Fracture Evaluation in the Pediatric Autopsy: Basic Pathology with Radiologic Correlation

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The importance of radiographs

Negative:
- Provide assurance to family, friends, and caretakers
- An extra measure of comfort to pathologist

Positive:
- Guide pathologist to areas not normally examined
- Effectively rule out the diagnosis of SIDS
- Provide graphic demonstration of injury

Why bother finding fractures?

- Fractures are evidence
- Radiologic-pathologic correlation
- Confirm multiplicity and/or chronicity of injuries
- Assess stage of healing
- Confirm/refute bony dysplasias
- Some fractures have a very high specificity for inflicted injury

Steps in the Forensic Pediatric Autopsy

- Skeletal survey
- External examination
- Clothing examination
- Internal examination
- Cultures (if needed)
- Collect toxicologic specimens
- Consider saving frozen tissue
- Collect material for metabolic screen (if needed)
- Remove eyes (if needed)
- Soft tissue exam
- Resect all abnormal bones
- Complete histologic examination

What injuries should the traditional autopsy find?

- External injuries
- Brain, eye, and visceral injuries
- Bone injuries
  - Skull
  - Ribs
  - Spinal column

What are we missing?

Specificity of Infant Fractures for Infliction

(from Kleinman, 1998)

HIGH	MODERATE	LOW
• Ribs (especially posterior)	• Multiple	• Subperiosteal new bone
• Metaphyseal	• Different ages	• Clavicle
• Scapula	• Epiphyseal	• Long bone shaft
• Spinous process	• Vertebral body	• Linear skull
• Sternum	• Digital	
	• Complex skull	

Since the only bones normally examined at autopsy are the ribs, cranial bones, and (to some extent) the spinal column and pelvis, radiographs become critically important in the evaluation of the extremities

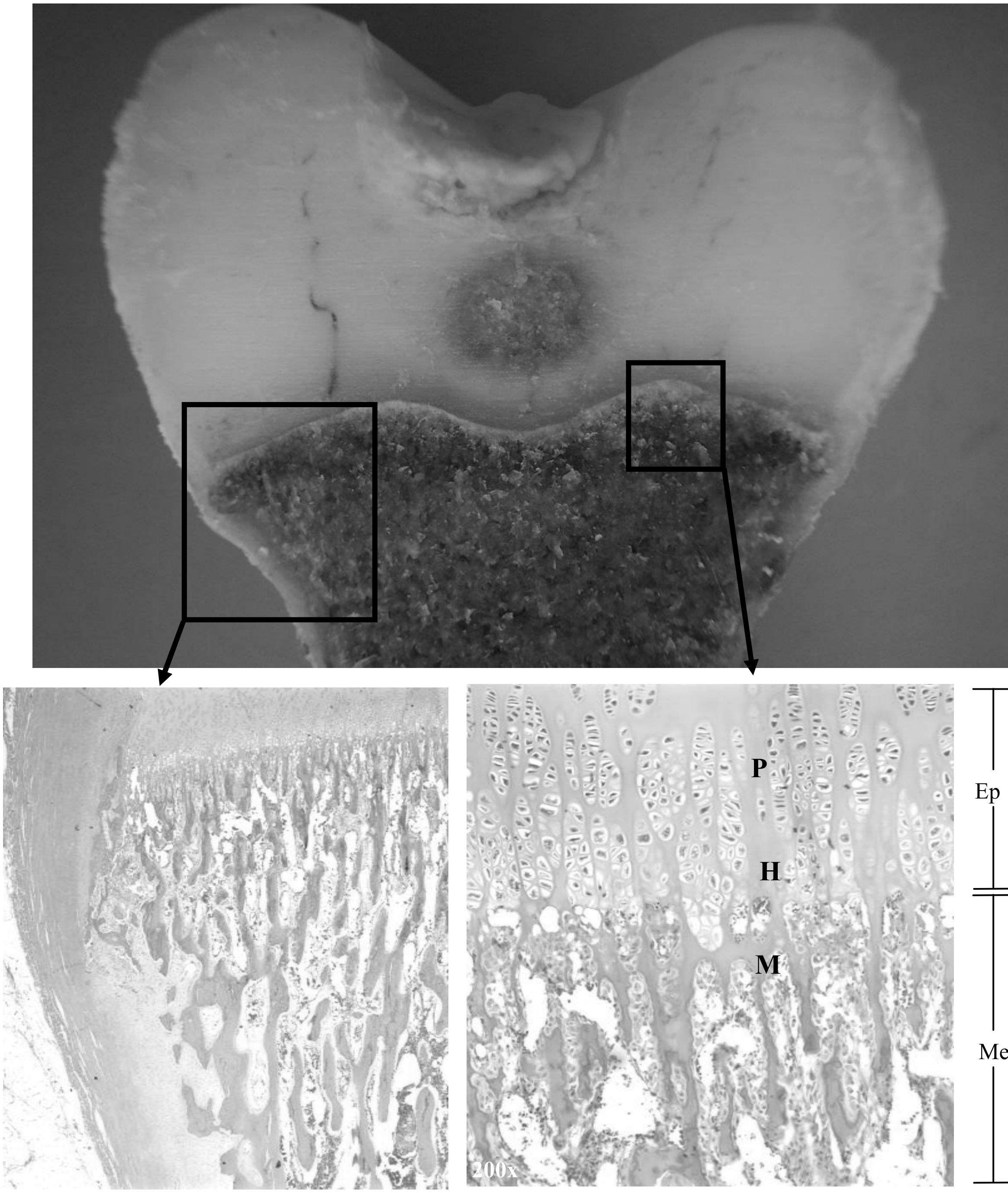
Why autopsy radiographs matter

- Provide compelling, understandable evidence
- Serve as an adjunct to autopsy to lessen chance of missed injuries
- Allow radiologic-pathologic correlation
- Direct pathologist to injuries that would otherwise go undetected
- Provide assurance to family, friends, and caretakers
- An extra measure of comfort to pathologist

The Classic Metaphyseal Lesion

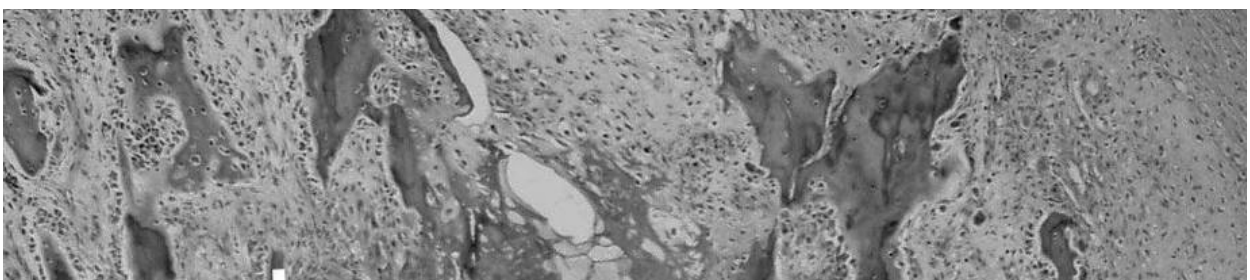
Of all the fractures described in child abuse, none appears more specific than the metaphyseal fracture, first described by the eminent pediatric radiologist John Caffey. Kleinman et al introduced the term *classic metaphyseal lesion* (CML) to describe the injury. CMLs are highly specific for abuse, although they are observed in half or fewer of cases. CMLs most often occur in the distal femur, proximal tibia, distal tibia, and proximal humerus, and are seen almost exclusively in children less than 2 years old. The lesion is a series of microfractures across the metaphysis, roughly parallel to the physis, although it may not travel the entire width of the bone. The long-term sequelae of CMLs appear to be minimal. Rarely, CMLs have been described in settings other than abuse, such as in accidents, caesarian sections, or during physical therapy.

The work of Kleinman et al documented the histologic appearance of the CML as a series of microfractures in the subepiphyseal region of bone; this region is the primary spongiosa, and it is the most immature area of the mineralized matrix in the growing metaphysis. When complete, the fracture fragment may be conceptualized as a wafer or disk of bone separated from the shaft by the series of metaphyseal microfractures. The CML, when complete, is a disk with a broad, thin center and a thick circumferential rim. Periosteal disruption and extension into the physis are relatively rare. When the acute CML heals, there is an increase in the number of regional osteoblasts and osteoclasts, as well as fibrin deposition. There is typically no periosteal disruption, and little or no callus is formed. However, changes at the physis subjacent to a CML may indicate a subacute CML. The normal physis is a disk of chondrocytes that extends in columns toward the metaphysis. Uninjured regions of the metaphysis-physis complex will grow and mineralize normally around the fractured area; however, the area distal to the CML does not mineralize normally, and the chondrocytes of the physis persist abnormally. Histologically, this pattern appears as an area of hypertrophic chondrocytes.

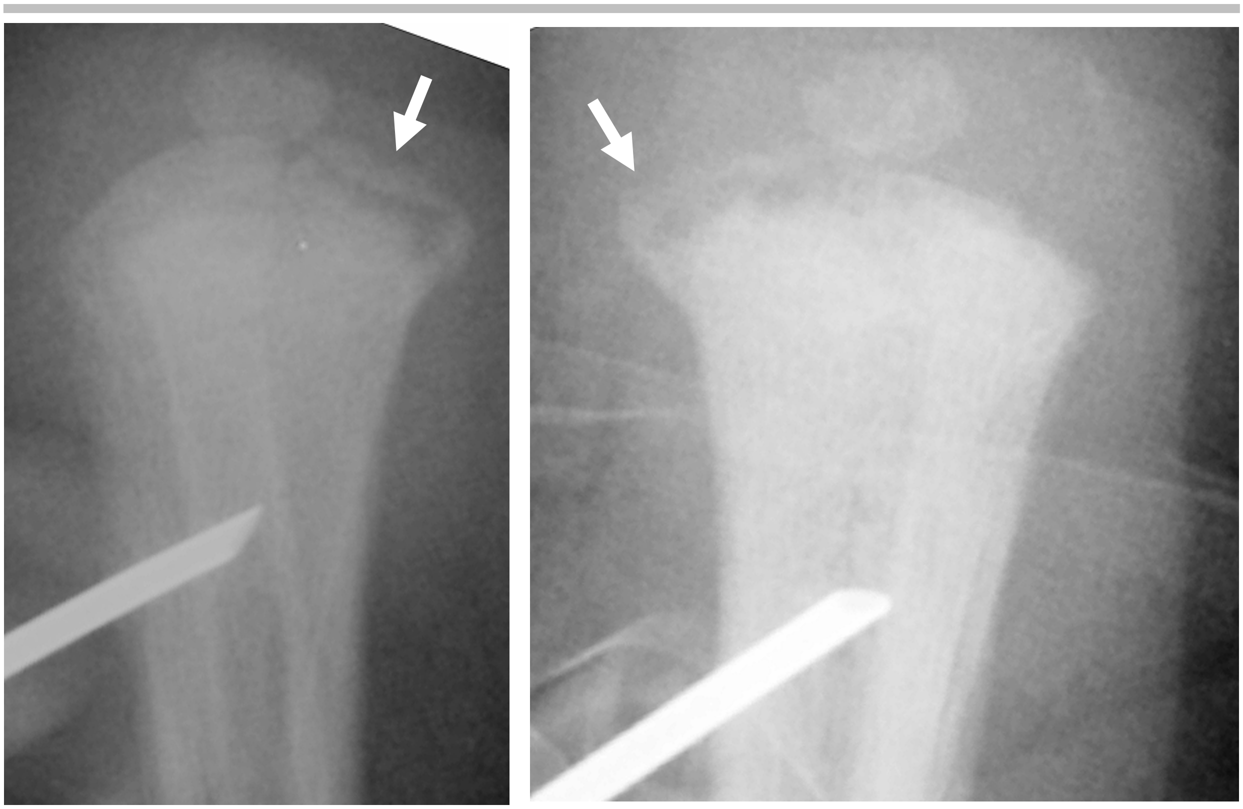


Normal distal femur from a 16-week-old. High magnification (right lower photo) shows the orderly progression in the epiphysis (Ep) and Metaphysis (Me) from proliferating (P) to hypertrophying (H) to mineralized (M) chondrocytes.

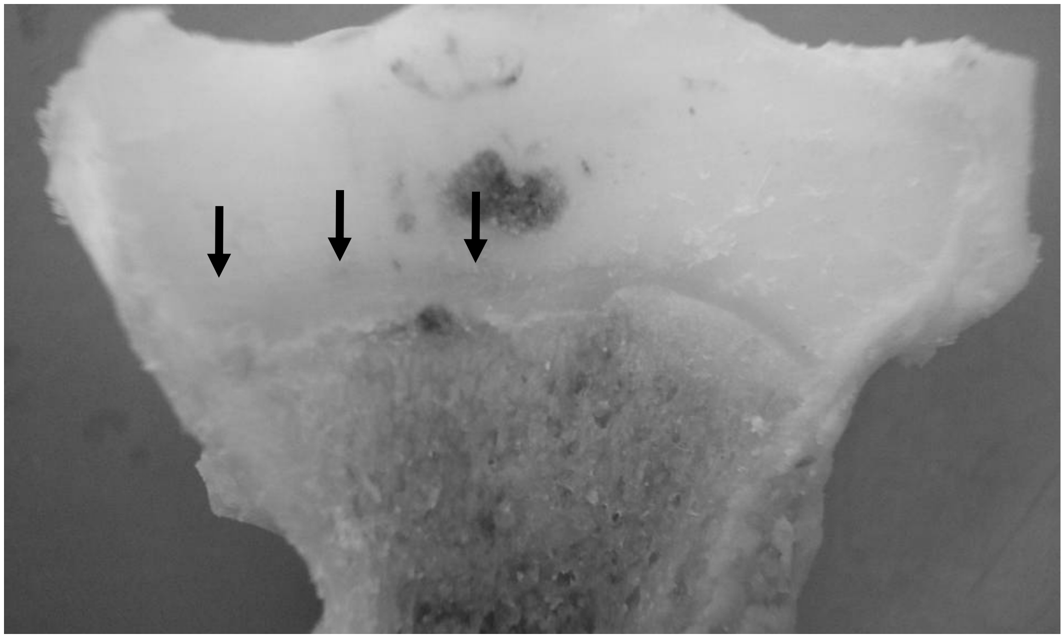
Radiographic and gross appearances (above) of metaphyseal lesion in the distal femur of a fatally battered 7-week-old. The fracture line (below, white arrows) is through the primary spongiosa; hypertrophied chondrocytes (below, black arrow) persist abnormally in the fracture site, indicating that the injury is subacute.



