Nicholas P. Herrmann, M.A.[1] *and Joanne L. Bennett, M.A.*[1]

The Differentiation of Traumatic and Heat-Related Fractures in Burned Bone*

REFERENCE: Herrmann NP, Bennett JL. The differentiation of traumatic and heat-related fractures in burned bone. J Forensic Sci 1999;44:(3)461–469.

ABSTRACT: Interpretations of antemortem and perimortem trauma are complicated when dealing with cases involving extreme exposure to fire. This investigation attempts to discern the signatures of perimortem trauma from heat related trauma. Femora of domestic pig, *sus scrofa,* with minimal soft tissue and articulated patellae were subjected to varying traumatic forces. Skeletal elements were impacted with blunt and sharp forces, cut with varying instruments, subjected to torsional forces or shot.

Bones were burned in various situations in conjunction with Knox County Rural/Metro Fire Department training exercises conducted in Knox County, Tennessee. Following recovery, fragments were subjected to radiographic, macroscopic, and microscopic analyses. Skeletal elements were reconstructed to permit accurate comparison with pre-fire visual records. In addition, fracture surfaces were examined under both transmitted light and scanning electron microscopy in an attempt to discern surface signatures of the causal fracture (trauma, heat, or situational).

Results indicate that signatures of sharp force trauma remain evident following incineration. Furthermore, radiopaque spatter was not observed in any shot specimen. However, these initial findings suggest that the interpretation of blunt force and torsional trauma requires a rigorous examination and comparison of fracture patterns in conjunction with surface morphology.

KEYWORDS: forensic science, forensic anthropology, burned bone, fracture morphology, perimortem trauma

The accurate interpretation of perimortem trauma is crucial to anthropological and pathological analyses. However, such determinations are complicated when dealing with cases involving extreme exposure to fire. Burned skeletal elements typically exhibit severe fragmentation and fracturing limiting interpretations of antemortem and perimortem trauma. Although the effects of fire upon skeletal material have been considered by numerous researchers (1–10), these investigations were not designed to address traumatic interpretation. These archaeologically inspired works provide useful information concerning the intensity and duration of heating as well as data on structural changes. This research, however, does little to aid forensic or contemporary interpretations of burned human remains. Recently, limited examinations and analyses have been advanced towards isolating and recognizing heat induced trauma (11–13). Nevertheless, more specific investigations are necessary to formulate criteria with which to accurately differentiate between perimortem fractures (i.e., traumatically induced) and heat-related fractures as well as situational fracturing. Situational fractures occur during post-fire recovery or as a result of physical forces impacting the skeletal remains late in the fire episode. It is important to note that these fractures are not directly heat-induced.

Forensic anthropologists and pathologists commonly classify traumatic events as resulting from sharp forces, gunshot or blunt forces (see 14–17). Through the documentation and interpretation of traumatic signatures, the forensic anthropologist can infer details concerning the manner of death. Sharp force trauma traditionally includes cutmarks, sawmarks, and stab wounds evidenced by sharp margins, blade striae, kerf walls and sheering of cortical and cancellous bone surfaces (15,18–22). Gunshots are characterized by beveling, radiating fractures, concentric fractures and is often confirmed by the presence of lead spatter (17,23,24). Blunt force trauma is commonly associated with diverse fracture patterns and is often evidenced by an impact point (11,12,16,25–28). Each of these forces generates unique skeletal attributes that are usually readily identifiable in unmodified remains, however, exposure to heat can significantly blur traumatic signatures. The aim of the present study is to investigate which, if any, markers of skeletal trauma remain visible following incineration.

Heat Induced Fractures

Bone is a resilient yet fragile structure predominantly comprised of collagen, which provides tensile strength, and hydroxyapatite crystals which provide compressive strength or hardness (28). With extreme heat, the dehydration of collagen decreases the elasticity of bone which dramatically alters the structural integrity causing shrinkage, distortion, and deformation. Descriptions of heat induced fractures have been generated by anthropologists as a result of investigations of archaeological cremations and experimentally burned bone (1–3). Commonly defined by location and direction of propagation, heat induced fractures are classified as longitudinal, curved transverse, straight transverse, patina and delamination (see 13). Fractures that follow the long axis of the bone and usually propagate with the grain are recognized as longitudinal fractures. Curved transverse fractures occur in a stacked arc formation across the grain of the bone and are commonly associated with the reduction of soft tissue during incineration. They are traditionally referred to as thumbnail fractures, and are considered a unique product of heat exposure as they do not resemble defects attributable to trauma. Straight transverse or step fractures extend from the mar-

[1] Department of Anthropology, The University of Tennessee, Knoxville, TN 37996.

* Presented in part at the 49th Annual Meeting, American Academy of Forensic Sciences, New York, NY, February 1997.

