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Healing Following Cranial Trauma*

ABSTRACT: This paper reports on the gross appearance of the initial osseous response following cranial gunshot wounds. A total of 127 adult crania and cranial sections were analyzed for four types of bone response: osteoblastic, osteoclastic, line of demarcation, and sequestration. In general, no osteoblastic or osteoclastic response was noted during the first week. This response was followed by an increasing prevalence of expression after this time. By the sixth week postfracture both osteoclastic and osteoblastic activity was scored for 100% of the sample. Further, our observations suggest that the line of demarcation may establish the boundary between the living bone and bone not surviving the fracture. Sequestration appears to be a long-term event and was scored as present well past the eighth week of healing. The osseous expression of infection following fracture was also considered.

KEYWORDS: forensic science, forensic anthropology, skull fractures, fracture healing

Fracture is one of the most common pathological conditions of the skeleton, and its interpretation can yield important information. Often in the anthropological literature the number and type of fractures has been used to draw important conclusions about past lifeways including evidence of interpersonal violence, warfare, or general lifestyle hazards (see 1–3). Yet the primary question often remains: how long did the individual survive? Gross appearance of the condition of bone—callus formation, the presence of a periosteal reaction, or the rounding of fracture margins—clearly indicate antemortem fracture. Postmortem breaks are typically characterized by distinct fracture margins (4,5). However, drawing conclusions about the timing of perimortem fractures, that may have important medical and legal implications for the forensic anthropologist, can be more difficult.

Interest in the healing time of fractures dates back to Hippocrates who reported on the healing times of various bones and noted that cancellous bone healed more rapidly than cortical bone (6). In modern medical literature, the mechanism of bone healing is well understood (7–12) with most authors dividing fracture healing into phases. The following brief overview is extracted from Frost (8). Following the traumatic event, inflammation occurs, characterized by formation of a hematoma within the medullary cavity, around the fracture margins, and beneath any elevated periosteum. This occurs within the first week following injury. In the next phase, granulation tissue forms. In this phase, lasting about 2 weeks, the hematoma becomes organized and fibrous and a chondroid callus forms. In addition, surfaces of the fracture become eroded by osteoclasts during this phase. In the following stage, callus formation begins with the creation of osteoblasts in the granulation tissue. This phase ends with mineralization of the callus. The initial part of this phase begins 1 month after injury and may take up to 4 months to reach the end of mineralization. Ragsdale and coworkers note that radiographically, callus formation in adults can take 2–3 weeks before becoming visible (9). The next stage, remodeling, lasts from 1 to 4 years. In this stage, the mineralized callus replaces lamellar bone. In modeling, the final stage, the bone recontours toward its original shape.

While Frost's phases deal primarily with fractures of long bones, the fracture response by cranial bone has been reported by Sevitt (10). He writes that osteogenic activity is less important in cranial fracture healing than in long bone healing. In addition, Sevitt (10) (p. 232) notes:

> Small foci of new immature bone are often laid down on the margins of fissures during their fibrous bridging but fail to cross them. Previous episodes of marginal resorption by osteoclasts are indicated by cement lines under the new bone and by scalloping or multiple pits at the edges. Sometimes many osteoclasts are seen eroding necrotic calvarium by the fissure whilst other parts show focal appositional deposits of new bone.

In a similar vein, Shipman et al. (12) note that the sequence of the bone healing response differs according to bone type. In compact bone, the lack of space to accommodate new bone formation results in the production of many more osteoclasts. As a result of these osteoclasts carving out space within the compact bone, localized areas of resorption called cutting cones are formed where the osteoclasts have removed the dead bone. Once the osteoclasts have made sufficient space within the compact bone, the osteoblasts begin secreting the calcifying osteoid.

While the process of bone healing is well understood, the timing of specific responses remains largely unexplored. In the forensic literature, several recent reports are of note. Sauer and Dunlap (13) report on a case study involving the healing of two neurosurgical burr holes in the skull of a 16-year-old female. Both burr holes, made 5 years before death, were well-healed. One hole retained its original size and shape with remodeling observed around the edges of the lesion. The other hole was covered over with bone. Neither showed any signs of infection.