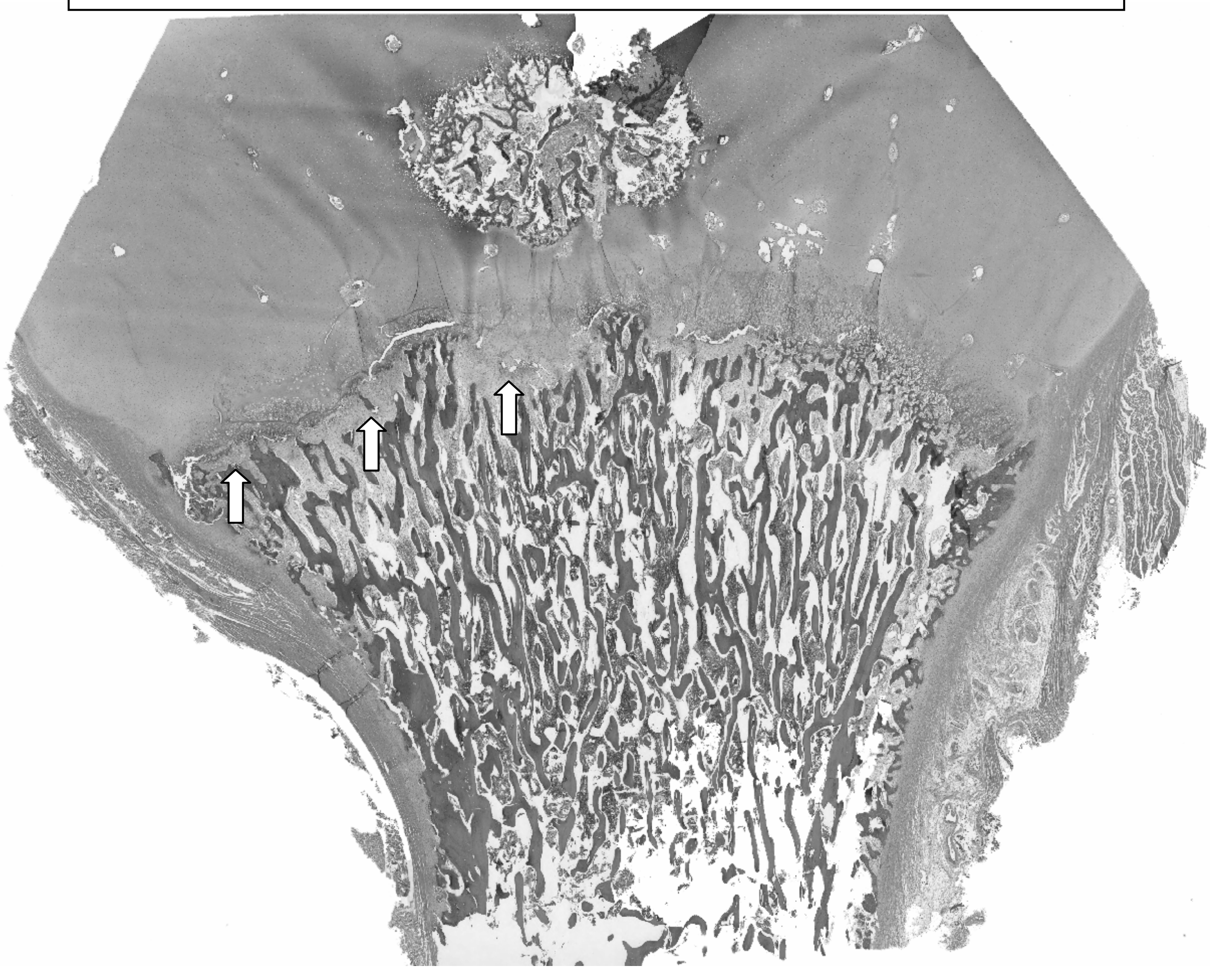
Classic metaphyseal lesion in the proximal tibia of a fatally battered 8-week-old. The “corner fracture” appearance is readily seen by radiography (white circle), and confirmed histologically (black arrows).

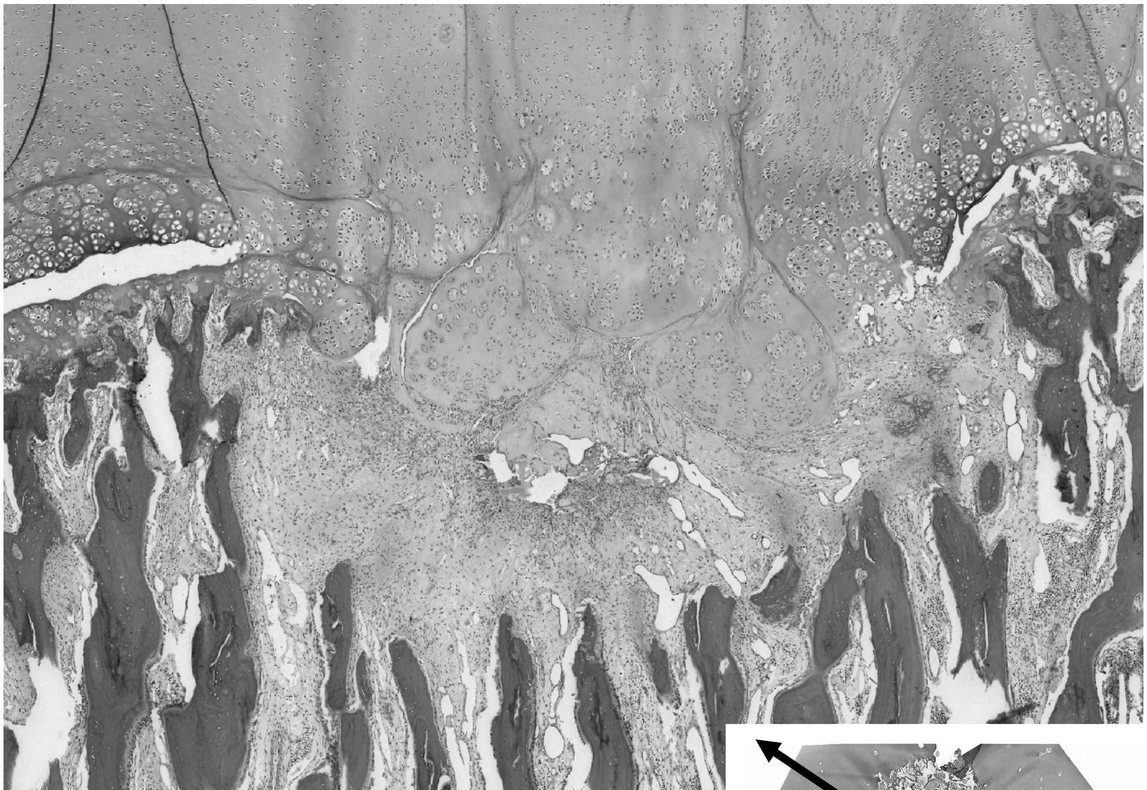


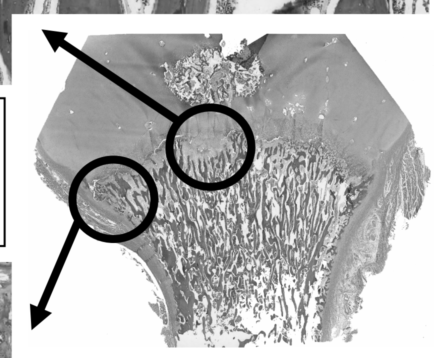
Radiographic appearance of metaphyseal lesions in the proximal tibias of a smothered 4-month-old. The radiograph resembles a “bucket handle” (white arrows).



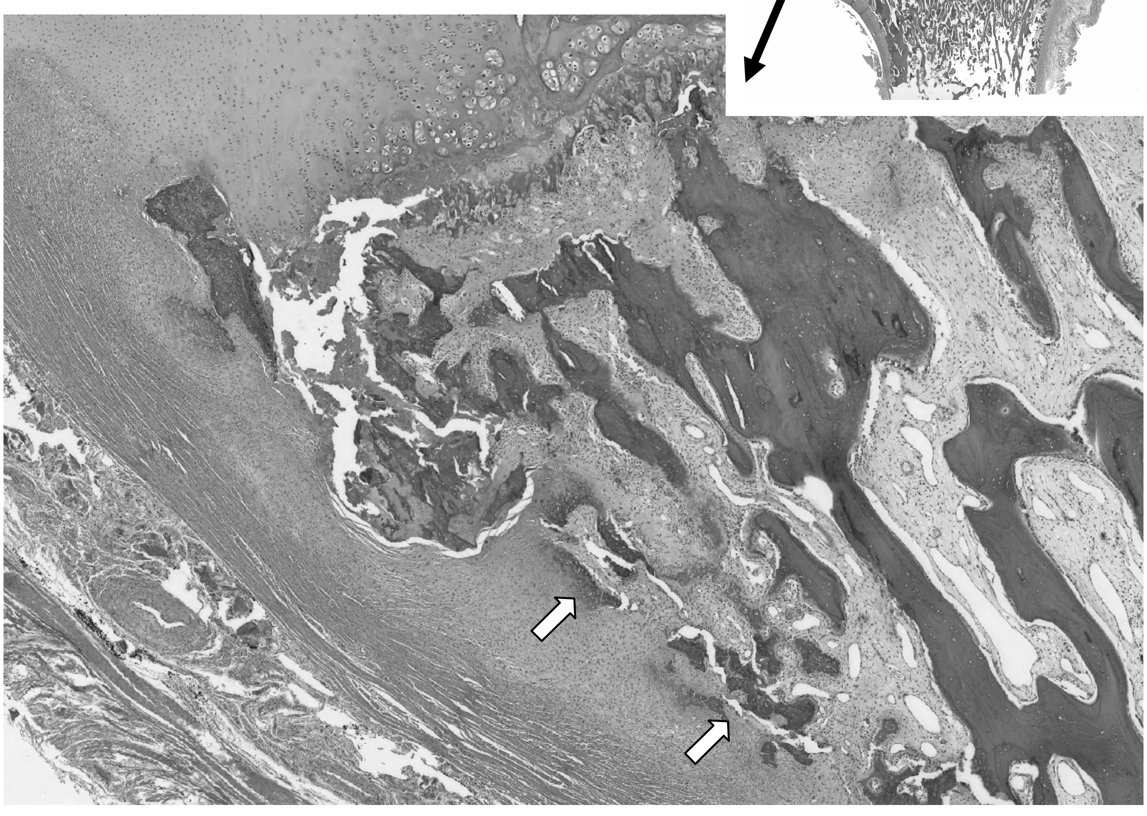
Gross and microscopic appearance of the left metaphyseal lesion from the bottom of the previous page. Compare the grossly ragged appearance of the physis (black arrows) to a normal, smooth physis (page 4). The loss of the primary spongiosa and abnormally persistent cartilage (white arrows) can be seen on the whole mount.

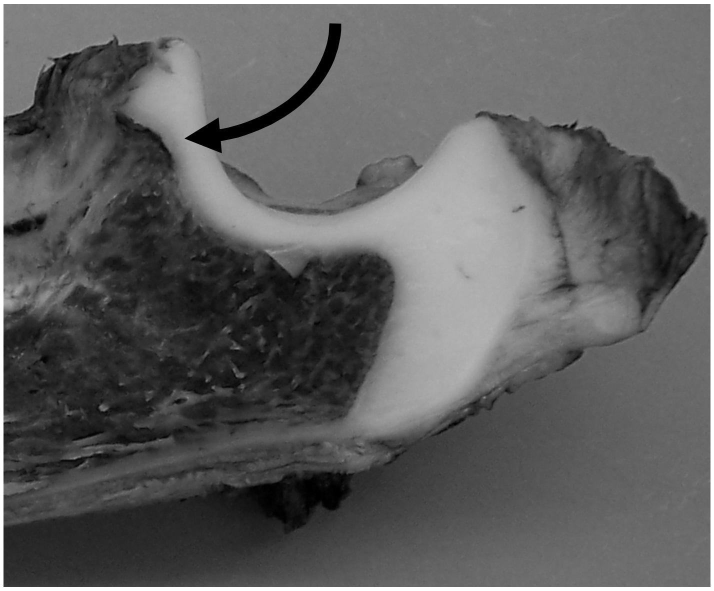
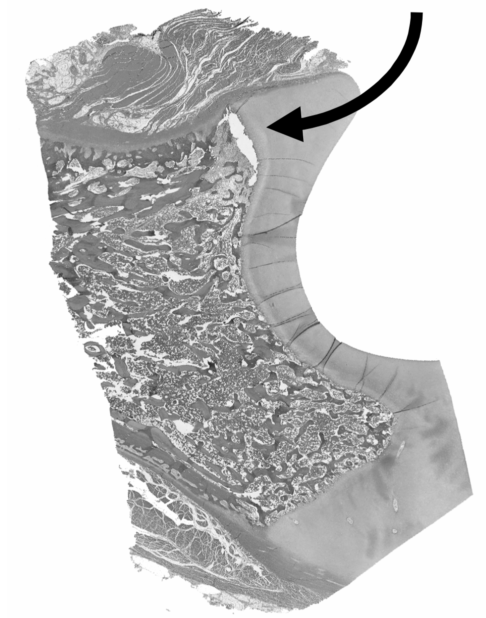




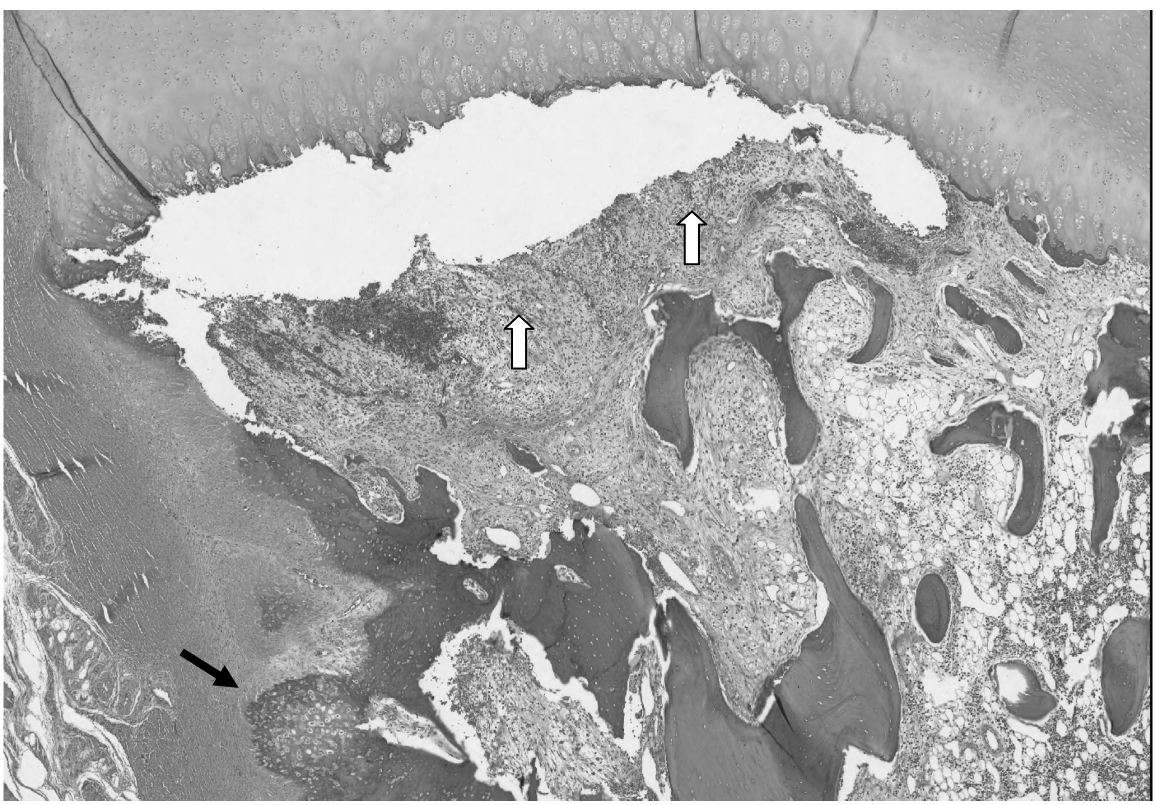


Microscopy of the metaphyseal lesion from the bottom of the previous page. Proliferating cartilage persists centrally (above) and peripherally (below). Reactive subperiosteal bone is also seen (below, white arrows).



Gross and whole mount (curved arrows) view of a metaphyseal lesion in the ulna of a fatally abused 13-month-old. Below, granulation tissue is seen in the fracture site (white arrows), along with some new bone formation on the adjacent cortex (black arrow).



Rib Fractures

Rib fractures occur in older children and adults as a result of trauma such as falls and motor vehicle accidents. Outside the setting of abuse, rib fractures are distinctly unusual injuries in infants without metabolic bone disease. A very tight hold around the infant chest by adult hands generates substantial squeezing force on the immature skeleton and may result in fractures of the anterior, lateral, and posterior aspects of the rib. In rare cases, rib fracture (including posterior rib fracture) may be produced by birth trauma.

Of course, medical conditions predisposing to fracture should be considered where appropriate. The most common underlying bone diseases likely to occur are metabolic bone disease of infancy (rickets of prematurity), rickets, and osteogenesis imperfecta. Risk factors for the former include delivery at <28 weeks, necrotizing enterocolitis, late establishment of enteral feedings, chronic lung disease, and use of furosemide (Bishop et al).