* This study was supported by a Lucas Research Grant from the Forensic Sciences Foundation.

Received 11 June 1998; and in revised form 31 Aug. 1998; accepted 31 Aug. 1998.

gin of longitudinal fractures across the grain of the bone. Patina affects outer layers of cortical bone and is typically found in epiphyseal regions. It is characterized by a cracked and dehydrated appearance and is commonly likened to the surface of an oil painting. Delamination is the peeling or flaking away of bone layers, particularly the separation of cortical and cancellous bone in epiphyseal regions (see 13). Although anthropological experimentation has demonstrated that these fracture types are related to pre-incineration condition of the material, duration of heating, and exposure temperature, several of these patterns mimic traumatically induced fracture propagation.

Traumatic Fractures

Fractures, as defined by basic beam theory, are caused by the application of a load to a given span (e.g., a long bone) and will develop where stress exceeds the tensile strength of the material. The type and degree of fracture is, in part, related to the energy absorbing capacity of the material (i.e., the condition of the bone) (29). In addition, response to a directional force is related to the velocity, rate and repetitive nature of that stress or force. In an investigation of the properties of bone fracture, Piekarski (29) found that the discontinuous structure of fresh bone influences the direction and propagation rate of fractures. He observed that fractures which propagate around vascular structures, such as osteons, require more energy to travel though the entire bone. In addition, research has suggested that the rate of fracture propagation dictates the resulting fracture surface morphology (29,30). Researchers found that low energy or slowly propagating fractures typically produce "rough" fracture surfaces as a result of the fracture traveling around vascular structures. Whereas high energy fractures with rapid propagation rates indiscriminately cut across these structures producing a smoother fracture surface. Furthermore, Bonfield and Li (31) concluded that the energy absorbing capacity of heated bone was far less than unheated bone, such that elements heated over 200°C absorb little, if any energy. Similarly, Lakes and coworkers (32:973) found that "wet bone can redistribute strain in homogeneous fields in a way favorable to toughness" whereas dry bone cannot regulate strain in such a fashion. Given this, fire induced fractures should exhibit characteristics similar to those resulting from high energy forces (i.e., rapid propagation) due to the reduced energy absorbing capabilities of heated bone. The fracture mechanics of dry/burned bone differ significantly from wet/unburned bone and signatures of these mechanical differences should be evident in the fractures produced in such structurally contrasting materials. Clearly the variation in properties between unheated and heated bone suggests that the differentiation between perimortem and heat induced trauma should be possible, although to date it has not been thoroughly investigated.

Materials and Methods

An actualistic study was conducted to investigate the parameters surrounding traumatic and heat induced failure of bone. This research attempts to discern signatures of perimortem trauma, heat induced trauma, and situational fracturing through macroscopic and microscopic assessment of fracture patterning and surface morphology. Given the quantity of bone needed and the destructive nature of this experiment, readily available non-human skeletal material was utilized.

Forty-one femora of domestic pig, *Sus scrofa*, with minimal soft tissue and articulated patellae were acquired from local processing plants (Table 1). A total of 28 specimens were subjected to sharp, gunshot, and blunt forces. Five additional specimens were subjected to torsional loading resulting in spiral fractures. Eight unaltered specimens served as controls. Specifically, 12 specimens were impacted with sharp force; two bones were cut with a scalpel and two were incised with a knife. Four femora were cut with a stryker saw; two specimens were marked with transverse cuts and two specimens were impacted with longitudinal cuts. Incisions were made at various depths with at least one perforating the medullary cavity. Four specimens were transversely bisected at midshaft using a standard rip saw. A total of eight femora were shot with a range of calibers including a 22 long rifle, 45 full metal jacket, 38, 357, and 357 hollow point. Eight of the 41 femora were subjected to blunt trauma. Elements were positioned on a flat surface supported only by the posterior greater trochanter and distal condyles. Femora were impacted on the anterior midshaft to failure; though no more than two blows were required to fracture each bone. Three femora were hit with the flat edge of a hammer and five with the ball portion. Blunt force trauma commonly produces complex comminuted fractures in addition to micro-fractures not radiographically visible (25). In an attempt to reduce the influence of micro-fractures during incineration, five femora were subjected to torsional loading which typically produces a single spiral fracture and an associated longitudinal fracture (Kress personal communication 1996). Spiral fractures were generated with the assistance of Dr. Tyler A. Kress, Department of Industrial Engineering, University of Tennessee, and Dr. David J. Porta, Department of Biology, Bellarmine College. The specimens were torqued to failure following the methodology set forth by Porta (25,26). Small fragments were removed from three of these specimens prior to burning to facilitate comparison (i.e., burned and unburned) of mirror (i.e., adjacent) fracture surfaces. Prepared specimens were photographed and radiographed prior to exposure to heat.