A paper by Walker and coauthors (14) examined forensic skeletal evidence for child abuse, focusing on five cases exhibiting healed and healing fractures. Of these five cases, three showed evidence of healed or healing trauma to the cranial vault. In these cases of cranial fracture, the appearance of certain bone responses

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was used to determine time elapsed since injury. The responses Walker and co-workers attribute to several weeks of healing are new subperiosteal bone formation and remodeling at the fracture edges. In one case, the bone response associated with injuries to the ribs, nasal area, and sphenoid showed "surface resorption of margins but no periosteal bone formation" and are assumed to have occurred 2 weeks before death. In injuries occurring within 2 weeks to a few months of death, fibrous new bone formation was evident.

In a chapter discussing trauma analysis, Maples (4) reports that the first evidence of bone response is slight rounding of the sharp edges of broken bone with the edges appearing polished under magnification. He notes that a period of at least a week or more is required for this response.

These authors provide important information on the gross appearance of fractures during the healing process. However, these reports provide little empirical data about the derivation of these time frames. We suggest that with an appropriate sample, a more definitive model for estimating the time elapsed since injury can be created. For this study, we used an adult skeletal sample for which the dates of injury and death are known. In this paper, we report on the gross appearance of the initial osseous response following contusion and penetrating cranial fractures over time.

Methods

The Civil War skeletal collection at the National Museum of Health and Medicine, Armed Forces Institute of Pathology, contains nearly 2000 skeletal specimens showing disease and trauma. For each specimen detailed reports by physicians exist with significant case history information regarding the nature of the injury, the time elapsed from insult to recovery or death, and the methods of medical treatment (15).

A total of 127 adult crania, calvaria, and cranial sections were examined for evidence of bone response. Specimens with completely healed fractures and those for which we could not observe both ectocranial and endocranial surfaces were excluded from this study. For each specimen the following information was collected: type of fracture (either perforating or contusion), the size of the cranial section, and the appearance of osseous response. For the majority of the specimens (n = 119), the fracture was caused by a bullet or other missile wound to the skull. The remainder was the result of stabbing or blunt force trauma. Gross examination of each specimen was performed under a bright light with the aid of a 5× magnifying lens. In some cases, a Nikon binocular zoom microscope was used to verify the type of bone response.

Each specimen was examined and scored for the presence or absence of four types of bone response: osteoblastic response, osteoclastic response, line of demarcation, and sequestration around the site of fracture. Osteoblastic response was defined as the deposition of new subperiosteal bone typically seen in a periosteal reaction. Osteoclastic response was defined as areas of pitting affecting the existing cortical bone and occasionally exposing the diploe (Fig. 1). A line of demarcation was seen as an "etched" line running adjacent to the fracture margin, appearing as a shallow depression or canal with sharp margins. Sequestration was noted when a segment of the bone was necrosed or necrosing often observed as a difference in color to the surrounding bone (Fig. 2). All four of