Maguire et al (2006) published a review on CPR and rib fractures spanning medical literature from 1950 through October of 2005. They concluded that rib fractures related to CPR (three of 923 children) were most likely to be anterior and could be multiple. They did not find posterior rib fractures related to CPR, noting “sound biomechanical reasons for this.” They did note that weaknesses in the literature were likely related to the degree to which rib fractures were actually being sought, radiographically and/or at autopsy.

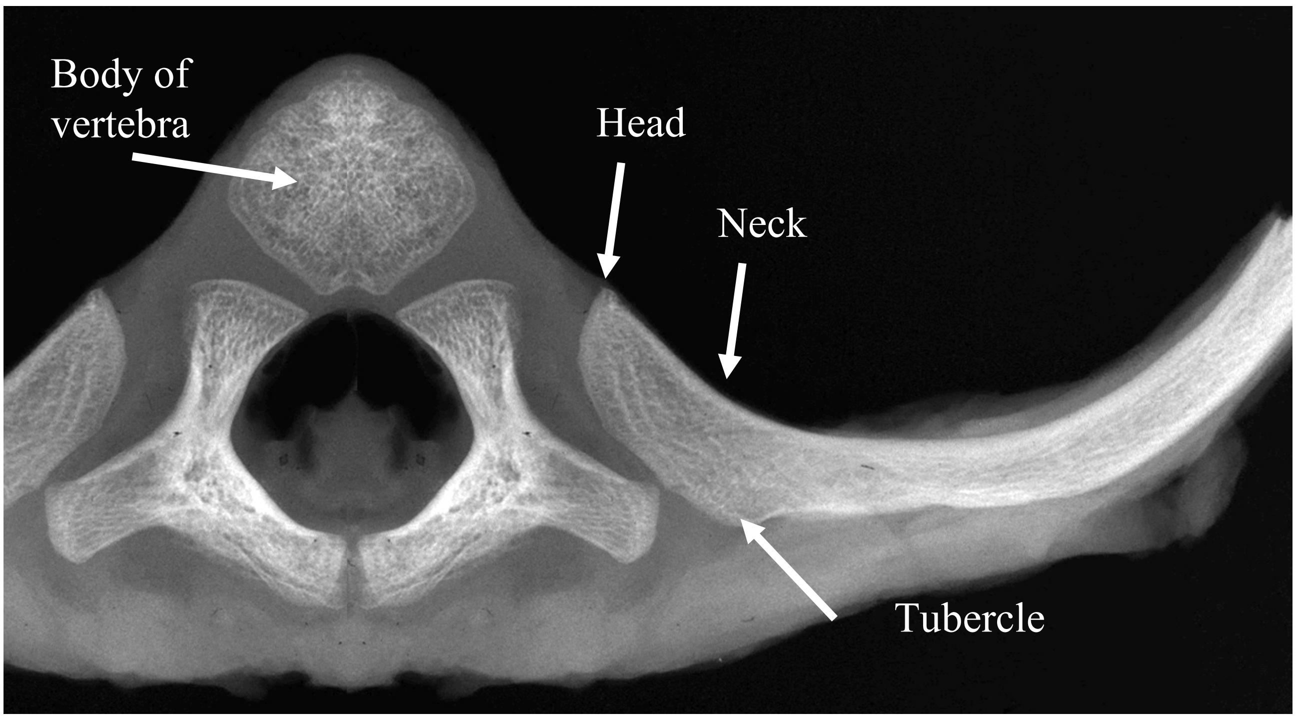
A recent study by Dolinak (2007) suggests that anterolateral fractures from CPR may be more common in infants than previously appreciated; such fractures would not be expected to be visible on radiographs. In this study, eight of 70 autopsies in infants—with no autopsy or historical evidence for injury—were found to have anterolateral rib fractures. Most of these involved multiple ribs, in many instances bilateral. In all cases, the fractures were noted to be “subtle,” with “little if any associated blood extravasation,” and “would have been easily missed had the parietal pleura not been stripped.”

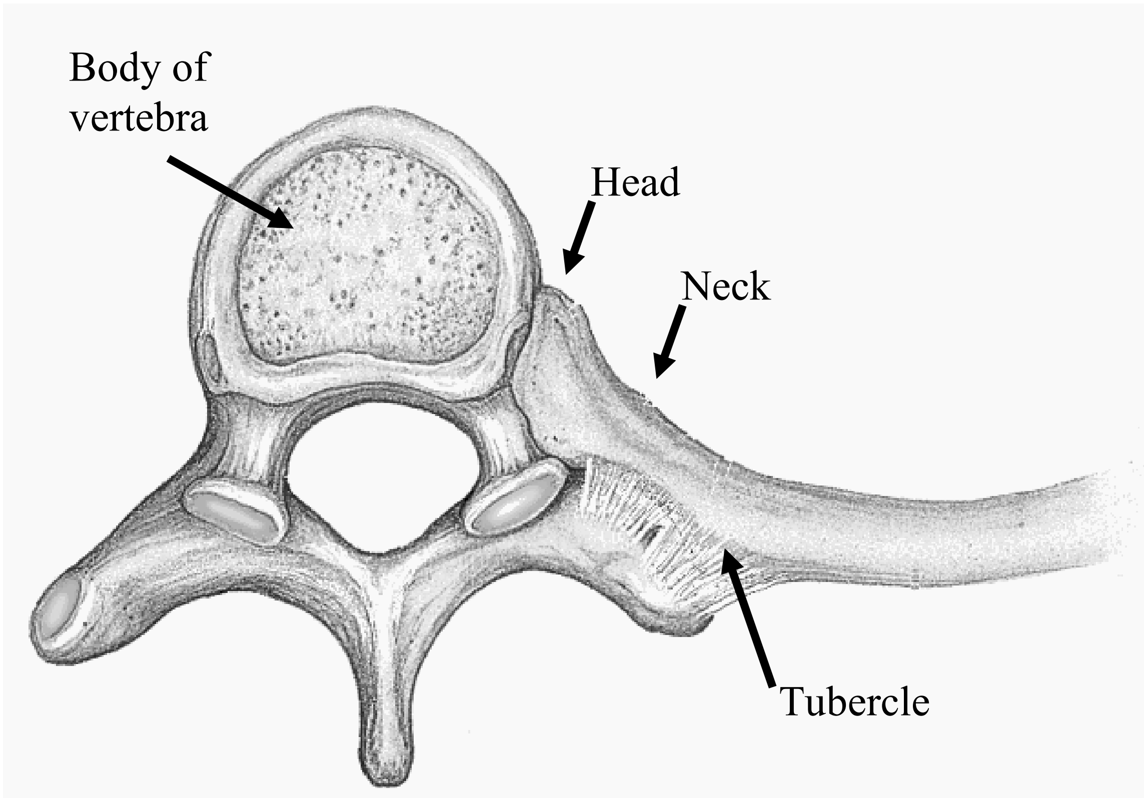
Clouse and Lantz, in work presented in 2008, described four cases of hospitalized neonates and infants who were found to have posterior rib fractures apparently related to CPR performed in accordance with current American Heart Association recommendations for infants (thumbs on the sternum with the fingers encircling the chest and back). Three of their cases were classified as acute fractures; one case had evidence of healing ascribed to prior episodes of CPR. Though noting that rib fractures in small children are most commonly the result of non-accidental injury, the authors wisely point out that such injuries must be interpreted in the context of “a complete autopsy and a thorough investigation of the circumstances of death.” Duval and Andrew reported a case in 2007 in which posterior rib fractures, presumably related to this method of CPR, were found in a previously healthy 47-day-old.

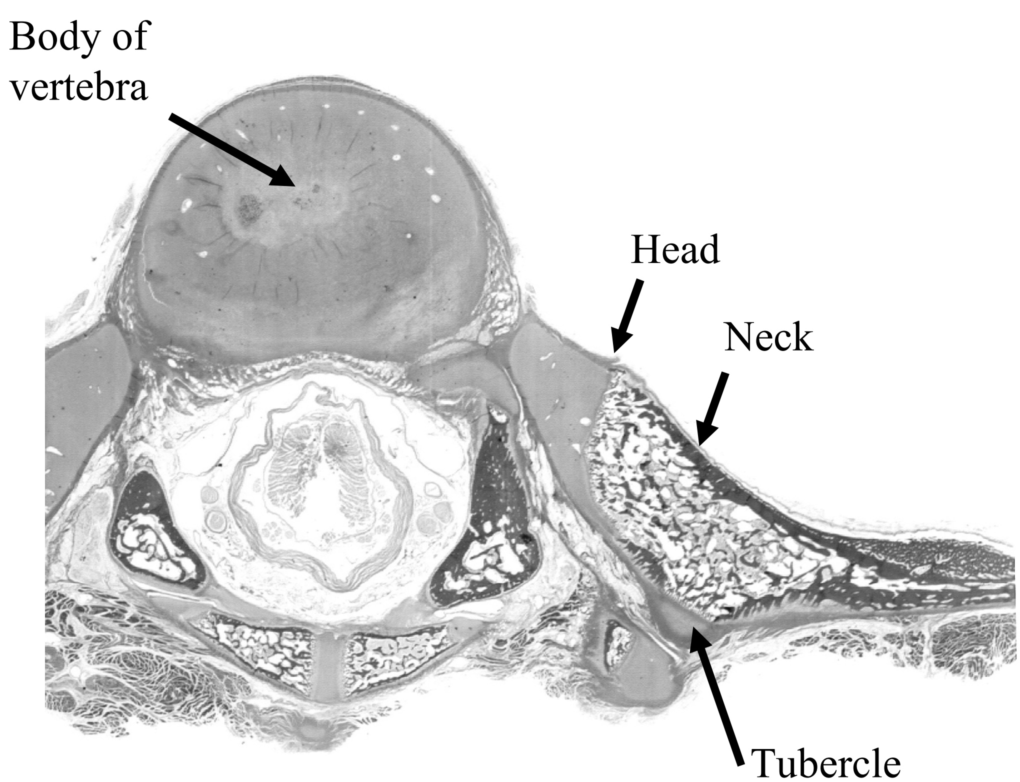
When an infant is squeezed around the chest, different mechanical forces are exerted on different parts of the rib cage. Posteriorly, the ribs are attached relatively tightly to the vertebral bodies and transverse processes; as the ribs are squeezed, the posterior rib arc is levered over the transverse process, resulting in ventral (and sometimes complete) cortical disruption. Laterally, squeezing creates both anterior and posterior compressive forces, resulting in buckling and impaction of the inner cortex and distraction of the outer cortical fracture margins. Anteriorly, sternal compression produces inward bending of the costochondral junction, leading to fracture.

Acute fractures of the rib are characterized by disruption of the cortex and subjacent bony trabeculae. Hemorrhage is often observed at the fracture site. Radiographically, acute rib fractures may be quite difficult to discern, especially if the fracture is incomplete, nondisplaced, viewed in an area with many superimposed structures, or if the fracture line is oblique to the x-ray beam. Fractures of the costovertebral articulation are particularly difficult to appreciate radiologically for all of these reasons. With healing, most fractures become more visible on radiographs, as subperiosteal new bone and callus become evident.

Normal anatomy of the posterior rib-vertebral complex: radiographically (below), anatomically (next page, top), and histologically (next page, bottom). The radiograph and whole mount histology are from an infant; thus, there is a cartilaginous cap on the rib head and rib tubercle.




Body of
vertebra
Head
Neck
Tubercle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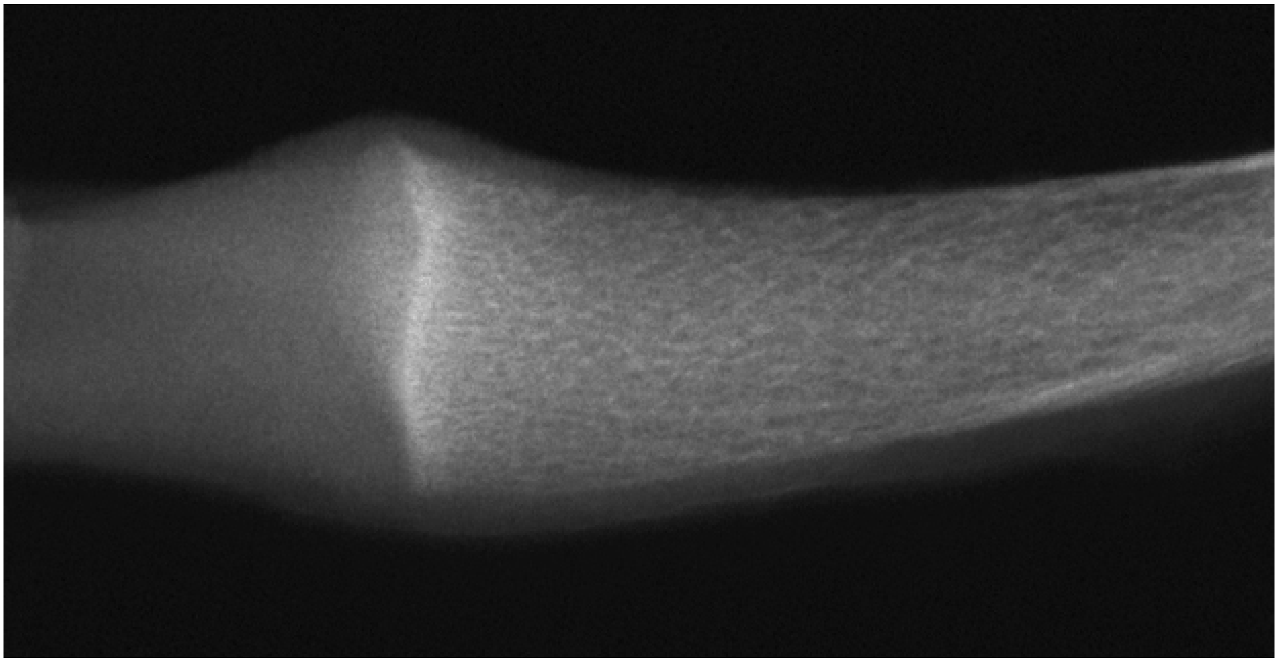
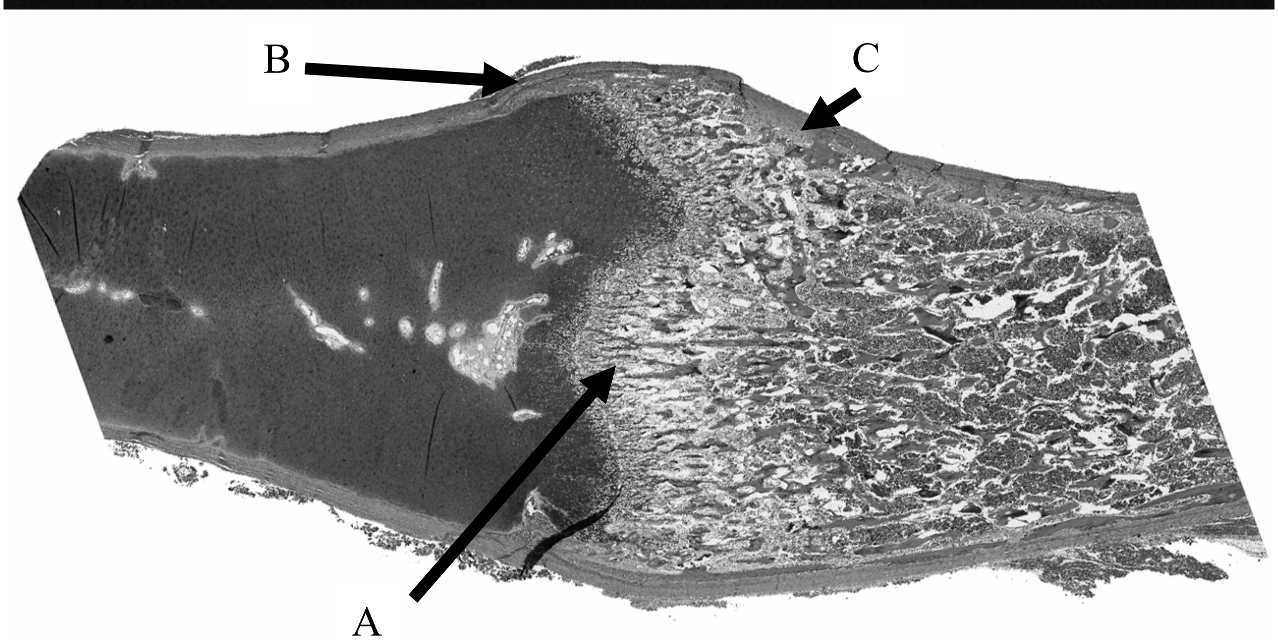
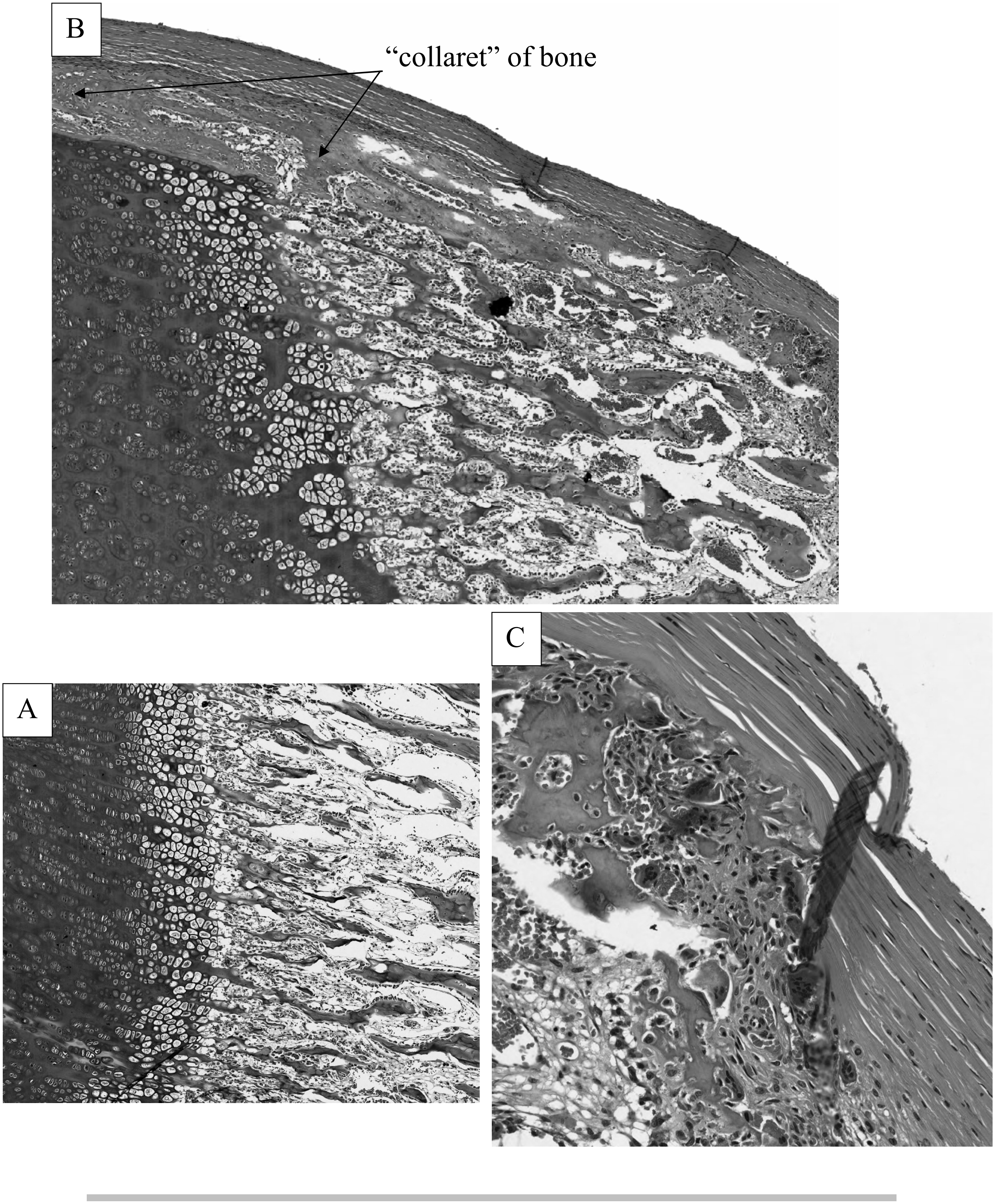
Normal chondro-osseous junction from a 3-month-old