TABLE 1—*Summary counts of induced trauma.*

Sharp Force	
Scalpel	2
Knife	2
Stryker saw	2
Longitudinal	2
Transverse	2
Rip saw	4
Gunshot Caliber	
22 long rifle	3
45 full metal jacket	2
38 solid	1
357 solid	1
357 hollow point xtp	1
Blunt Force	
Flat end hammer	3
Ball end hammer	5
Torsional loading	5
Control Specimens	8
Total specimen number	41

All elements, with the exception of the spiral fractured specimens, were burned during a joint training exercise by the Knox County Fire Investigation Task force and Rural/Metro Fire Department, Knox County, Tennessee. Specimens were systematically positioned inside a single story frame house with the location of each recorded. Traumatized specimens were situated at 1–2 m intervals against the outside walls of the structure (see Fig. 1). This served to increase the level of recovery while potentially decreasing the degree of commingling. Control specimens were situated along interior walls as depicted in Fig. 1. The fire was started at the rear of the house with accelerant and progressed naturally until the structure was completely reduced in approximately 2 h and 30 min. Maximum burning temperature for the structure was estimated at 700–850°C (Dalton personal communication 1995). Specimens were recovered 48 h after ignition of the house.

The five spirally fractured specimens were burned at the Knox County Rural/Metro Training Facility. These elements were placed within a large firebox and reduced in an intense wood fire and resulting ash pile for approximately 2 h. Soft tissue and fluids were completely burned away on all elements and each specimen exhibited partial calcination. Elements were removed from the firebox and excavated from the ashes after moderate cooling. Initial analysis of all elements involved a cursory assessment aimed at recognition of pre-incineration trauma. Evaluation of specimens impacted with sharp force and gunshot incorporated macroscopic and radiographic evaluation, while specimens altered by blunt force were submitted to a more rigorous examination.

As highlighted by previous research (11,12), the differentiation between heat and traumatically induced fractures (i.e., blunt and torsional) is potentially the most problematic aspect of forensic analysis. Realizing this confounding factor, it became apparent that mere assessment of fracture patterns would not be sufficient to discern the nature of such fracture forces. Therefore, based on previous work (29,30 N. P. Herrmann unpublished observations 1993), a series of variables which reflect the degree of burning, fracture patterning and fracture surface morphology were defined (see Table 2). Three randomly selected fragments from each of the specimens exposed to blunt force and torsional trauma were scored according to these variables. Bone fragments were categorized by size and the degree of burning. The angle of the fracture in relation to the long axis bone was determined for three arbitrarily selected surfaces on each fragment. Viewed at 35–70× magnification under an Olympus SZH10 Research Stereo microscope, collagen fibrils and vascular pullouts were assessed for each surface. In addition, the transverse and texture of each surface was evaluated. Based on these observations, the nature of each fracture (i.e., heat or traumatic force) was predicted for each surface.

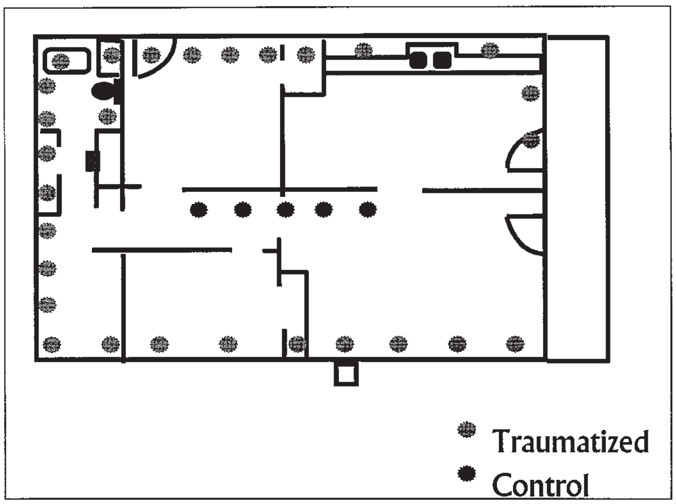

FIG. 1—*Schematic of house floor plan.*

TABLE 2—*Fracture characteristics recorded for this study (partially adopted from Woltanski).*

Variable	Descriptions
Degree of Burning for Entire Element	Partially Burned (i.e., smoked/ blackened) or Calcined
Number of Fragments	Number of Fragments Collected (Highly Dependent on the Recovery Rate)
Fracture Type as Drawn from Visual and Radiographic Examination	Oblique, Perpendicular, Comminuted, Spiral
Size of Fragment Examined	Small (<3 cm), Medium (3–5 cm) or Large (>5 cm)
Color of Fragment	Gray, Black, or White
General Fracture Surface Angle Description Oriented to the Long Axis of the Bone	Longitudinal, Perpendicular, or Sloped
Fracture Surface Texture	Rough or Smooth
Collagen Fibrils Evident?	Yes or No
Basic Classification of the Transverse Organization of the Fracture Surface	None, Poor, Slight, or Good
Canals Evident? (Vascular or Haversian Canals)	Yes or No
Vascular Pull-Outs Evident? (See Piekarski [29] for description of osteonal pull-outs)	Yes or No
Based on These Variables was the Fracture Trauma Induced? (Not a Heat-related Fracture)	Yes or No
Is the Fracture Trauma Related Based on the Pre-Fire	Yes or No