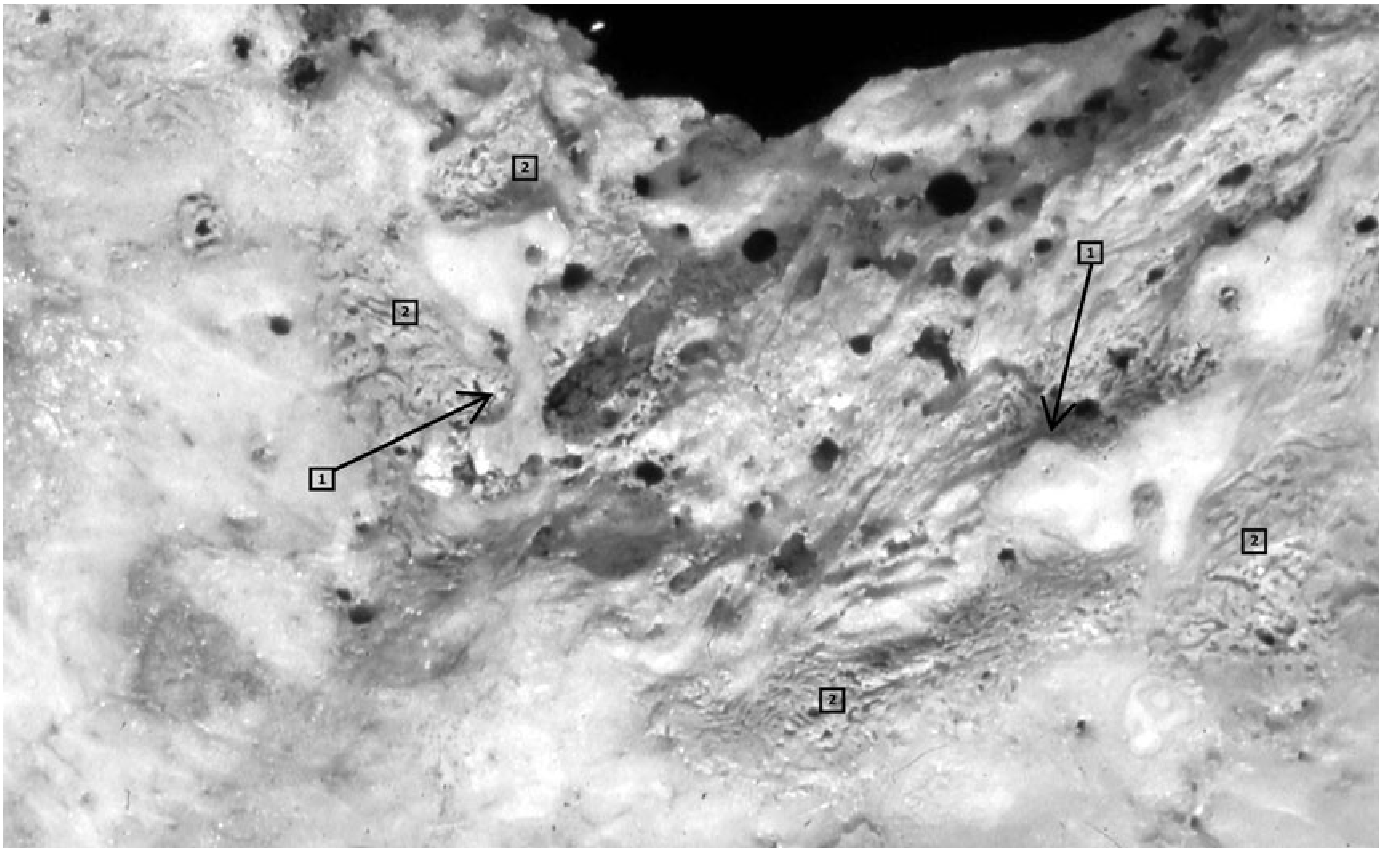

FIG. 1—*Cranial fracture with sharp margins and areas of osteoclastic (1) and osteoblastic (2) activity. Osteoclastic activity is expressed as areas of pronounced pitting and a scalloped or irregular ectocranial or endocranial surface which may expose the diploe. Osteoblastic activity is the deposition of new subperiosteal bone that does not appear to be incorporated into the pre-existing bone matrix.*

