healing rickets, including the excessive hypertrophic chondrocytes. They reported that CMLs have not been experimentally reproduced and are unrecognized in the accidental trauma literature. They proposed that the primary spongiosa location of the fractures was deemed to be inconsistent with the variable radiographic appearances and that bucket-handle and corner fracture CMLs resemble healing rickets within the growth plate and the perichondrial ring, respectively. Also, they indicated that the age of presentation was more typical of bone fragility disorders, including rickets, than reported in prior child abuse series. They stated that it is surprising that in the more than 25 years since the first description of classic metaphyseal lesions, independent researchers have not published replicated findings and that despite the lack of validation, the classic metaphyseal lesion has gained widespread endorsement, inclusive of the American Academy of Pediatrics. The totality of the observations that characterize the typical CML (i.e., clinically silent lesion, lack of hemorrhage, callus and periosteal reaction) raised a strong suspicion that the CML was unrelated to trauma.

In counteraction of the Ayoub paper, Kleinman's group (Perez-Rossello et al.) retrospectively reviewed the radiological and histopathological findings of CMLs in a cohort of 46 consecutive infant deaths between 1984 and 2012, which had been referred by the state medical examiner's office for evaluation of possible child abuse (37). Thirty-six infants with histological material from the distal femora were identified and further inclusion criteria consisted of 1) determination by the medical examiner that a homicidal head injury had been sustained, 2) at least one CML was evident on skeletal survey, 3) CMLs were confirmed at autopsy, and 4) non-CML fractures were also present. Nine infants who met the criteria (mean age 3.9 months; age range 1-9 months) were identified. Two pediatric

radiologists independently reviewed the skeletal surveys for rachitic changes at the wrists and knees. A single bone and soft tissue pathologist reviewed the distal femoral histological material for rickets. The result was that no radiographic or pathologic features of rickets were identified in the cohort. Their findings did not support the view that the CML was due to rickets but rather, strengthened the view that CML is a traumatic injury commonly encountered in physically abused infants. A traumatic origin for CMLs in this study was also supported by the other findings consistent with injury, inclusive of blunt head trauma and/or intracranial hemorrhage, facial bruises, frenular tears and other types of fractures. Additional support was obtained by the rare occurrences of similar-appearing fractures in other traumatic scenarios of iatrogenic origin (e.g., birth trauma, club foot casting, insertion of an intravenous line) previously mentioned above where the fractures were the result of pulling and twisting of the extremity (22-25). They also stated that the radiological appearance of the CML differs from the metaphyseal changes and fractures seen in rickets. However, it must be noted that despite an increase in the prevalence of vitamin D deficiency, rachitic changes and fractures are uncommon (38-42). The presence of multiple non-CML fractures in the infants in the Perez-Rossello et al. series was taken as further evidence to support trauma rather than rickets as the cause of the CMLs. They stated that if it were to be accepted that CML is not traumatic but rather a manifestation of rickets, then it would follow that CMLs in children are due to rickets but the failure to identify rickets in any cases in their series relegated the assertion of Ayoub et al. to nothing more than ungrounded speculation. They concluded that the notion that CMLs are not traumatic, but rather, a manifestation of rickets is without scientific support based on current research and previously published radiologic-pathologic studies of child abuse fatalities.

Jaffe opined that the metaphyseal fractures in vitamin deficiency rickets are very uncommon due to the higher plasticity of the metaphysis as a result of the protective effect of the abnormal increase in unmineralized osteoid which allows for bending of the metaphysis rather than breaking (43). In their

study of fractures in infants and toddlers with rickets, Chapman et al. reported that metaphyseal fractures in rickets occurred more toward the diaphysis, with an appearance suggestive of collapse from axial load (44). The metaphyseal fractures did not resemble CMLs and occurred in the presence of the characteristic rachitic fraying and cupping of the metaphyses. Although Chapman et al. did not find “chip” or bucket handle fractures, others have reported that discrete metaphyseal fragments may accompany other features of rickets (45).