Results

As expected, recovery was incomplete although only a single specimen was unaccounted for (one impacted with a 22 long rifle). The majority of specimens were calcined and highly fragmented. Approximately 50% of each specimen was recovered. In an attempt to appreciate the variable nature of burning, we calculated overall shrinkage on eight specimens. Four measurements, maximum length, maximum width at mid-shaft, and maximum width across both proximal and distal epiphyseal margins were taken on burned specimens and radiographs. A maximum shrinkage of 14.7% and a minimum of 6.8% was recorded. Shrinkage was greatest at the distal region adjacent to cancellous structures on all specimens.

Sharp Force

All sharp force traumas remained visible and recognizable following incineration. The transverse and longitudinal stryker saw cuts, and the rip saw kerf walls are clearly detectable in the burned bone. Knife cutmarks also remain recognizable and identifiable after incineration as previously demonstrated (13). Heat induced fractures traverse some of the more superficial cuts such as the scalpel etches. In several instances heat related fractures propagated along portions of deeper cuts (i.e., those that puncture the medullary cavity), although it does not appear that these cuts influenced the direction of fracture propagation during burning. Assessment of these specimens indicates that incineration does not obliterate signatures of sharp force trauma. However, the effects of morphological changes (i.e., shrinkage) resulting from burning must be considered during final interpretations of such traumas.

Gunshot

Specimens shot displayed a high degree of fragmentation prior to burning. This is related in part to the velocity and proximity of the weapon to the skeletal material (17,23). Pre-incineration radiographs demonstrate minimal lead spatter, none of which is evident in post burning radiographs. This is particularly relevant, as radiopacities are often considered indicative of gunshot trauma. The high degree of fragmentation prohibited post-incineration reconstruction and subsequent interpretation of fracture morphology.

Blunt Force

Elements subjected to blunt and torsional forces were partially reconstructed and compared to pre-incineration radiographs to facilitate designation of fractures as traumatic or heat induced. Our assessment may underestimate the frequency of traumatic fractures given the occurrence of infractions or micro fractures that were not apparent radiographically. However, in a blind test, we correctly assessed the nature of the fractures 77% of the time. Spiral fractured specimens displayed fewer situational fractures compared to specimens burned in the house due to the enclosed and protected environment of the firebox.

In our analysis of a total of 71 fracture surfaces, we observed some general trends. During reconstruction, it was noted that larger fragments are associated with traumatic fracturing while smaller fragments appear to be related to heat induced fracturing. Chi-square test of the relationship of fracture angle to fracture type revealed that perpendicular fracture angles (i.e., transverse) are typically associated with heating. This finding was expected given that a majority of the fractures evident prior to burning were longitudinal or oblique leaving adjacent areas (i.e., perpendicular zone) exposed to damage. Assessment of longitudinal fractures proved problematic, given a high frequency of occurrence and the fact that longitudinal propagation is related to both trauma and burning. Analysis indicates that smooth surfaces with occasional contaminates are most frequently associated with traumatically induced fractures. Situational fractures are characterized by sharply defined features and clean, richly colored margins. Analysis indicates that surface morphology (i.e., the texture of the fracture surface) in combination with fracture patterning is potentially the most useful method for assessing the time of fracture occurrence.

FIG. 3—*View of fracture surface shown in Fig. 2 at 100×.*

FIG. 2—*Burned traumatically induced perpendicular fracture sur-*

SEM Analysis

Based on observations drawn from the transmitted light microscope study, a series of fragments representing either fresh, burned, heat induced, or situational fracture surfaces as well as scalpel cutmarks were examined under a Cambridge Stereoscan 360 Scanning Electron Microscope (SEM). Dr. Charles Brooks and Mr. Gregory Jones of the Department of Material Science and Engineering of the University of Tennessee graciously provided access to the microscope as well as several hours of technical assistance in sample preparation and image production. Specimens were placed in a low vacuum for a minimum of 48 h prior to imaging to insure rapid microscope chamber evacuation. All specimens examined were sputter coated with gold within a nitrogen plasma field produced by a Hummer I Technics sputter coater. Due to microscope time constraints and preparation times associated with the specimens only a limited number of surfaces were examined. Specimen surfaces were scanned at 20Kv with varying probe currents in an effort to maximize image quality. Black and white Polaroid images were taken of select areas that were deemed representative of the overall surface morphology. Specific locations were isolated and photographed to highlight particular characteristics of fracture types. In the following section, to illustrate the features and patterns observed in this study, we provide general descriptions and photomicrographs of surfaces examined under the SEM. Descriptions and images are grouped according to trauma type and treatment.