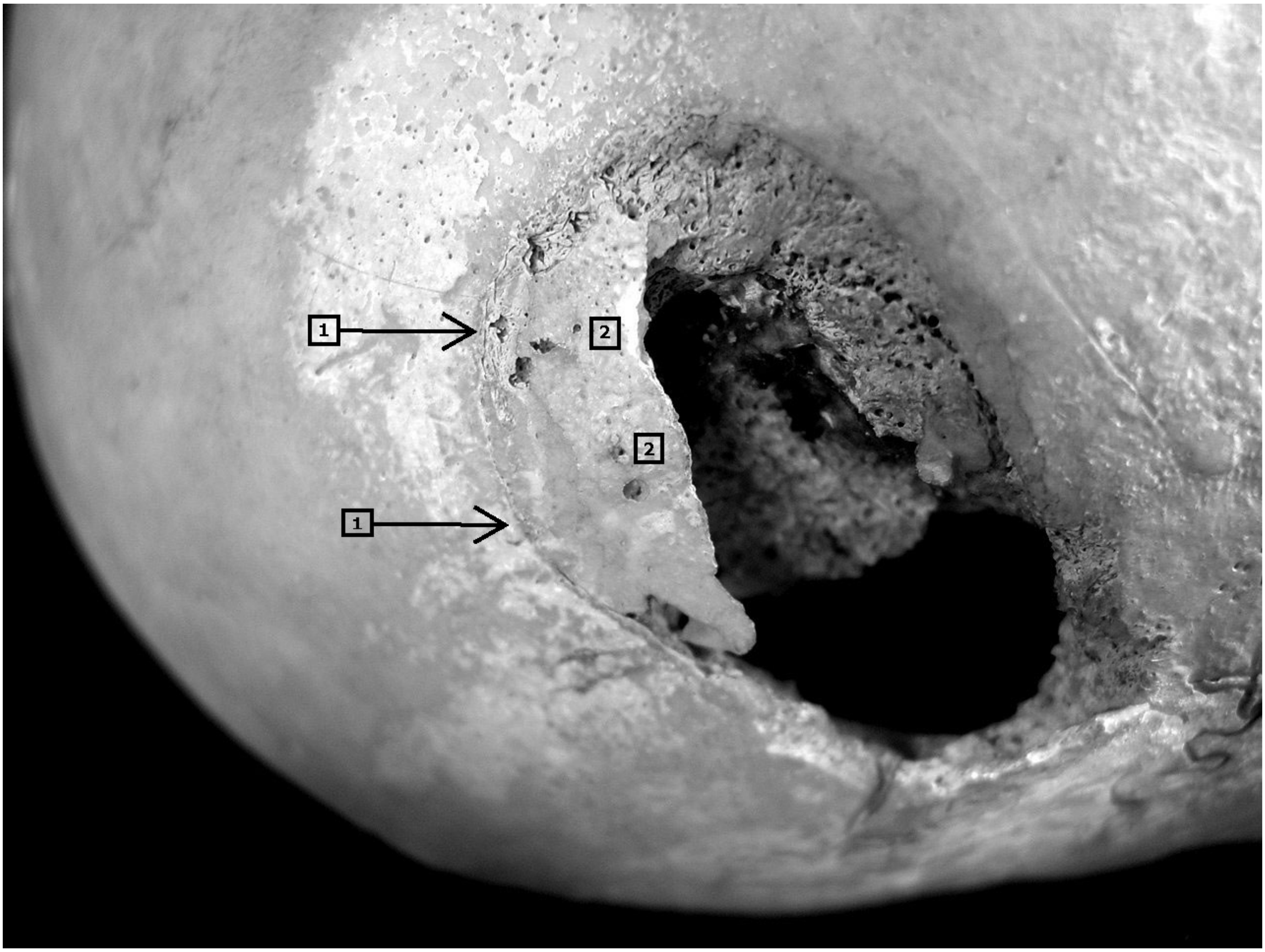

FIG. 2—*Cranial fracture with a line of demarcation present as a shallow channel with sharp margins running adjacent to the fracture margin (1). An area of apparent denser bone with a marked color difference indicates the presence of sequestration (2).*

these osseous responses were independently scored by both authors for ectocranial and endocranial surfaces.

Results

Of the 127 adult crania and crania sections available for observation, 53 (42%) were scored for the presence of at least one of the four osseous phases. While the ectocranial and endocranial surfaces were scored separately for each of the four bony responses, for this analysis a specimen was considered positive for the trait if it was present on either surface. Twenty-five percent of the specimens were scored for one or two of the defined osseous responses while only 17% of the fractured specimens displayed three or more of the bony traits. Table 1 presents the number of osseous responses scored per individual, and Table 2 presents the distribution of the number of osseous responses by weeks postfracture.

The earliest observed response to cranial fracture occurred at 5 days (Table 3). This represents a single case of osteoclastic response on the ectocranial surface. It appears that in most cases, no osseous response is discernible during the first week. However, after the first week, the prevalence of both clastic and blastic activity begins to rise. In fact, by the sixth week, 100% of the cranial fractures observed demonstrated some form of osteoblastic and

TABLE 1—*Number of osseous responses per individual.*

Number of Osseous Responses	*n*	%
0	74	58
1	15	12
2	17	14
3	12	9
4	9	7
Total	127	100

TABLE 2—*Distribution of the number of osseous responses by weeks postfracture.*

	Number of Osseous Responses				
	0	1	2	3	4
Week 1	59	1	–	–	–
Week 2	7	4	1	2	–
Week 3	6	7	5	2	1
Week 4	1	1	2	3	3
Week 5	1	–	3	2	1
Week 6	–	–	2	1	–
Week 7	–	–	–	1	2
Week 8	–	2	4	1	2
Total	74	15	17	12	9