Thackeray et al. retrospectively examined the association of CMLs with other traumatic injuries in a large data set of children under 120 months age who were radiologically examined for physical abuse (38). One hundred and nineteen (4%) of 2890 subjects were identified as having a CML and of those, 100 (84%) had at least one additional non-CML fracture, 33 (27.7%) had traumatic brain injury, 43.7% had cutaneous injuries, 10.1% had abdominal/thoracic injuries, and another 10.1% had oropharyngeal injuries. In all, 95.8% of children with a CML had at least one additional injury and 25% had three or more categories of injury. The conclusion was that CMLs identified in young children are strongly associated with traumatic injury. If the assertion of Ayoub et al. that CMLs were the result of metabolic bone disease were correct, then it would be expected that the large majority of infants with CMLs would not have other non-CML traumatic injuries. Thackeray et al. also commented that no peer-reviewed original data was provided by Ayoub et al. to support their assertion that CMLs were due to rickets.

Rib Fractures: How Specific are they for Abuse?

Rib fractures are common in cases of abusive trauma with a high specificity for abuse in very young children (46-61). They are among the most common reported fractures in physical abuse and account for 5-27% of all child abuse-related fractures (47, 48).

Barsness et al. reported a positive predictive value (PPV) of 95% that rib fractures were markers of abuse in children less than three years old (49). That PPV

increased to 100% based on all investigative and clinical data when all other causes of rib fractures could be excluded. They showed that 1) multiple fractures are more prevalent than single fractures in child abuse, 2) child abuse was likely when the fractures were located predominantly posterior and lateral, and 3) rib fractures (single or multiple) were the only skeletal signs of child abuse in 29% of their study population.

Leventhal et al. found that rib fractures were the third most common fracture in children younger than one year of age, with 69% attributable to abuse (50). Kleinman et al. had reported radiographic evidence of rib fractures in 51% of 164 fractures in 31 fatally abused children at autopsy (6). Of all rib fractures seen in child abuse, 90% occurred in those under age two (17, 51).

Kemp et al. conducted a systematic review of seven studies on abusive fractures and reported that there was a 71% probability that a rib fracture was caused by abuse, after controlling for motor vehicle crashes, violent trauma, and post surgical cases (52).

In the absence of a history of a significant accidental event, the most likely cause of rib fractures in an infant is nonaccidental injury (53). In this setting, the fractures are often multiple, of varying ages (healing or healed), located posteriorly, and associated with other features of abuse (54, 55).

Abuse-related rib fractures are frequently multiple. In their study of 336 rib fractures, Barsness et al. (49) found an average of 5.9 rib fractures in each case of abuse whilst Carty and Pierce reported that only approximately 20% of abuse-related rib fractures were singular in nature (56). This point is reinforced by the fact that accidentally incurred rib fractures are most commonly isolated in nature with Worlock et al. (57) having not found any cases with more than two accidental incurred rib fractures in 47 infants, and Barsness et al. reporting an average of 1.2 rib fractures in each case of accidental injury (49).

Rib fractures in young children are usually caused by compression and/or deformation of the chest, as can

occur with encirclement of the chest by both hands of an adult (20, 53). Compressive rib fractures are seldom accompanied by bruising but discoid bruises may be the only indicator (58). In a minority of cases, rib fractures will arise from the direct application of force onto the chest, which can occur in an accidental manner (e.g., fall onto an object) or nonaccidental manner (e.g., blow with a blunt object, punch or kick). Sudden deceleration of the chest such as can occur when the child hits a wall or blunt object can also give rise to this type of fracture. Rib fractures due to localized impact from the external application of force are mostly found in mobile children older than two years of age, and they tend to be associated with localized cutaneous bruising of the affected area whereas those due to compression of the chest are found in younger children (20).

Older children and adults sustain rib fractures from falls and motor vehicle collisions and in children less than age two years of age without congenital metabolic bone disease, it is rare to find another cause for rib fractures other than child abuse (62, 63).

Two different kinds of impacting forces are responsible for causing rib fractures. There are 1) static loading (compression) forces and 2) dynamic impact loading (direct external force application).

Analysis of ten articles from the medical literature by Williams and Connolly to arrive at a number of general conclusions on rib fractures in young children indicated the following (61): 1) the likelihood that child abuse is the cause of the rib fractures decreases as the child grows; 2) rib fractures in children under three years of age are very suspicious for child abuse; and 3) the absence of fractures on a radiograph does not exclude their presence. Fresh paravertebral-localized fractures are not always (clearly) visible on radiographs unless there is dislocation of the fracture.

Various publications state that child abuse should be considered as the cause of rib fractures when 1) there is no indication of underlying bone disease, 2) rib fractures are found after the perinatal period (although rib fractures have been reported in complicated de-

liveries), 3) there is absence of an adequate explanatory traumatic event or no offered explanation, 4) there are multiple, bilateral rib fractures, particularly in the lower ribs, on the posterior and lateral aspects, and 5) there are multiple rib fractures of differing ages (based on new bone formation) (60, 62, 63).