FIG. 4—*Burned trauma-induced spiral fracture surface.*

FIG. 5—*A close-up of a pull-out located in the center of the image (view of boxed area in Fig. 4 at 1000×).*

Burned Traumatic Fracture Surface

A burned traumatically induced torsional fracture surface is illustrated in Fig. 2. The depicted surface represents a portion of a perpendicular fracture across the medial aspect of the proximal shaft. This area is located at the terminal end of the spiral fracture. Note the melted appearance of the bone surface, a characteristic also observed with a transmitted light microscope. At low magnification, contaminants frequently mask the true surface morphology of the burned specimen.

Figure 3, a close-up (100×) of the fracture surface shown in Fig. 2, illustrates the irregular surface topography and the high percentage of field area masked by contaminants (ash and other small combusted particulate matter). The surface is characterized by cleanly sectioned vascular/haversian systems, although several areas appear rough. These rough edged canals are interpreted as Piekarski's vascular pull-outs (29). In addition, numerous cracks traverse the image likely a result of burning or pre-imaging vacuum preparation, which dries the specimen.

Burned spiral or oblique traumatic fractures typically appear smooth under low-power transmitted light. However, as is seen in Fig. 4, such fractures are characterized by a complex surface topography when viewed with a SEM. Often vascular canals are longitudinally sectioned thus the surface appears "rough" and irregular.

The image seen in Fig. 5 is the selected area of Fig. 4 viewed at 1000×. Located in the center of the photomicrograph is an excellent example of a vascular pull-out. The sharp, cusp-like margin of the feature is clearly evident. Several other vascular structures within the frame display sharp edges, but most canals are sectioned without marked topographic relief. These features and coarse quality of the surface are indicative of a fracture, which likely propagated at a slower rate across this area (29,30).

Heat/Situational Fracture Surface

Figure 6 represents a heat induced straight transverse fracture occurring on the posterior distal shaft. Under transmitted light the surface appears very smooth and is vividly colored black to white. In this photomicrograph, the earlier topographic observations are confirmed. The fracture surface is very smooth in comparison to both burned and fresh traumatic fracture surfaces. Vascular canals are evident, but most are cleanly sectioned.

Figure 7 is a close-up (100×) of the straight transverse fracture surface shown in Fig. 6. The surface is located near the endosteal margin and the large void represents a large vascular canal. Similar to the low-magnification view of this fracture surface, vascular canals are cleanly sectioned and the surface has a vitreous appearance. In fact, some areas display concentric ridges typical of fracture propagation through glass-like materials. The presence of these features would typify fractures occurring late in the burning process or after the element had cooled (i.e., a situational fracture not related to burning).

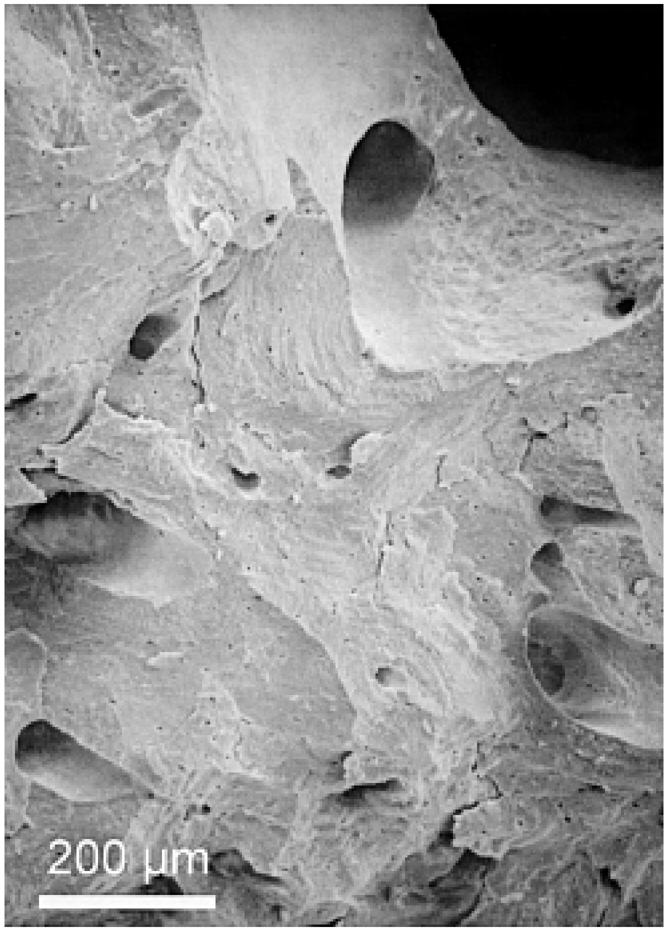

FIG. 7—*A close-up at 100× of the straight transverse fracture surface shown in Fig. 6.*