TABLE 3—*Distribution of osseous responses by weeks postfracture.*

	Type of Bony Response							
	Clastic		Blastic		Line of Demarcation		Sequestration	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent
Week 1	1 (2%)	59 (98%)	–	60 (100%)	–	60 (100%)	–	60 (100%)
Week 2	3 (21%)	11 (79%)	6 (43%)	8 (57%)	3 (21%)	11 (79%)	–	14 (100%)
Week 3	10 (48%)	11 (52%)	12 (57%)	9 (43%)	4 (19%)	17 (81%)	1 (5%)	20 (95%)
Week 4	9 (90%)	1 (10%)	5 (50%)	5 (50%)	8 (80%)	2 (20%)	4 (40%)	6 (60%)
Week 5	5 (71%)	2 (29%)	5 (71%)	2 (29%)	5 (71%)	2 (29%)	1 (14%)	6 (86%)
Week 6	3 (100%)	–	3 (100%)	–	1 (33%)	2 (67%)	–	3 (100%)
Week 7	3 (100%)	–	3 (100%)	–	3 (100%)	–	2 (67%)	1 (33%)
Week 8	7 (78%)	2 (22%)	8 (89%)	1 (11%)	3 (33%)	6 (67%)	3 (33%)	6 (67%)

osteoclastic activity. The limited number of specimens in the late stages of healing indicate both osteoblastic and osteoclastic activity decline somewhat, although both responses were present in over 80% of the observations after the sixth week.

In a pattern similar to the osteoblastic and osteoclastic response, the line of demarcation and sequestration typically showed a latent period followed by increasing prevalence. For the line of demarcation, an initial latency during the first week was followed by increasing prevalence through the fifth week. The pattern of expression is less apparent following the fifth week but appears to follow a general trend of decreasing frequency in the sixth and subsequent weeks.

Sequestration, on the other hand, appears not to follow any trend. There is an initial latency period during the first 2 weeks. Following this latent period, sequestration was scored at relatively low but varying frequencies. At no point did the frequency sequestration encompass 100% of our sample.

FIG. 3—*Specimen failing to demonstrate any osteoblastic activity at 8 weeks. This individual suffered a contusion wound that was treated by removing bony fragments and smoothing the edges of the fractured bone with a cutting forceps (AFIP 1001036).*

Discussion

In this study, an initial latency period was observed for all of the four osseous responses scored. This latent period lasts from 1 to 2 weeks and is followed by a period of increasing prevalence. In this study, the clastic and blastic responses peaked at the sixth week and were followed by decreasing frequencies in the seventh and subsequent weeks. While this may appear to be contradictory to our understanding of the process of bone healing, a more detailed examination of the three specimens that were not scored for osteoclastic or osteoblastic responses after the sixth week reveals a number of factors that may account for this apparent discrepancy.

First, there is evidence suggestive that the osteoclastic and osteoblastic response as defined for this study represents the initial phase of bony response that may be followed by a more mature phase in which a coordinated clastic and blastic response is manifest. This "true bone remodeling" was characterized by rounded fracture margins and closed or closing diploe with or without bony bridges uniting fragments to the vault. True bone remodeling was scored as present on specimens at 78 and 225 days.

Second, a single specimen was scored positive for sequestration and clastic activity but failed to demonstrate osteoblastic activity at more than 8 weeks postfracture. This specimen displays a massive area of sequestration covering more than 50% of the cranial vault (Fig. 3). Examination of this specimen suggests that despite substantial bony response around the fracture site, sequestration and the osteoclastic activity appear at the expense of any observable osteoblastic response. In fact, the lack of either osteoclastic or osteoblastic activity after the seventh week postfracture should not be interpreted as a lack of osseous response since all individuals displayed at least one of the four bony responses after the fifth week (Table 2).

While the pattern of clastic and blastic osseous response to cranial fracture seems clear—a latent period of approximately 1 week followed by an increasing prevalence—the expression of the line of demarcation and sequestration are less apparent. The line of demarcation likely establishes the boundary between the living bone and bone that will not survive the fracture due to a disruption in its blood supply. Blood supply damage may be caused by the periosteum tearing away from the bone or by the pressure of the hematoma restricting blood flow to the bone. When these conditions are met, the first osteoclastic activity concentrates along the line of demarcation. The progression of the clastic response eventually sequesters a portion of the cranial bone. The apparent relationship between the line of demarcation and sequestration is further supported by our observations in this study. For the 11 specimens scored as positive for sequestration, 91% were also scored positive for the line of demarcation ($n = 10$). Nearly 50% of the sequestration scored in this study occurs after the sixth week, suggesting that the resorption or exfoliation of the sequestrum is a long-term event. The long-term nature of sequestration is further supported in radiographs taken of several specimens, suggesting that only small portions of these areas had actually become avascular and necrotic.