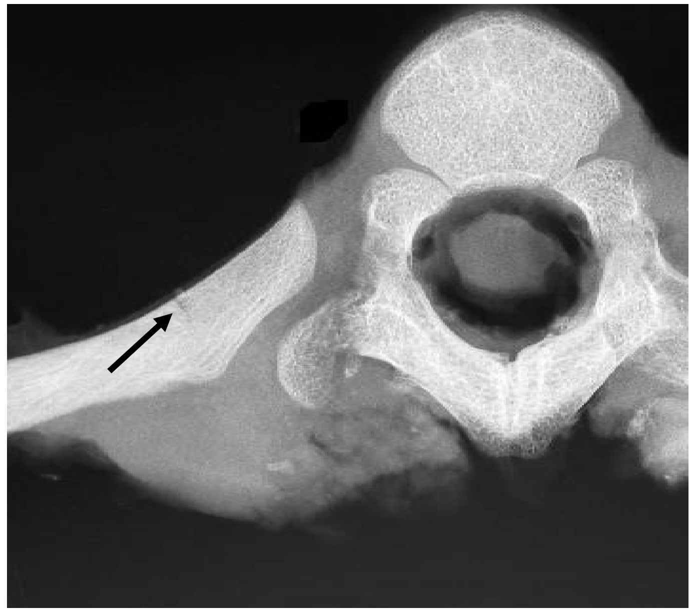


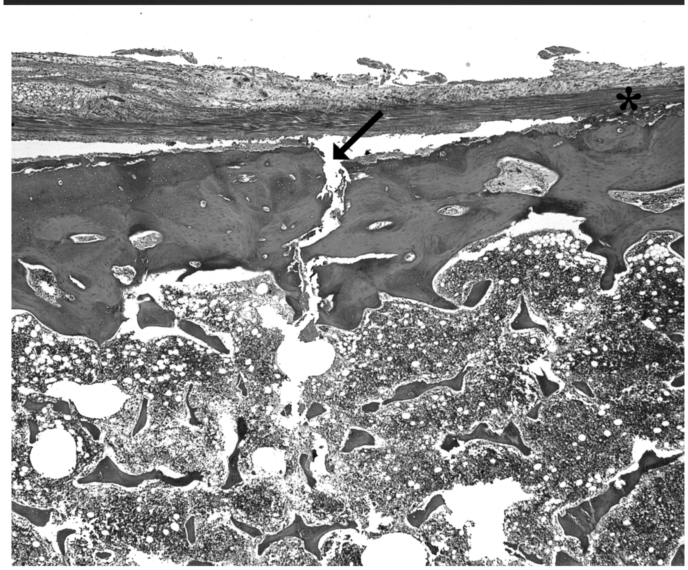


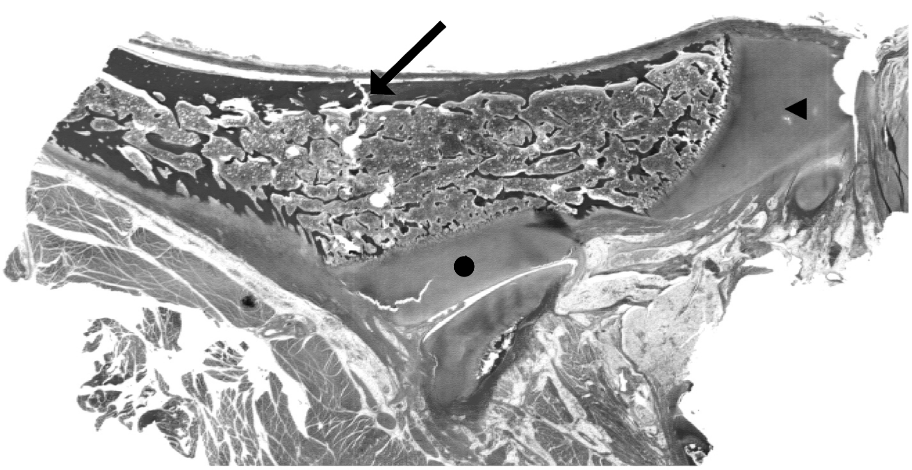
Close-ups (images on next page)

(A) Normal progression of chondrocytes into mineralized bone in the primary spongiosa
(B) A “collaret” of bone typically surrounds the chondro-osseous junction
(C) The cortex near the chondro-osseous junction often appears osteopenic due to the remodeling and “cut-back” that takes place during longitudinal growth (note the numerous osteoclasts). This is true of all growing long bones.


B
“collaret” of bone
A
C



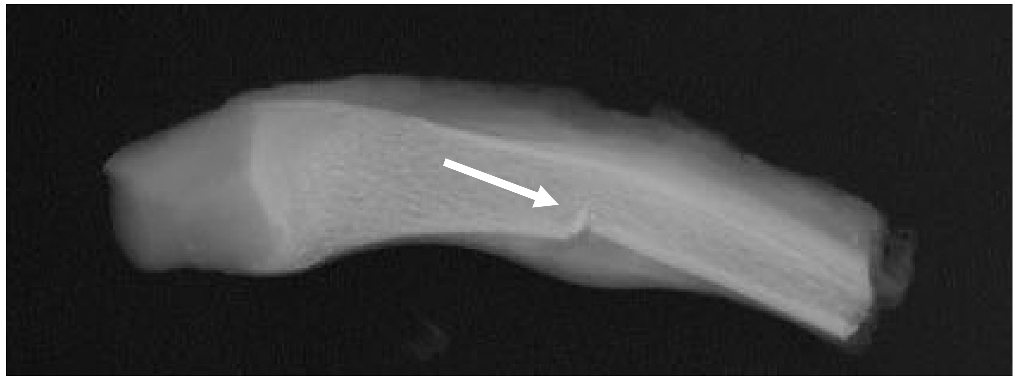


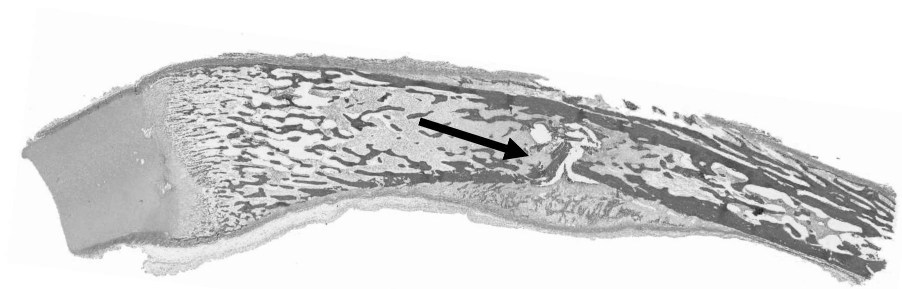


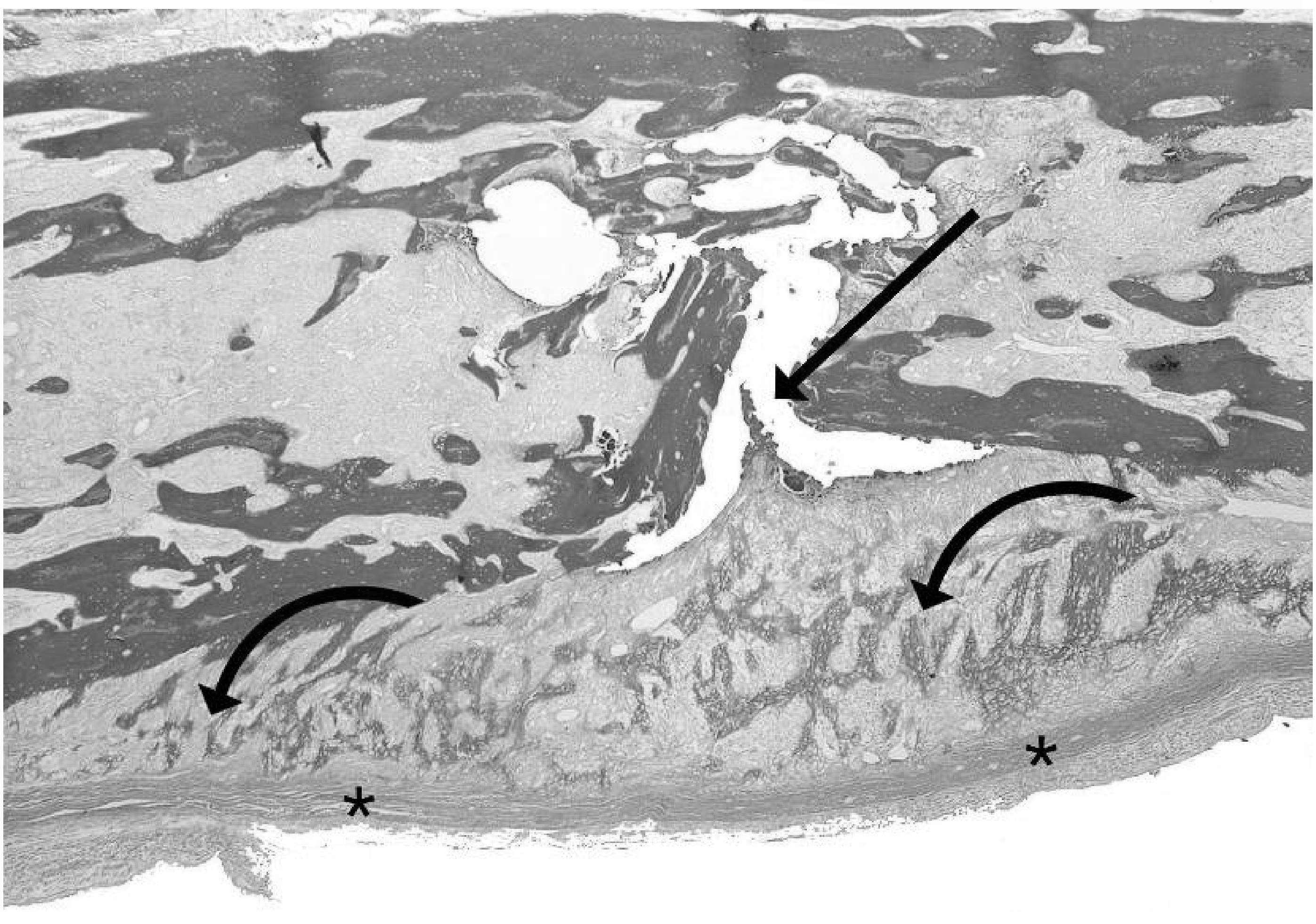
Acute posterior rib fractures (black arrows) in a battered toddler pronounced dead at the scene of injury. The pleura has been stripped away to better demonstrate the injuries. The cartilage of the rib head (◄), cartilage of the rib tubercle (●), and periosteum (*) are seen.

Healing anterolateral rib fracture in a fatally smothered 7-week-old. Note that only the inner cortex of the rib is disrupted (straight arrows). Histologically, the fracture is evident (straight arrow), as are the soft callus of subperiosteal new bone (curved arrows) and the elevated periosteum (*).

The marrow is largely absent since this specimen was obtained by exhumation, but the bone is well-preserved.