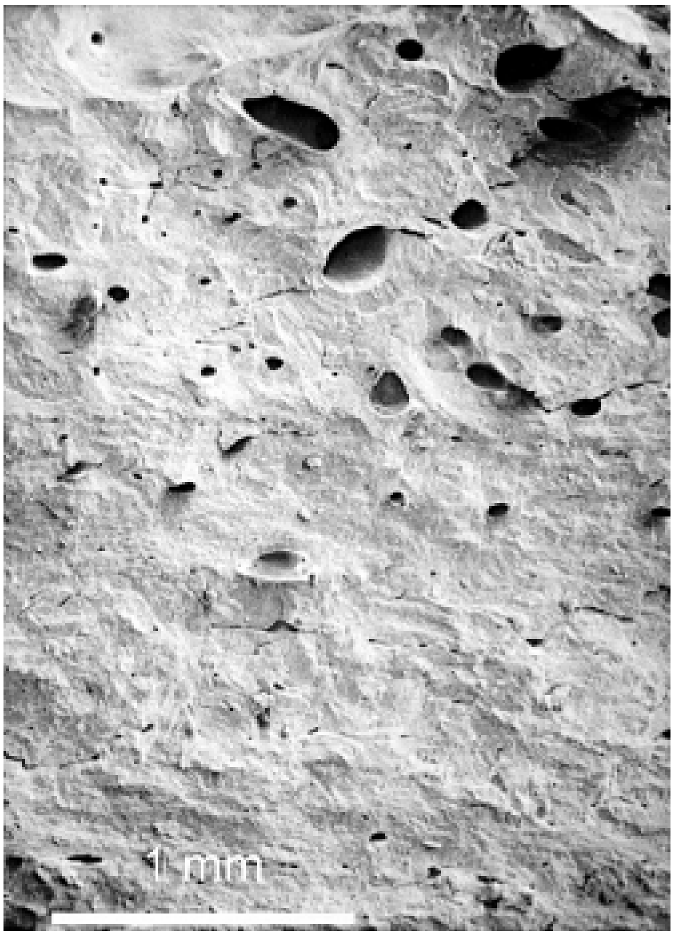

FIG. 6—*Example of a heat induced straight transverse fracture surface at 35×.*

A heat-induced longitudinal fracture surface is depicted in Fig. 8. Overall this surface appears fairly uniform and rough in texture with slight transverse organization. However, the fracture surface does not appear to be glass-like such as the straight transverse heat-induced fracture seen in Fig. 4. Numerous vascular canals are longitudinally sectioned, which is similar to the spiral and oblique traumatic fracture surfaces examined in this study. Differentiating between these two patterns would be difficult in a forensic context. Heat fractures, such as the one shown here, might be produced in a very similar fashion as traumatic fractures given that heat-induced fractures of complete (i.e., intact) bones can result from a rapid expansion of medullary fluids.

Figure 9 represents the highlighted area of Fig. 8 at a magnification of 150×. The surface topography of a heat-induced longitudinal/oblique fracture surface is generally characterized by sectioned vascular canals and a rough surface texture.

Fresh Traumatic Fracture Surface

Figure 10, a transverse fracture, is a portion of the unburned fracture surface opposite to the surface depicted in Fig. 2. In general, the unburned surface displays greater definition of bony structures