Mechanism of Infantile Rib Fracture

An infant rib cage possesses a degree of plasticity that allows for deformation rather than breakage of the ribs, up to a threshold point, when a compressive force is applied to it. It is this property that offers strong correlation between rib fractures in infancy and abuse as a consequence of the specificity of the injurious mechanism and the magnitude of the injurious force required.

The likely mechanism of rib fracture in infantile abuse is generally believed to be anterior-posterior compression of the chest as a result of an adult perpetrator gripping the infant around the chest with both hands and either shaking it violently or by applying sudden violent compression (17, 56, 58, 64, 65). The tight squeezing of an infant's chest produces a complex array of compressive and levering forces on all parts of the roughly tubular rib cage.

The compressive forces are exerted both anteriorly and posteriorly, and results in buckling and impaction of the inner cortex with distraction of the outer cortical fracture margins. The posterior rib arches also lever over the transverse processes of the vertebral bodies to cause ventral and often complete cortical disruption (6). This levering action on squeezing of the infantile chest is what makes posterior rib fractures highly specific for inflicted injury, as it is not a feature when most other traumatic or iatrogenic forces are applied. Injury to the costotransverse process articulation, the posterior arc, and rib head can result.

Shaking produces a complex combination of both anterior-posterior and lateral compressive forces that produces both compression and tension in the rib cage. Worn and Jones opined that the shaking mechanism involved an initial potentially injurious quasi-stat-

ic loading of the ribs in the gripping phase followed by a dynamic shaking phase, with the shaking phase further compounding the pre-loaded state (53). It is believed that the shake mechanism produces an initial level of strain in the ribs during the grip phase, which is followed by a periodic high rise in strain during the dynamic shake phase (66, 67).

Site of Rib Fracture

In infants, the position of the rib fracture is important for the correct interpretation of its significance (55) (**Figures 2 and 3**). Posterior rib fractures consist of fractures of the costotransverse process articulation (CPA), the posterior arc (PA) and the rib head (RH). Lateral rib fractures consist of fractures of the lateral arc of the rib. Anterior rib fractures consist of fractures of the anterior arc of the rib and the costochondral junctions. A number of studies attempted to establish a link between certain rib fractures and abuse (68). Posterior rib fractures are considered highly specific for abuse (17, 69-72). Ng and Hall reported that in a study of over 75 children with suspected abusive fractures, over 95% were located posteriorly or laterally (73). Reece stated that over 80% of abusive rib fractures were posterior and that lateral rib arch fractures were also common in abuse (74). Barsness et al. showed that approximately 43% of abusive rib fractures were posterior and approximately 35% were in the lateral arc (49). Posterior rib fractures are most prevalent between the fourth and ninth ribs. Lateral rib fractures are more prevalent in the lower aspect of the chest. Injury to the anterior costochondral junction is usually between the second and ninth ribs. Child abuse is most likely when there are flail segments due to multiple ribs with multiple fractures at different locations in the same rib (75).

Fractures of the First Rib

The first rib is the shortest, the thickest and the most curved and requires considerable force to fracture it. In their analysis of 35 children under four years of age with rib fractures over a two-year period to determine if fractures of the first rib were an indicator of abuse, Strouse and Owings identified rib fractures in 12 chil-

Figure 2: Anatomy of a typical rib and relevant vertebral landmarks. Created under contract by professional medical illustrator Diana Kryski.

Figure 3: Classic sites of rib fracture from application of external force. Created under contract by professional medical illustrator Diana Kryski.

dren with three abused children having fractures of the first rib, bilaterally in one case, and two additional cases of fractures of the first rib were identified outside of their study period. They concluded that fractures of the first rib are very suspect for child abuse since a great deal of force is required to fracture them (76).

Acute Rib Fractures

Acute rib fracture may not be detected on skeletal survey for a variety of reasons and multiple projections may be required to completely exclude them. These may include a fracture line that is oblique to the X-ray beam, superimposition of a transverse process over a posterior rib fracture site, and nondisplacement of the fracture as a result of preservation of the periosteum (70). Oblique radiographs of the chest should be performed to increase the likelihood of detection. That said, fresh/acute rib fractures without surrounding tissue reaction and new bone formation may not be identified on skeletal survey even when the images are interpreted by pediatric radiologist specialists with an interest in nonaccidental injury. The majority of these fractures would only be identified at autopsy on detailed examination of the ribs (55), thereby accounting for the more frequent detection of fresh rib fractures at autopsy compared to imaging (77). Histologically, a small amount of local hemorrhage will be evident in the absence of an associated inflammatory response or new bone formation.