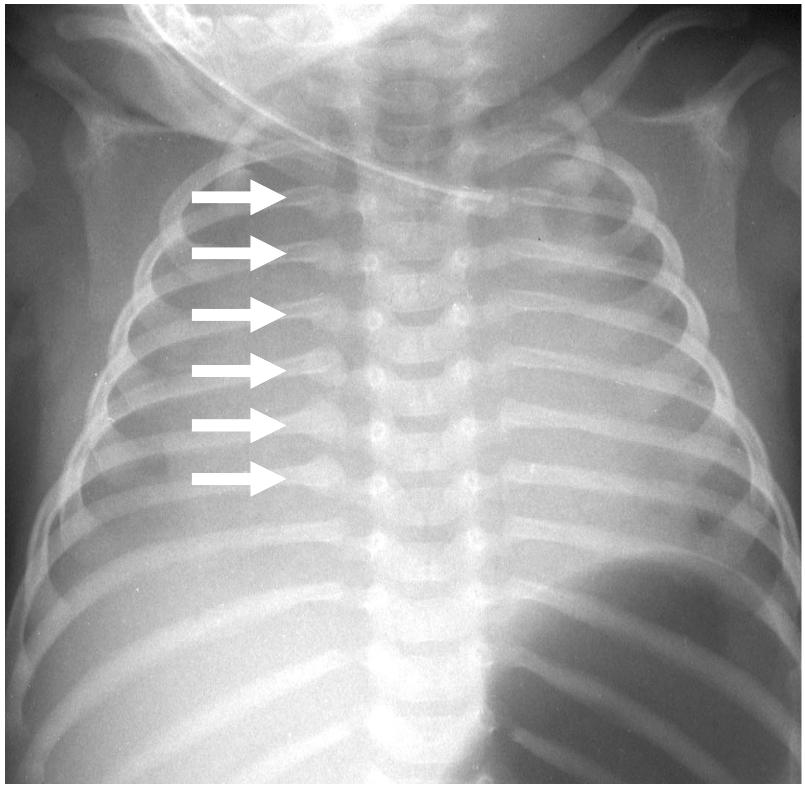


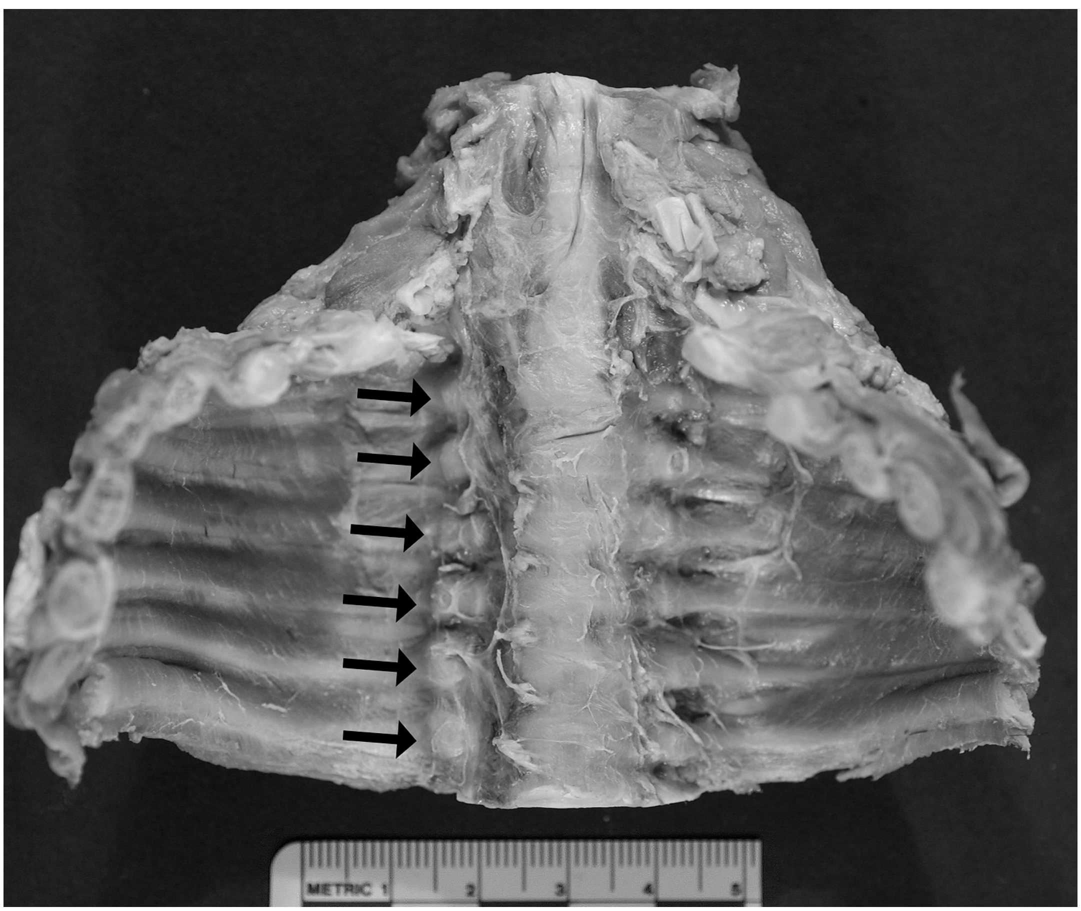


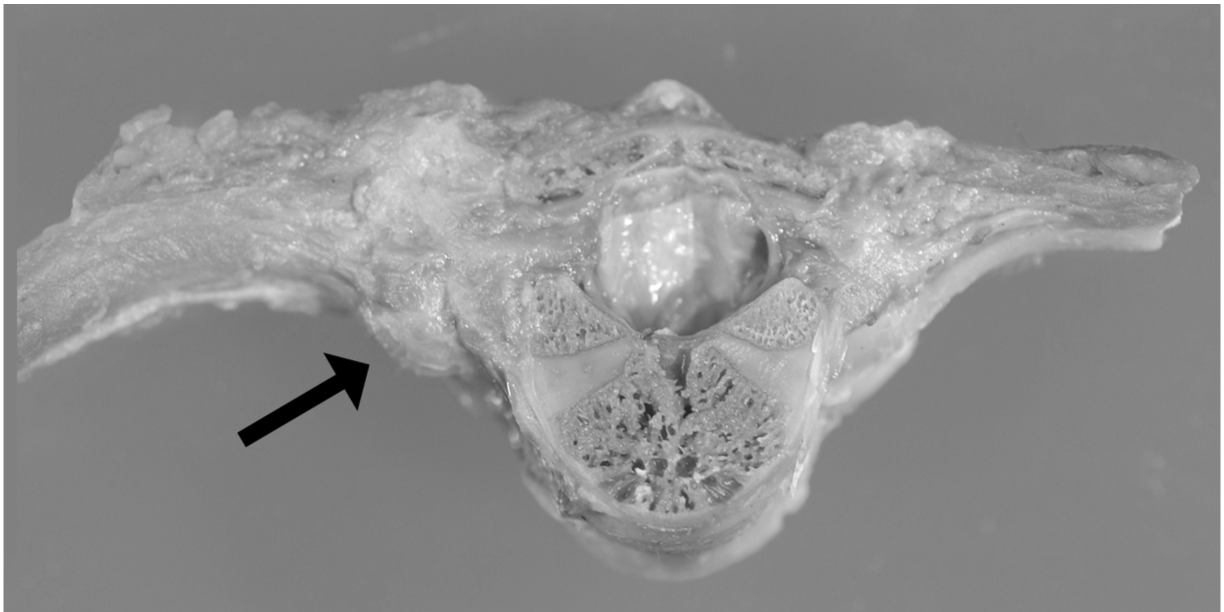
Multiple healing right posterior rib fractures (arrows) in infant on preceding page. The radiograph was taken at the time of autopsy.

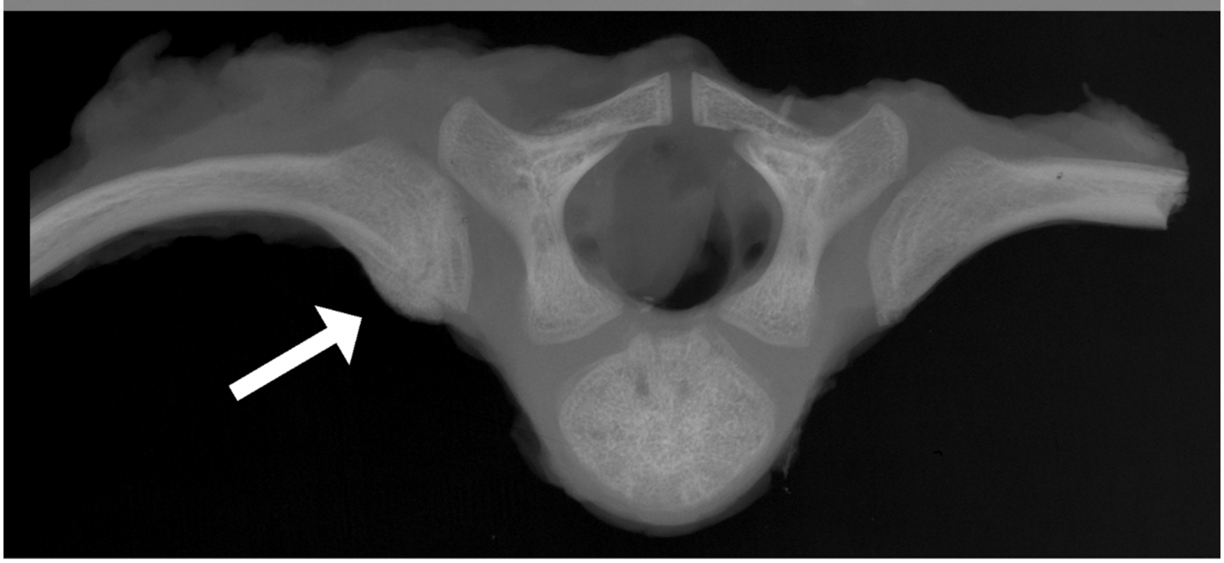
The gross photograph (below) was taken at the time of exhumation.

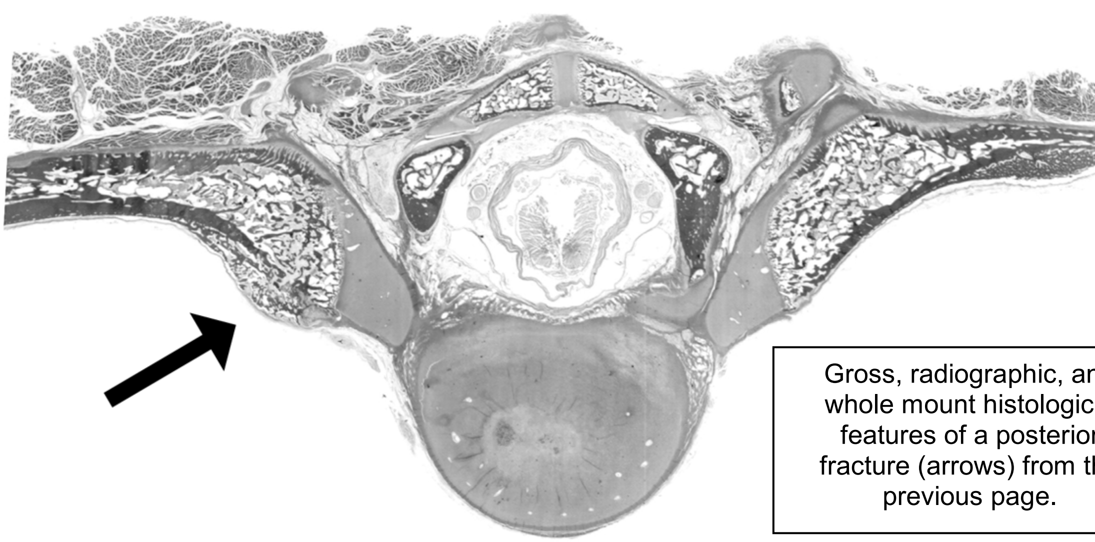
Unfortunately, this case was not recognized as a homicide until a subsequent infant was killed by the same parent.