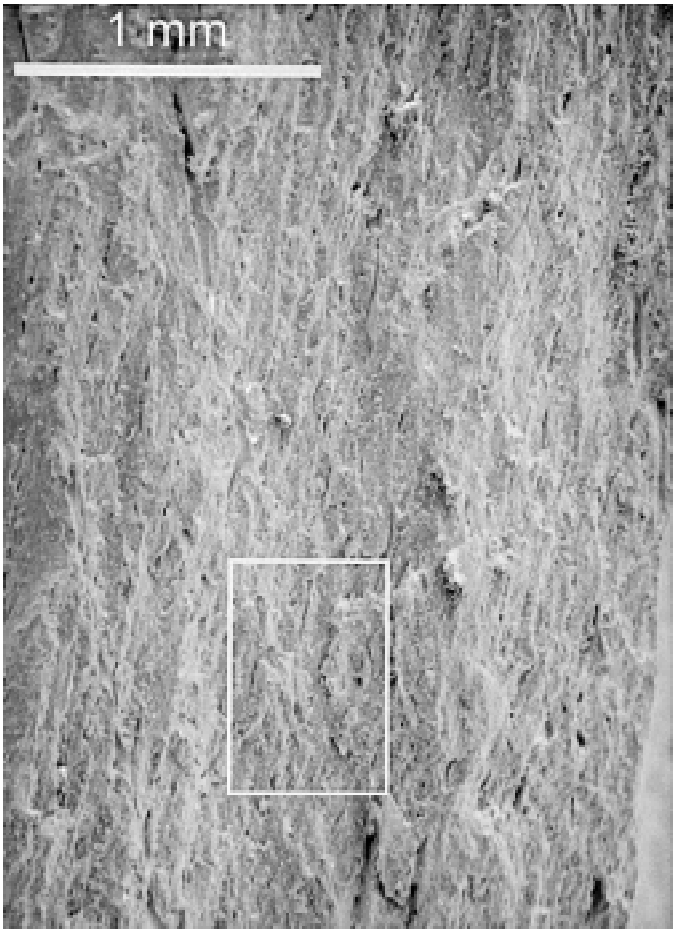

FIG. 8—*Heat induced longitudinal fracture surface at 35×.*

FIG. 9—*Detail at 150× of heat induced longitudinal fracture surface in Fig. 8.*

compared to burned fracture surfaces. Surface contaminates are adhering detergents resulting from specimen cleaning.

Burned Sharp Force Trauma

Figure 11 represents a back-scattered electron image (BSE) of a scalpel cut across the anterior surface of a partially calcined bone. The margins of the cut are well preserved with distinct relief along the cut edges. Surface contaminates fill portions of the cut; however, these materials do not chemically differ from the surrounding bone.

Discussion

This pilot study is an attempt to discern signatures of perimortem trauma and heat related trauma through macroscopic and microscopic assessment of fracture patterning and surface morphology. Signatures of sharp force trauma remain evident following incineration whereas signatures of gunshot trauma could not be discerned. Interpretations of blunt force trauma require a rigorous examination of fracture patterning and surface morphology although the appearance of certain traits reflects the mode of fracturing: burning, situational, or traumatic. Situational fractures are the most readily differentiated. Traumatic and heat-induced fractures do display very similar qualities, especially the surfaces of longitudinal fracture. Differentiation of these fracture types based on surface morphology alone would be difficult. Therefore, the initial stage of a traumatic analysis of burned remains must include the reconstruction, macroscopic examination, and assessment of suspect elements. Based on these preliminary conclusions, select fracture surfaces should be subjected to microscopic examination.

While we do not offer these findings as guidelines for fracture interpretation, we present them as evidence that differentiation of traumatic and heat induced fractures is possible. Given that living and burned bone are of different physical properties, ductile and fragile, respectively, it follows that they should yield distinctive signatures. The development of criteria with which to differentiate these signatures requires us to augment information derived from the assessment of fracture patterns with a more intensive investigation of specific fracture surfaces.

Acknowledgments

The authors are indebted to the Forensic Sciences Foundation, which provided funding for this project in the form of a Lucas Research Grant. Fire Investigator Mike Dalton of the Knox County Sheriff's Department/Fire Bureau, Lieutenant Chris Allen and firefighters with Rural/Metro Fire Department built and extinguished many fires for us. Thanks to Dr. Tyler Kress and Dr. David J. Porta for helping us break the bones without injury. Lays Packing Com-

FIG. 10—*Example of an unburned trauma induced perpendicular fracture at 35×. (Note: opposite surface of that depicted in Fig. 2.)*

FIG. 11—*BSE image of a burned scalpel cut at 100×.*

pany and Swaggerty Sausage Company provided us with all the pig femora we could ever need. Dr. Charles Brooks and Mr. Gregory Jones offered suggestions and assistance in reference to electron microscopy. Thanks to the graduate students in the Department of Anthropology at University of Tennessee who helped collect the burned bones from the house. Thanks also to our ballistics specialist, Robbie Klippel, for shooting several specimens.