Rib Fractures and Resuscitation

Cardiopulmonary resuscitation (CPR) related rib fractures in infancy are rare and have been reported in less than 1% of witnessed CPR (58, 60, 64, 65, 73-76, 78). This is in stark contrast to the reported rates in adults of 16-80% and 10-80% (60, 73). They can be located anteriorly or anterolaterally with bilaterality.

A systematic review of six publications on resuscitation and rib fractures yielded a prevalence of 0.3% (3/923), which were all anteriorly located (79). A greater incidence of CPR-related fracture was detected at autopsy (2%) as a result of detailed examination

of the ribs, inclusive of stripping of the parietal pleura (55). Ironically, resuscitation-induced rib fractures were more frequently caused by physicians than in nonmedical personnel (64). Although resuscitation is frequently invoked to explain posterior rib fractures in cases of suspected child abuse (65), literature is lacking to support this. Spevak et al. argued that the excessive levering of the ribs over the transverse process, which is required to effect posterior rib fractures, was not possible during resuscitation when chest compressions are conducted on an infant who is laid supine on a supportive, flat surface which would restrict that motion. At the time of their publication, the authors were referring to the “two finger” method of chest compression in which two fingers of one hand (index and middle fingers) are placed over the sternum with the application of a force at right angles to the chest through then, with the infant laid on a flat surface with the other hand positioned on the infant’s head to provide support (78). This was the recommended method of chest compression during infant resuscitation at that time (80).

The “two finger” method was replaced with the “two thumbs” method in 2000 (80-82). The “two thumbs” method involves the placement of both hands on either side of the chest to encircle it, such that the thumbs are over the sternum on the front of the chest and the fingers are along the spine on the back of the chest to provide stability posteriorly. The chest is then compressed in the anterior-posterior direction by the thumbs and laterally by the hands. This method is preferred as it has been proven to produce improved hemodynamic states in experimental models (83) but has a striking resemblance to the method of injury commonly believed to be attributable to abusive compression or shaking of an infant.

Rib fractures have been reported with the new method (84). A 2011 article indicated that CPR-associated rib fractures had become more frequent in infants since changes in CPR techniques were introduced in 2005 (85). The authors studied 571 infants subjected to resuscitation between 1997 and 2008. The difference in annual frequency of CPR-related fractures between the periods before and after revision of the pediatric

CPR guidelines was statistically significant. A 2014 study looked at CPR over a ten-year period since the introduction of the new technique in 2000 (86). It identified 80 infants with 546 chest radiographs and 50 of those infants had undergone CPR immediately after birth. Data concerning the length of CPR was available for 41 infants. The mean length of CPR was 11 min (range: 1-180 min, median: 3 min). On average, there were seven radiographs per infant. A total of 39 infants had a follow-up radiograph after at least ten days. No rib fracture was visible on any chest X-ray.

Overall, the data indicates that resuscitation-induced rib fractures in infants are highly unlikely due to the relative compliance of the ribs, which have a tendency to bend rather than break when subjected to deformations that would result in fractures in adults. However, the likelihood significantly increases if there is underlying fragility of the ribs from bone disease (e.g., rickets, osteogenesis imperfecta, osteopenia, bone dystrophy).

Birth-Related Rib Fractures

Skeletal injury as a result of delivery may occur in an otherwise normal child but is extremely rare. Breech delivery is the most noteworthy of birth-related causes. Clavicular and rib fractures can occur, with clavicular fractures being the most prevalent. No rib fractures were found by Rubin in a prospective study of 15 435 births (87). Forty-three cases had a clavicular fracture, seven had a humeral fracture, and a single skull fracture was identified. A retrospective study of over 20 000 births did not identify any rib fractures (88). Bhat et al. also did not identify any rib fractures in their study of 34 946 live born infants (89). Only a limited number of case reports of rib fractures in newborn infants exist in the medical literature (59, 90-97). Rib fractures due to delivery are unlikely in normal term birth without supporting features of a traumatic delivery (cephalic hematoma, hematomas, swelling and subcutaneous crepitus). When they did occur, the associated rib fractures were multiple but unilateral and posterior.