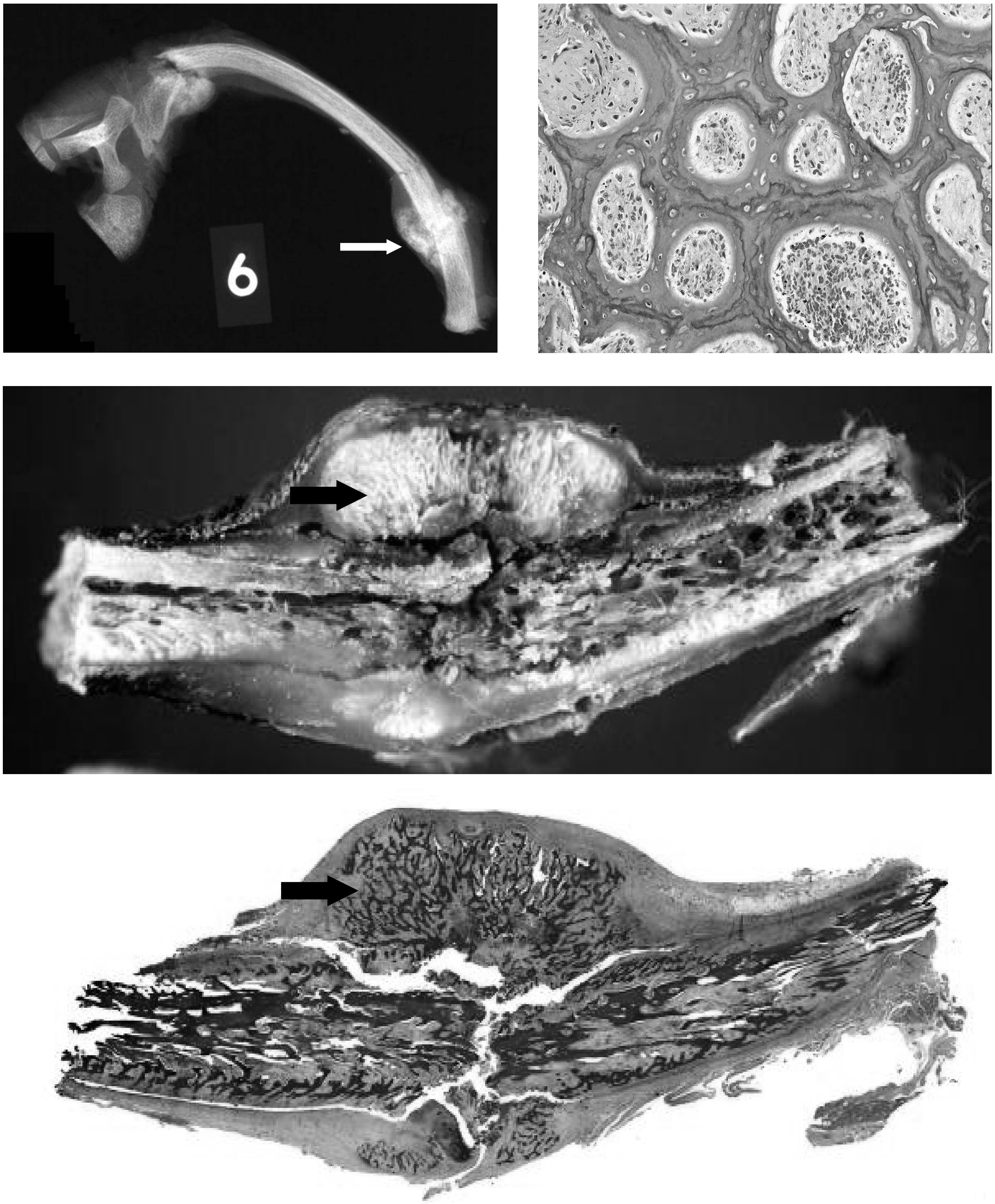






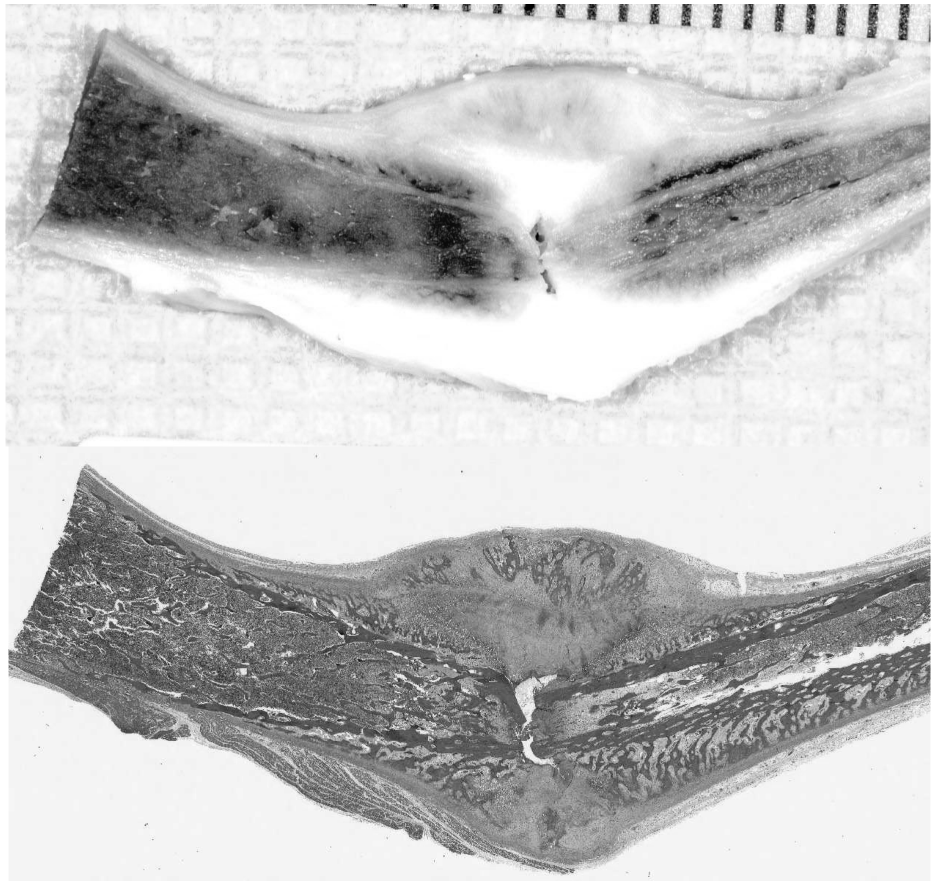


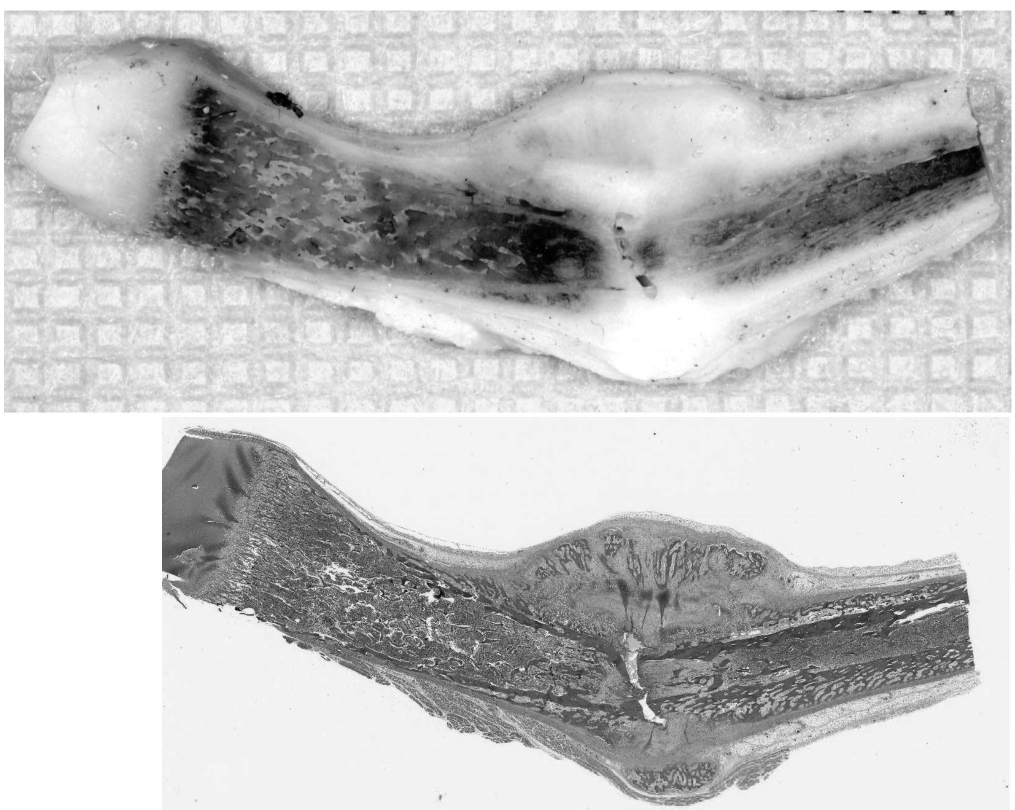
Gross, radiographic, and whole mount histological features of a posterior fracture (arrows) from the previous page.

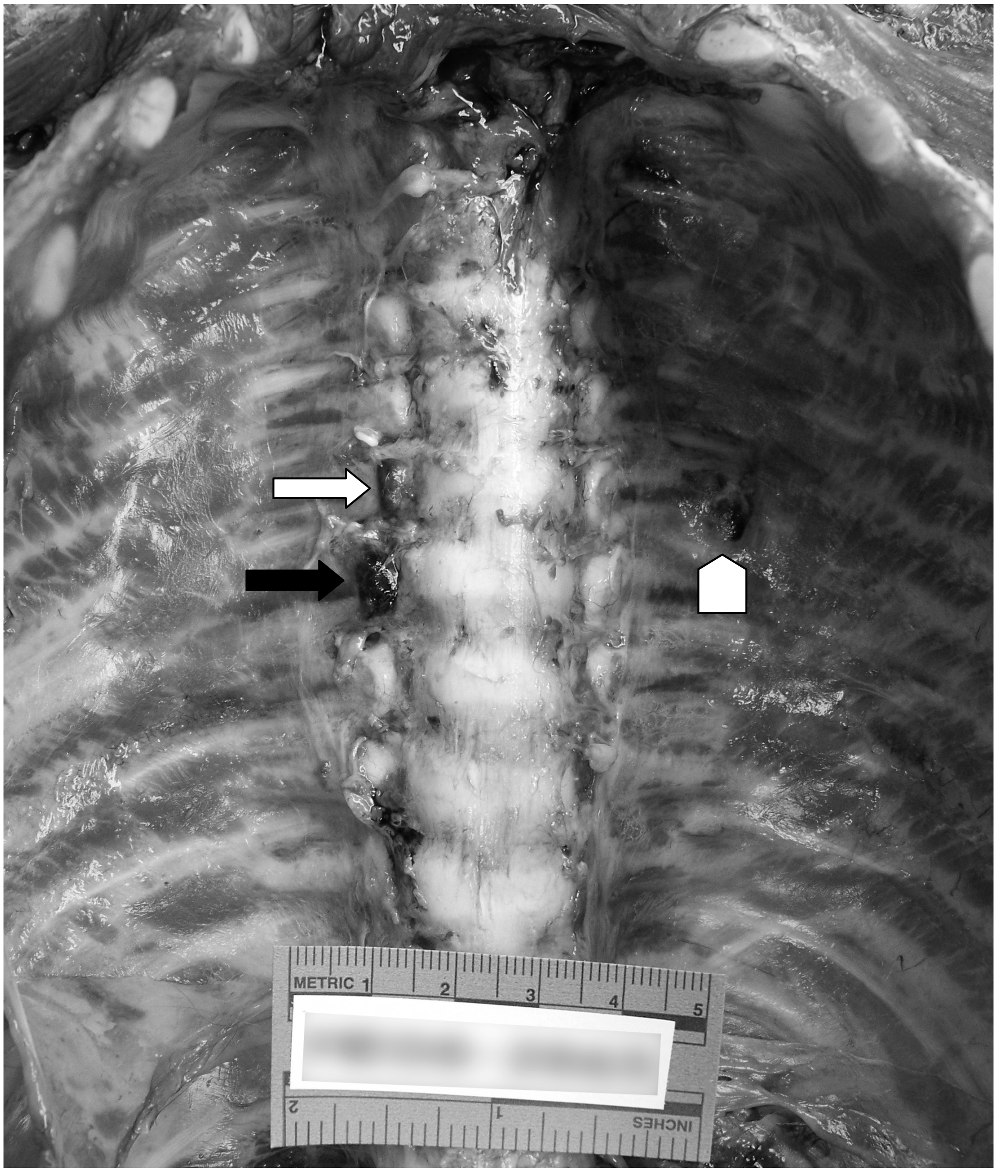


Axial radiograph, gross photo, and whole mount histologic section of a healing rib fracture in a battered 7-week-old. Hard callus is visible radiographically, grossly, and histologically (arrows). The presence of lamellar bone superimposed on woven bone (upper right) is evidence of relatively advanced healing.

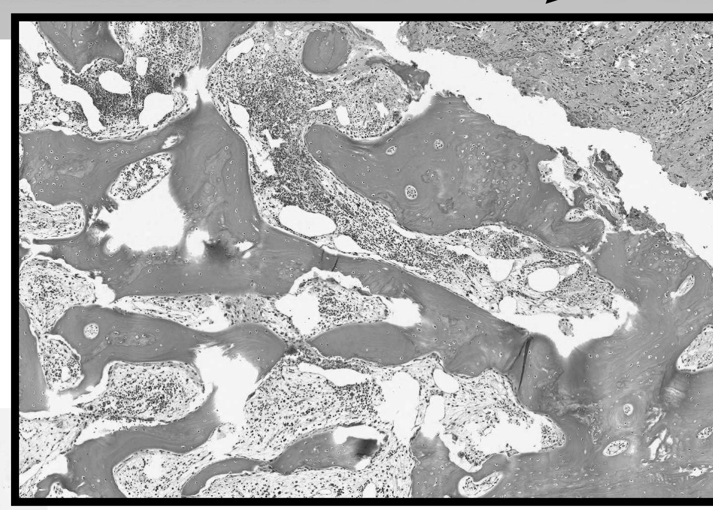
Gross photos and whole mount sections of rib fractures from a battered 3-month-old whose terminal event was multiple head impacts into a clothes dryer.



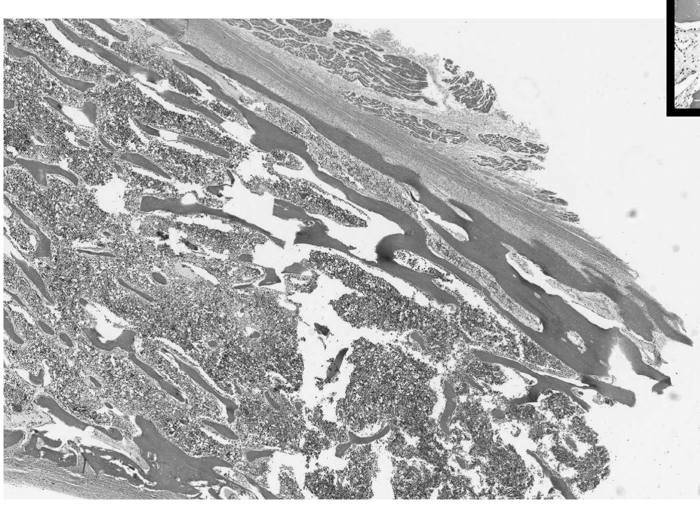




Gross photograph of the chest cage and axial radiograph of the 5th vertebra and ribs: fractures of the right 5th rib head and neck (white arrows) and left 5th rib posterior arc (white block arrow) in an infant with multiple other abusive injuries. The right 6th rib is also fractured (black arrow).

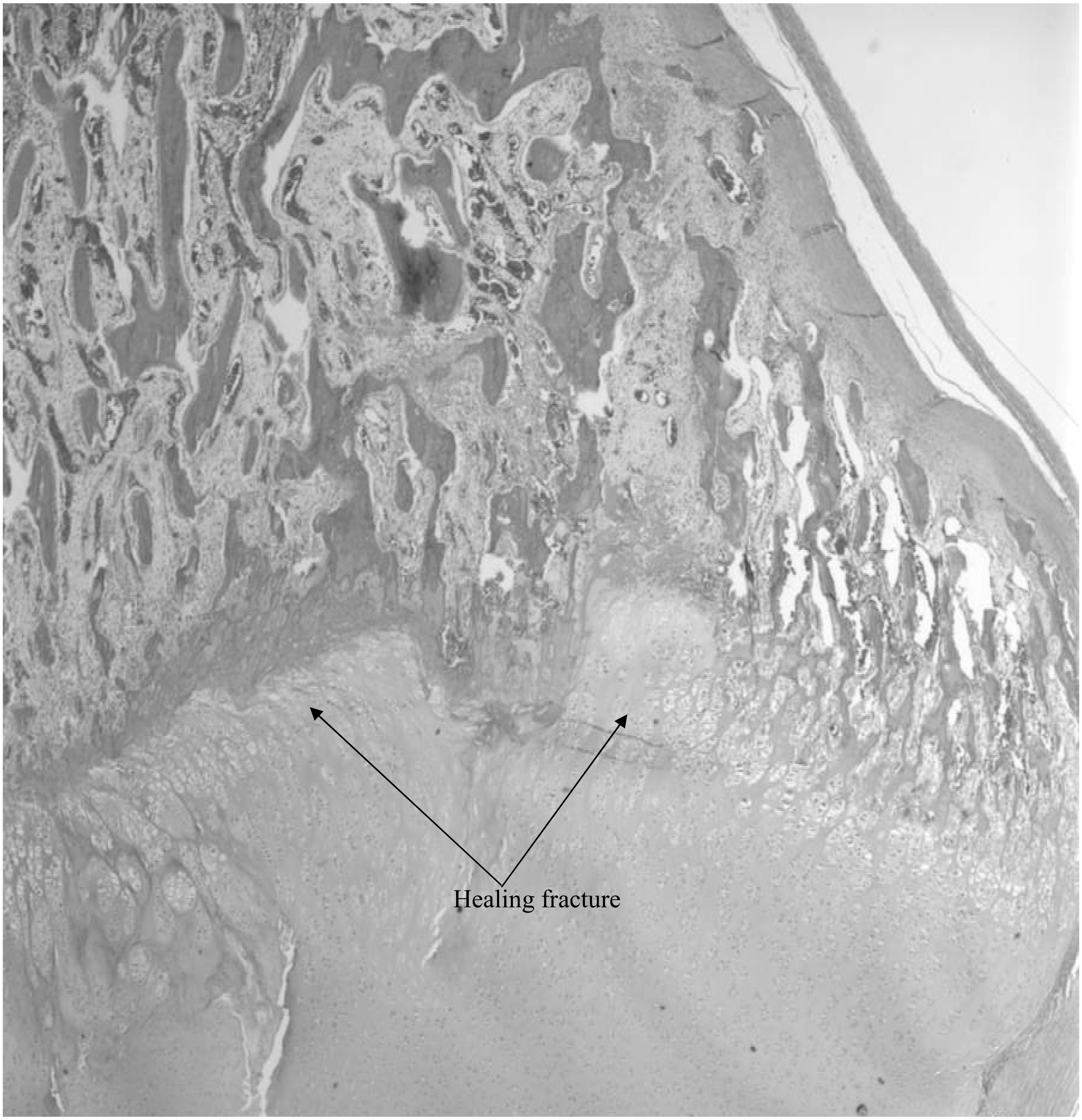


Anterolateral fracture of rib in an infant with dozens of fractures A consulting pathologist wrote that the child had severe osteogenesis imperfecta. Closer examination of the fracture healing (right) showed perfectly normal progression of healing from woven to lamellar bone.



Uninjured bone from the same child (left) showing a normally thick, normally developed cortex.

An adult caretaker admitted to having injured the child after the surviving identical twin, also riddled with fractures, healed all of his injuries following removal from the home.