References

1. Baby RS. Hopewell cremation practices. Columbus: Ohio Historical Society, 1954.
2. Binford L. An analysis of cremations from three Michigan sites. Wisc Archaeologist 1963;44:98–110.
3. Buikstra J, Swegle M. Bone modification due to burning: experimental evidence. In: Bonnichsen R, Sorg M, editors. Bone modification. Orono: University of Maine 1989;247–58.
4. David B. How was this bone burnt? In: Solomon S, Davidson I, Watson D, editors. Problem solving in taphonomy: archaeological and paleontological studies from Europe, Africa and Oceania. Tempus vol. 2. Queensland: University of Queensland 1993;65–79.
5. Gilchrist M, Mytum H. Experimental archaeology and burnt animal bone from archaeological sites. Circaea 1986;4:29–38.
6. McCutcheon P. Burned archaeological bone. In: Stein JK, editor. Deciphering a shell midden. San Diego: Academic Press 1992;347–68.
7. Nicholson R. A morphological investigation of burnt animal bone and an evaluation of its utility in archaeology. J Arch Sci 1993;20:411–28.
8. Shipman P, Foster G, Schoeninger M. Burnt bone and teeth: an experimental study of color, morphology, crystal structure and shrinkage. J Arch Sci 1984;11:307–25.
9. Stiner M, Kuhn S, Weiner S, Bar-Yosef O. Differential burning, recrystallization, and fragmentation of archaeological bone. J Arch Sci 1995;22:223–37.
10. Thurman M, Willmore L. A replicative cremation experiment. No Am Archaeologist 1981;2:275–83.
11. Mayne P. The identification of precremation trauma in cremated bone [thesis]. Alberta (Canada): University of Alberta, 1990.
12. Mayne P. The identification of traumatic fractures in cremated bone: final results. Proceedings of the American Academy of Forensic Sciences; 42nd Annual Meeting 1990 Feb; Cincinnati.
13. Rockhold LA. Burned bone. In: Symes SA, editor. Bones: bullets, burns, bludgeons, blunders, and why. Proceedings of the Bone Trauma Workshop: American Academy of Forensic Sciences; 1996 Feb 19–24; Nashville, TN.
14. Knight B. Forensic pathology. New York: Oxford University Press, 1991.
15. Symes SA. Sharp trauma. In: Symes SA, editor. Bones: bullets, burns, bludgeons, blunders, and why. Proceedings of the Bone Trauma Workshop: American Academy of Forensic Science, 1996 Feb 19–24; Nashville, TN.
16. Berryman HE. Blunt trauma (cranial and tubular bone). In: Symes SA, editor. Bones: bullets, burns, bludgeons, blunders, and why. Proceedings of the Bone Trauma Workshop: American Academy of Forensic Sciences; 1996 Feb 19–24; Nashville, TN.
17. Smith OC. Ballistic bone trauma. In: Symes SA, editor. Bones: bullets, burns, bludgeons, blunders, and why. Proceedings of the Bone Trauma Workshop: American Academy of Forensic Sciences; 1996 Feb 19–24; Nashville, TN.
18. Symes SA. Morphology of saw marks in human bone: Identification of class characteristics [dissertation]. Knoxville (TN): University of Tennessee, 1992.

19. Guilbeau MG. The analysis of saw marks in bone [thesis]. Knoxville (TN): University of Tennessee, 1989.
20. Frayer DW, Bridgens JG. Stab wounds and personal identity determined from skeletal remains: A case study from Kansas. J Forensic Sci 1985;30:232–8.
21. Houck MM. Forensic taphonomy: Characteristics and identification of knife marks in bone. Proceedings of the American Academy of Forensic Sciences; 41st Annual Meeting 1989 Feb 13–18; Las Vegas.
22. Bromage TG, Boyd A. Microscopic criteria for the determination of directionality of cutmarks on bone. Am J Phys Anth 1984;65:359–66.
23. Di Maio VJM. Gunshot wounds: Practical aspects of firearms, ballistics, and forensic technique. New York: Elsevier, 1985.
24. Smith OC, Berryman HE, Lahren CH. Cranial fracture patterns and estimate of direction from low velocity gunshot wounds. J Forensic Sci 1987;32:1416–21.
25. Kress TA. Impacts biomechanics of the human body [dissertation]. Knoxville (TN): University of Tennessee, 1996.
26. Porta DJ. The anatomy and biomechanics of experimentally traumatized human cadaver lower extremity components [dissertation]. Louisville (KY): University of Louisville, 1996.
27. Porta DJ, Kress TA, Fuller PM, Frick SJ, Smock WS, Nichols GR, et al. Spiral fractures—definition and determination of torsional direction from radiographs. Proceedings of the American Academy of Forensic Sciences; 48th Annual Meeting 1996 Feb 19–24; Nashville, TN.
28. Smith OC, Peters CE. Biomechanics and the bone. In: Symes SA, editor. Bones: bullets, burns, bludgeons, blunders, and why. Proceedings of the Bone Trauma Workshop: American Academy of Forensic Sciences; 1996 Feb 19–24; Nashville, TN.
29. Piekarski K. Fracture of bone. J Applied Physics 1970;41:215–23.
30. Woltanski TJ. Determination of the pretreatment of bone: a macroscopic and microscopic approach to fracture patterns [thesis]. Knoxville (TN): University of Tennessee, 1993.
31. Bonfield W, Li CH. Deformation and fracture of bone. J Applied Physics 1966;37:869–75.
32. Lakes RS, Nakamura S, Behiri JC, Bonfield W. Fracture mechanics of bone with short cracks. J Biomechanics 1990;23:967–75.

Additional information and reprint requests:
Nicholas P. Herrmann, M.A.
Department of Anthropology
250 South Stadium Hall
University of Tennessee
Knoxville, TN 37996-0720