Multiple Unexplained Fractures in Various Stages of Healing

Fractures in various stages of healing are suspicious for abuse, as they suggest injury on more than one occasion (5, 98, 99). Although an infant's presentation with multiple unexplained fractures in various stages of healing usually invokes an initial diagnosis of child abuse as the cause, it must be borne in mind that underlying metabolic bone disease is possible and attempts must be made to assess for these. Infantile rickets and osteogenesis imperfecta must be considered and attempts made to exclude them.

Cannell and Sanchez stated that in clinical medicine, child abuse specialists consider one unexplained fracture as possible but consider abuse as the only valid explanation when two or more fractures (especially of differing ages) are detected radiologically without adequate explanation (100). The position of the American Academy of Pediatrics' Committee on Child Abuse and Neglect (AAPCOCAN) is that these fractures always indicate abuse (101). Wei et al. had reported eight cases of posterior rib fractures in hospitalised infants who were radiographed prior to discharge from hospital, thus excluding the possibility of parental abuse (102).

In a critique of the seminal article of Kempe et al. on the battered child syndrome, Ayoub reported that one of the radiographs in the Kempe article showed classic bowing of the legs which is diagnostic of rickets (103, 104). Cannell and Sanchez indicated that the seminal paper, which initiated the position that multiple infantile rib fractures in various stages of healing was always due to abuse, was fatally flawed. They opined that medical science cannot always say that multiple infantile rib fractures in various stages of healing is from child abuse.

Several authors have written that child abuse and healing infantile rickets are readily confused on imaging. Radiologists Keller and Barnes wrote that infantile rickets is common and readily misdiagnosed as child abuse (105). Others have stated that healing infantile rickets gives a much different radiological

appearance than classic rickets (37). Few dispute that rickets is becoming more common as a result of vitamin D deficiency and others have stated that little is known about healing infantile rickets in the modern age (106-108). Ayoub et al. stated that radiologists in training no longer study rickets. It was also reported that a search of the National Library of Medicine for “healing infantile rickets” did not reveal any useful references except for the single paper by Ayoub et al., which surmised that healing infantile rickets might be quite common. A study out of the United Kingdom in 2010 discovered that approximately one-third of modern day fetuses have rickets as demonstrated by the classic finding of widening of the end of the femur as detected on uterine ultrasonography (108).

Cannell and Holick reported that radiology misses biopsy proven rickets 80% of the time (normal radiology reported) and therefore, the gold standard for the diagnosis of rickets is histology, but this view is not widely accepted by radiologists (109). Although it was emphasised that the reporting pathologist must be knowledgeable about infantile rickets, it is prudent to highlight that loss of mineralization of bone to the order of 20-30% must occur for the demineralization to be detectable on plain radiography.

A current textbook of orthopedic pathology makes the point that tissue examination is required in subtle cases (on radiology) and further added that a bone biopsy is indicated in every patient in whom a cause of the fracture is unexplained (110). However, it is known that bone biopsy is seldom performed in the clinical evaluation of infants of suspected abuse (109).

Osteogenesis imperfecta (OI) must also be considered and appropriate ancillary testing for the genetic mutations of the deficient collagen coding genes (*COL1A1* and *COL1A2*), which are responsible for 90% of cases, must be entertained. At postmortem, collection of samples for fibroblast culture (skin biopsy) and DNA sequencing is indicated. It must be noted that 10% of cases of OI are not detectable by the current methods of genetic testing (111).

CONCLUSION

The investigation of sudden unexpected or unexplained deaths in infants and young children should always include postmortem radiological surveys of the body. Pathologists are in the advantageous position of being able to examine bones microscopically and not have to rely on radiologic images alone. In the autopsy workup of infant with radiological suspicion of abusive bony injury, bones with identified or suspected injuries seen on skeletal survey should be excised and examined further. The contralateral bone should also be examined as a control. These should be submitted for histologic examination. The use of controls helps to determine artifacts and normal variants of bone. Sections of undecalcified bone can be stained and examined for metabolic bone disorders, this is not easily available and can be expensive to perform but this is not required to examine routine fractures.

While there have been challenges to metaphyseal fractures and rib fractures being caused by trauma rather than underlying bone conditions, the pathologist can examine the bones histologically to determine the presence or absence of metabolic bone disease, along with additional targeted genetic studies for the same. At present, the current literature supports these lesions as being highly associated with inflicted injury.

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