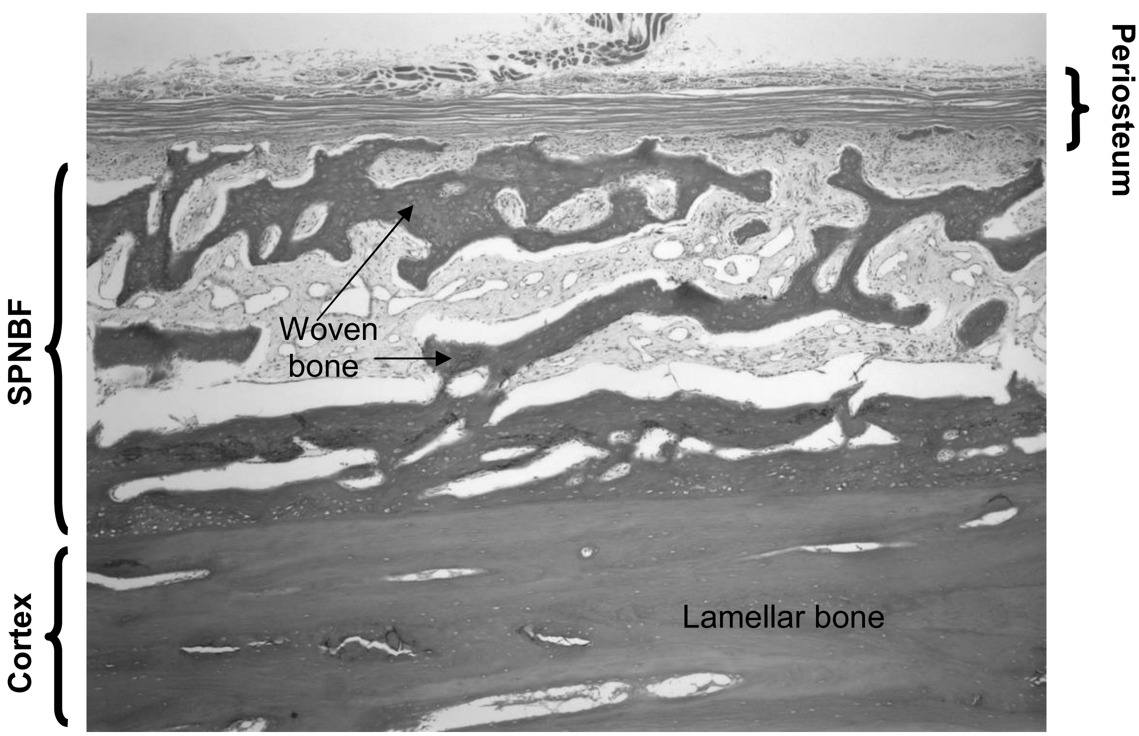


The infant costochondral junction is normally bulbous and can sometimes be hard to distinguish from a fracture grossly. Histology can be very helpful.

Basic Bone and Fracture Histology

Bone structure

Compact bone makes up the cortex, where there is little soft tissue. *Cancellous bone* makes up the central region (medulla), where spicules of bone are admixed with soft tissue. At the microscopic level, one can distinguish lamellar bone (regularly arranged sheets) and woven bone (an irregular feltwork). *Lamellar bone* predominates in areas of slow growth and remodeling, and deposition of lamellar bone requires a preexisting lattice of woven bone or lamellar bone. *Woven bone* predominates in areas of rapid bone growth, including embryonic bone, Codman's triangle, tumor bone, and fracture callus. While woven bone is flexible and allows rapid mineralization, bone formation, and bone resorption, it is also less rigid and has less strength than lamellar bone.



Bony cortex of the ulna of a fatally battered 8-week-old. The normal cortex and periosteum are separated by subperiosteal new bone formation (SPNBF), and the appearances of woven bone and lamellar bone are readily distinguished.

Periosteum surrounds the bony cortex except in articular cartilage. Perisosteum has two layers: the outer fibrous layer and the inner cellular (cambium) layer. Sharpey's fibers anchor periosteum and tendons to bone. These fibers are less developed in children, and fractures of children's bone often result in fraying or displacement of the periosteum, rather than actual breaking of the periosteum. Subperiosteal new bone formation in children is a sequel of periosteal-cortical separation–occurring in response to hemorrhage beneath the periosteum–and is often readily visible on radiographs. In adults, the periosteum is firmly adherent due to Sharpey's fibers, with the periosteum tending to break at the bony fracture site.

Bone formation

Enchondral and intramembranous formation are the two mechanisms of bone embryogenesis in humans. In *enchondral bone formation*, bone replaces a preexisting cartilaginous model. This occurs in the long bones–ribs, vertebrae, and extremities. Eventually, the only continuous enchondral growth occurs at the physis. In *intramembranous bone formation*, progenitor cells organize into trabeculae, differentiate into osteoblasts, and form trabeculae of woven bone. It is upon these trabeculae of woven bone that lamellar bone is then placed. Bone growth occurs via inner resorption and outer apposition of new bone. Intramembranous growth occurs in the flat bones of the skull and face. Fracture healing is essentially the process of bone regeneration, recapitulating embryonic intramembranous bone formation.

Fracture healing

The stages of fracture healing may be divided into four broad ranges: inflammation and induction, soft callus, hard callus, and remodeling.

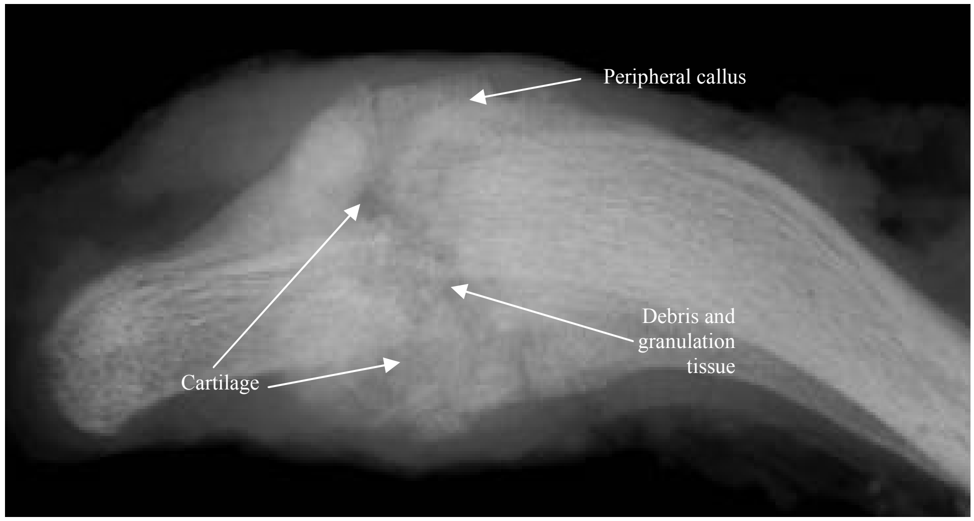
Inflammation and induction spans the time from injury to the appearance of new bone. This stage consists of two competing processes: osteolytic activity along with removal of hemorrhage and dead tissue; and deposition of granulation tissue, fibrous tissue, and osteoid. The lysis taking place within the fracture site explains the radiolucency often appreciated on radiographs. When examining fractures under the microscope, the pathologist must take care not to interpret the resorption of normal bone adjacent to the fracture as evidence of bony dysplasia.

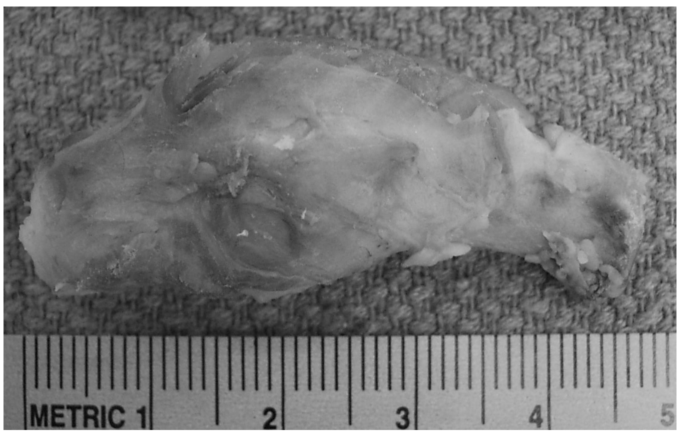
Soft callus is thought to begin at about 10-14 days post-injury in older children; probably earlier in infants. New woven bone and cartilage are laid down; the woven bone will gradually mature into trabeculae. The progenitor cells entering the fracture site are actually pluripotent, and can differentiate into osteoblasts (producing osteoid), chondroblasts (producing cartilage), or fibroblasts (producing fibrous tissue). The predominant pathway taken depends on how well immobilized and oxygenated the fracture site is. Unlike many animal models, a callus composed largely of cartilage is not the preferred route in humans. The soft callus stage usually lasts about 3 to 4 weeks, at the end of the stage the ends of bony fragments are no longer easily moved, and there is obliteration of the radiographic fracture line.

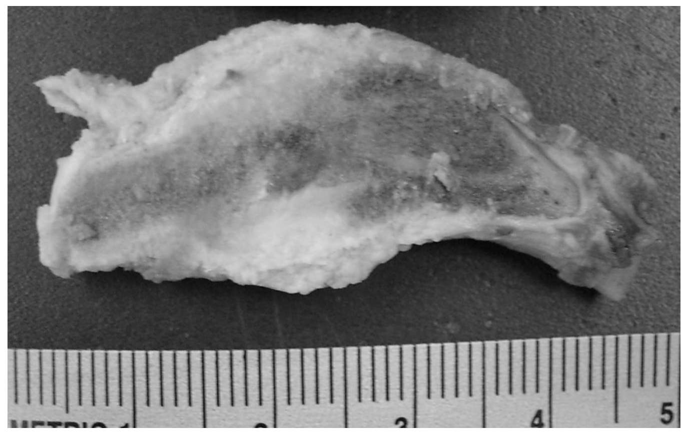
In the *hard callus* stage, both periosteal callus (outside the bone cortex) and endosteal callus (inside the bone cortex) are being converted to lamellar bone. Nearly all of the hematoma, inflammation, and necrotic tissue have been removed from the fracture site, although it should be noted that histologically, the healing of the endosteal portion of a fracture may lag far behind the periosteal portion. At the end of the hard callus stage, radiographically the fracture is now solidly united.

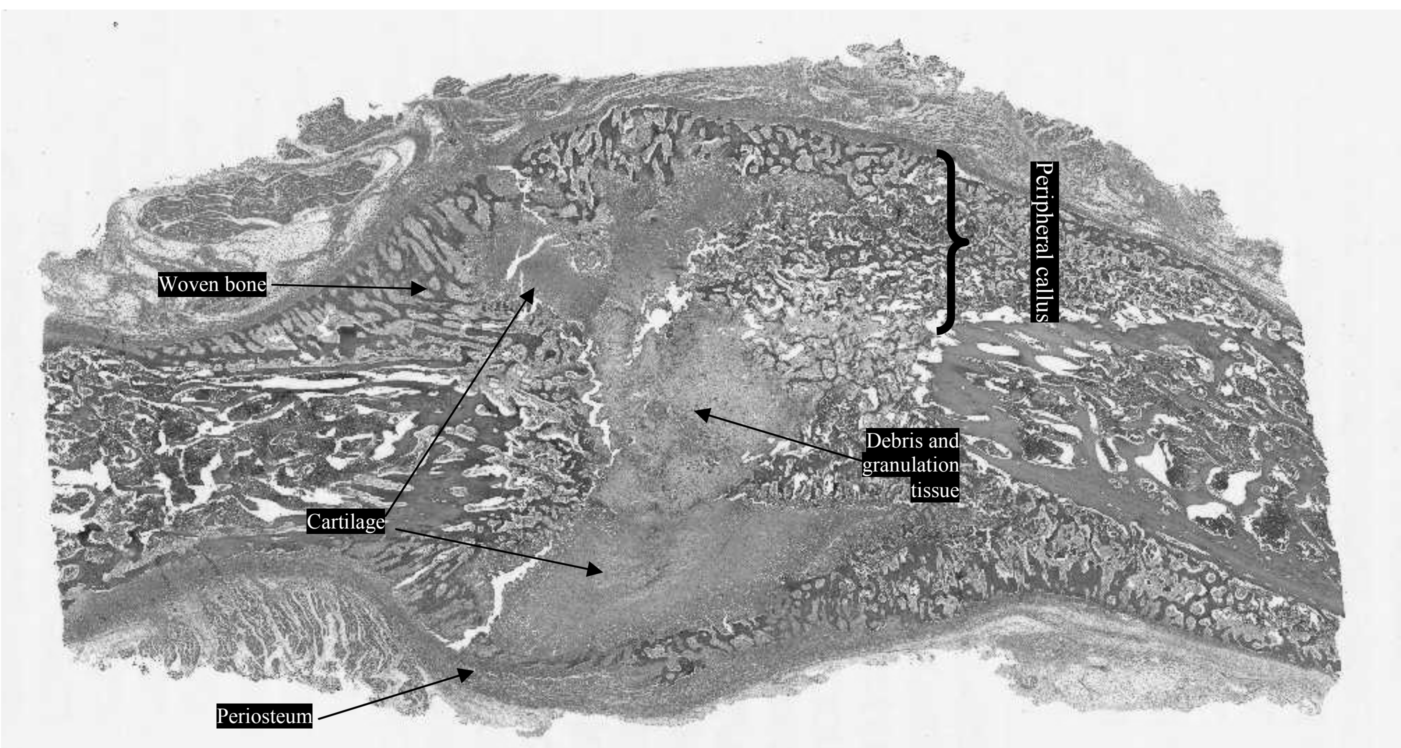
The goal of *remodeling* is complete restoration of the medullary cavity and the cortex. While this might never occur completely in some adult fractures, in children it may occur despite wide displacement or angulation of the fracture.

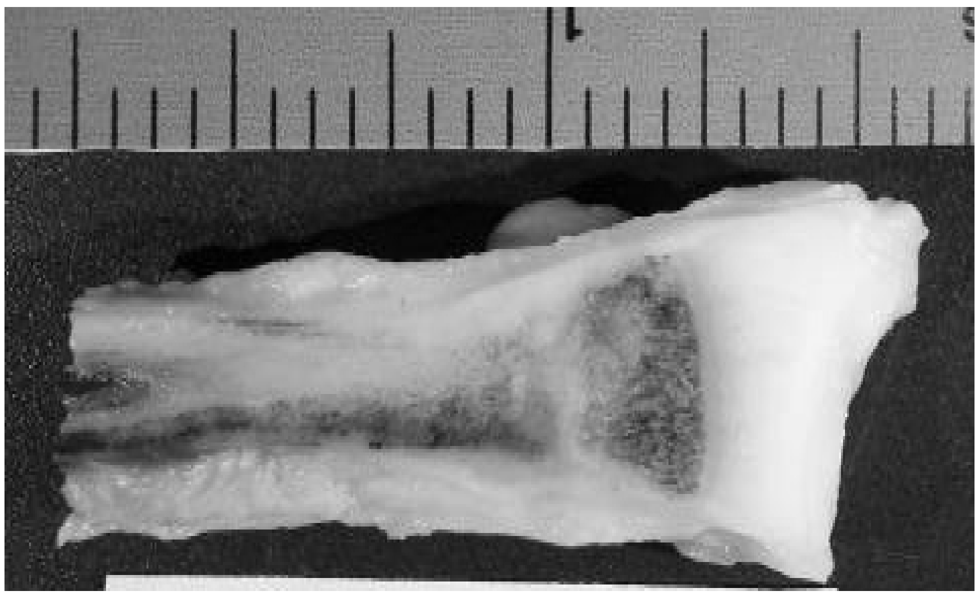
Healing clavicle fracture in a 17 week old boy. The radiograph and whole mount histology show "soft" callus, cartilage, and a relatively radiolucent fracture line. Though little data exist to "date" fractures, the lack of remodeling and lamellar bone in the callus strongly suggest this fracture is far too recent to be a birth injury.