Many factors, both internal and external, promote or retard the fracture healing process. Location of the injury, damage to soft tissue, degree of bone loss, impairment or loss of blood supply, nutrition, sex, age, hormones, immobilization, physical constitution, and a variety of other chemical and biological factors play important roles in the rate of fracture healing (7). For the specimens used in this study, the role of infection must be given special consideration.

During the U.S. Civil War, nearly 100% of soldiers who survived gunshot injuries suffered from infection. Often the initial injury was sufficient to induce infection, but the common medical practice of wound debridement with unsterilized instruments and the lack of aseptic surgical technique virtually guaranteed introduction of pyogenic organisms into the wound (16,17). Infection causes an immunological response to eliminate the pathogen (7,18), and it is possible that some of the bony manifestations scored in this study represent the affects of infection and not healing. In fact, there is evidence that two of the osseous responses we scored (widespread new subperiosteal bone and sequestration) are most likely due to infection.

In a 1946 study of cranial healing in adult rats, Pritchard (19) observed that when infection occurred, widespread new bone formation was observed under the pericranium. In another study, Chege and coauthors (20) analyzed 71 Peruvian trephined crania using gross appearance, radiography, and computed tomography (CT) for evidence of healing. They noted that subpericranial bone regeneration with bone resorption, extensive bony nodules and depressions, or extensive thickening of the new bone appeared to be the bony manifestations associated with infection. Similar response was observed in the Civil War sample with the formation of new subperiosteal bone formation at distances >5 cm from the fracture margin and sometimes involving the facial bones.

Similarly, the presence of sequestration seems to indicate the presence of an infectious agent. Although some necrosis of bone is associated with almost any fracture, the dead bone normally is removed by osteoclastic activity or is replaced due to revascularization by surrounding osteogenic tissue. Sequestration is rare when pyogenic infection is not present. For this study, sequestration was selected as an important scoring criterion following a survey of the sample suggesting that sequestration was a common sequelae of Civil War cranial fractures. In fact, sequestration was scored as present in over 8% of the observations we made.

Clearly much work remains to be done to further our understanding of fracture timing in dry bone specimens. The study presented here focused on the macroscopic appearance of bone response. It is possible that histologically assessed healing rates may differ from those reported here. Certainly, the relationship between the gross appearance of bone healing and histological changes remains to be further explored. In addition, in forensic contexts determining the timing of multiple fractures is often important in child abuse cases. Our results are derived from a sample of male adults from the Civil War and, therefore, may not be applicable to modern juvenile remains.

However, the results from this study elucidate a number of characteristics regarding the temporal progression of the osseous response to cranial fracture that can inform forensic observation of healed and healing fractures. First, the osteoclastic response can occur earlier than the osteoblastic response. In this study, the osteoclastic response was observed to occur during the first week. However, osteoblastic observations are more common during the second and third weeks, and it is not until the sixth week that 100% of the sample showed both an osteoclastic and osteoblastic response.

Second, the first osteoblastic response was observed as new subperiosteal bone formation. While the clinical and histological evidence indicates that it should take at least 3 weeks, blastic responses were observed on 43% of all second week postfracture observations, and 14% of all osteoblastic observations occurred during the second week. Third, infection may cause widespread new bone formation, and sequestration is common in such cases.

As a final word of caution, when calculating time elapsed since trauma, the examiner should provide only a minimal response time, given that a certain number of days is needed for a response to occur. Some individuals will respond more slowly, but given the physiology and pathophysiology, there is a limit to how quickly individuals can respond. Based on this study, it appears that rarely do individuals demonstrate a macroscopic response to either trauma or infection following trauma during the first week. However, the frequency of bony response noticeably increases in the subsequent weeks, and by the sixth week postfracture, all individuals display some bony response to the cranial injury.

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