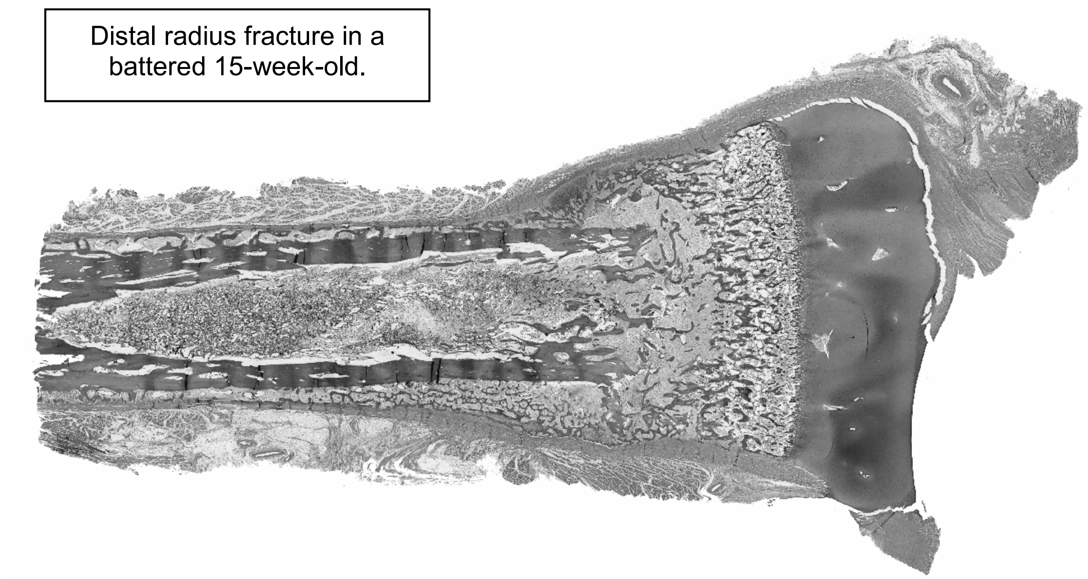




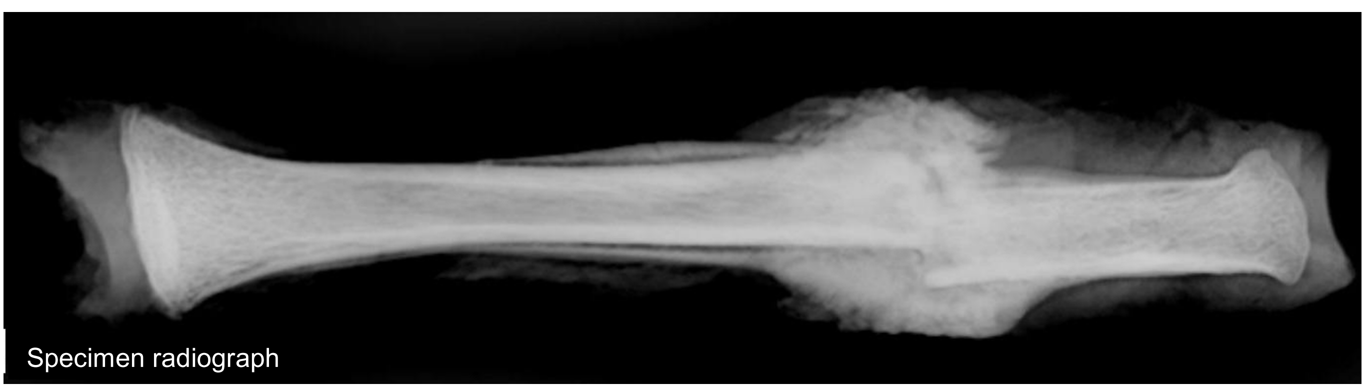




Distal radius fracture in a battered 15-week-old.

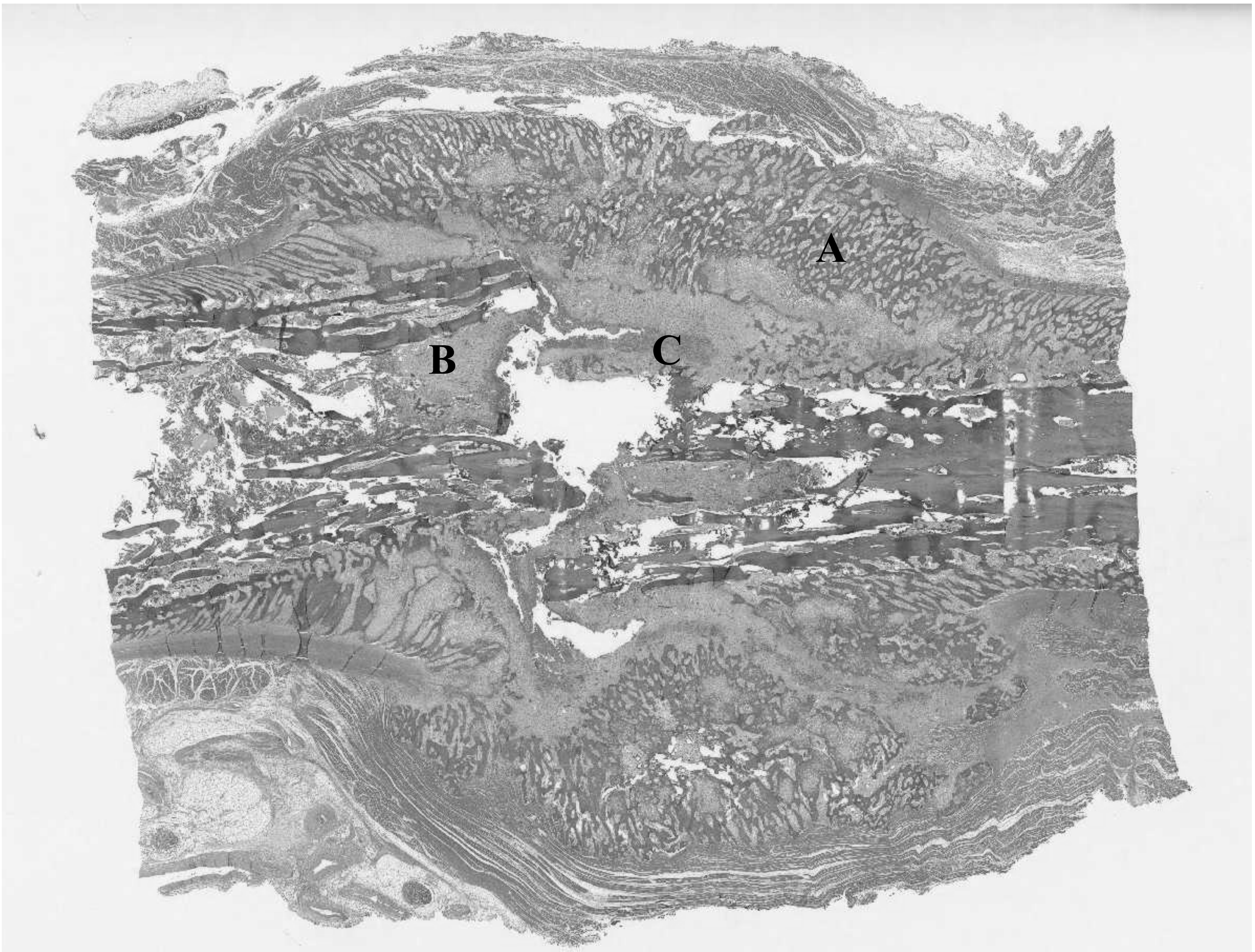


Antemortem skeletal survey

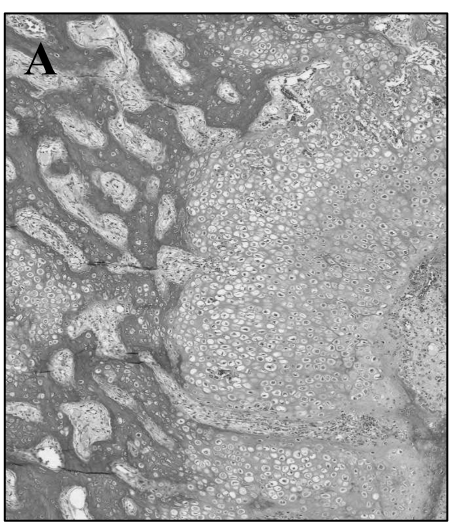


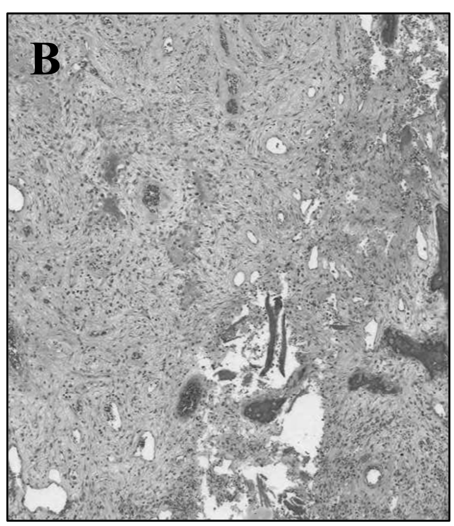
Specimen radiograph

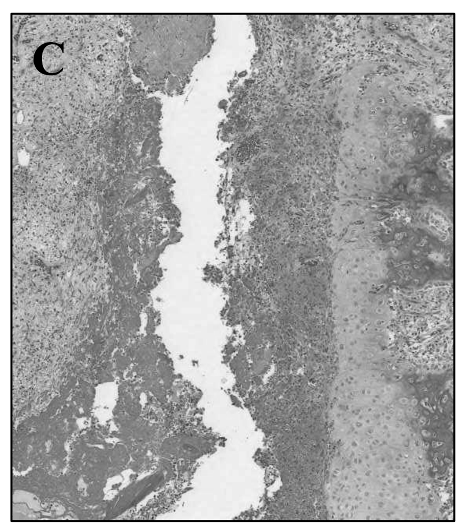
Radial shaft fracture in a fatally abused 13-month-old.
Callus is readily visible radiographically and grossly.

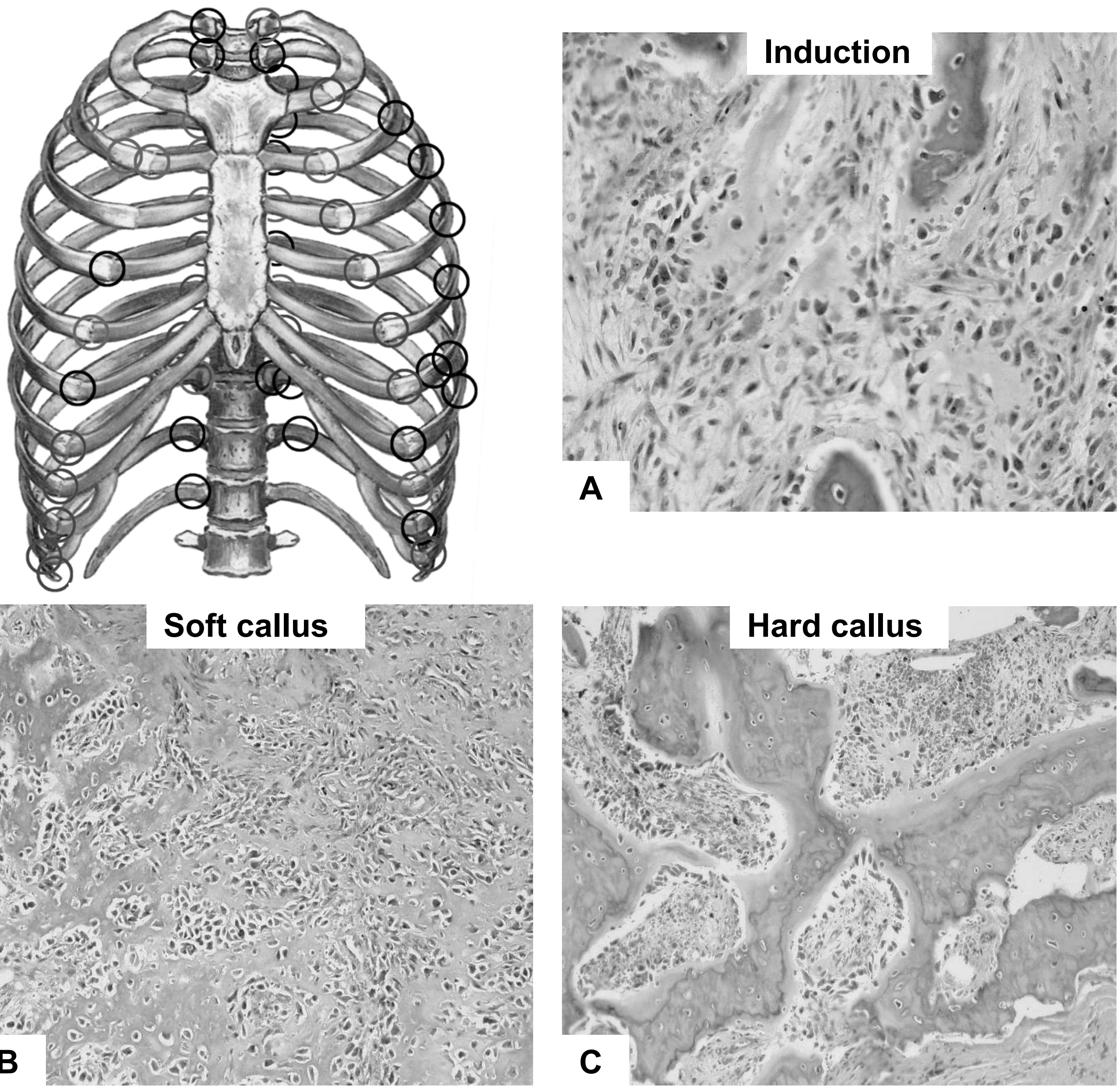


Microscopy of the fracture on the preceding page. The periphery of the fracture callus (A) is composed of cartilage and woven bone (with very early lamellar bone), while the central part of the callus consist of granulation tissue (B) and persistent necrotic debris (C). When assessing "age" of the fracture, look at the whole fracture and not just selected areas.









Schematic representation (used at trial) of 52 rib fractures in a fatally battered 7-week-old who died of a blow to the chest (commotio cordis). The fractures are in various stages of healing, as illustrated by the early organization of osteoblasts into trabeculae, with osteoid production (**A**, H&E, 200x); formation of mineralizing trabeculae of woven bone (**B**, H&E, 100x), and mineralized trabeculae of woven bone upon which lamellar bone is being deposited (**C**, H&E, 100x). A, B, and C represent the "oldest" areas in three different fractures.

From the Society for Pediatric Radiology and the National Association of Medical Examiners:

The skeletal survey is an important component of the forensic evaluation of unexplained death that is suspicious for abuse in infants younger than 2 years of age. It may detect highly specific inflicted injuries (such as the CML) that may otherwise be missed at autopsy or during a less than complete radiographic assessment. Accurate forensic analysis of all injuries, including those documented radiographically, yields the best and most thorough information about the manner and cause of death. The Society for Pediatric Radiology and the National Association of Medical Examiners make the following recommendations:

1) *Radiographic studies should be obtained in all unexplained deaths that are suspicious for abuse in children under 2 years of age. These should consist of, at a minimum, well-collimated views of the long bones, with additional views obtained as necessary.*
2) *When possible, studies should be performed by certified radiographic technicians. If this is not possible, jurisdictions need to ensure that the employees performing the studies receive adequate training. Certified radiographic facilities within the jurisdiction should make technologists available to conduct occasional training sessions where the post mortem radiographs will be obtained.*
3) *It is the civic responsibility of pediatric radiologists to work with the Medical Examiner/Coroner's Office in their jurisdiction to make sure that post mortem radiological examinations are optimally performed and interpreted. Professional fees, when charged, should be at a rate that would not preclude the jurisdiction from availing itself of radiological services.*

* Pediatric Radiology 2004; 34: 676-677

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