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Microscopic Characteristics of Hacking Trauma*

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ABSTRACT: The purpose of this study was to determine if it is possible to associate machetes, axes, and cleavers with the microscopic parallel striations they leave on the cut surfaces of the bone. Hacking trauma was experimentally inflicted on pig bones using machetes, axes, and cleavers. Negative impressions of both the cut surfaces of the bone and the weapon blades were analyzed using scanning electron microscopy. The results of this investigation indicate that it is possible to correlate a class of hacking weapons to trauma inflicted on bone by these weapons.

KEYWORDS: forensic science, forensic anthropology, hacking trauma, scanning electron microscopy (SEM), microscopic striations, sharp-force trauma, cut marks, weapons, cleavers, axes, machetes, tools

Hacking trauma is inflicted by chopping tools or weapons. It is differentiated from puncture wounds inflicted by implements such as screwdrivers and other edged metal weapon trauma such as that resulting from saws and knives. Forensic investigators commonly identify such "toolmarks" (thus encompassing a wide variety of human activity and weaponry) by comparing these marks with experimental markings made by the same class of suspect weapon (1,2). This study was conducted in order to determine the association of certain hacking weapon types to the microscopic parallel striations on the kerf (cut) wall.

Most studies of toolmark trauma have focused on implements other than those which inflict hacking trauma. Although hacking trauma from historical and archaeological contexts has stimulated some research, recent investigations have been limited to discussions of the metal weapons and gross descriptions of the wounds (3–12). Investigators in forensic contexts have concentrated on certain signatures or characteristics left by other types of weapons and tools on the cut surfaces of the bone (13–24). For instance, Symes et al. (25) were successful in demonstrating that the analysis of saw mark striations on the cut surface of the bone enabled individuation of the specific saw that inflicted the damage. They recount several experiments in which various types of saws (hand saws, power saws, Gigli saws) were used to cut through bone and demonstrate the differential patterning of striae resulting from the saw blades. These demonstrations have been used on several occasions in forensic investigations and legal proceedings to associate a class of saw to a specific incidence (usually involving postmortem dismemberment) (25,26). There are few investigations that form the bulk of the specific knowledge on hacking trauma (2,27–30). These studies identify criteria which serve to macroscopically identify edged metal weapon trauma and distinguish it from other types of trauma, such as postdepositional fracturing and other taphonomic processes, as well as to identify the "wedge" action of the blade and subsequent fracturing point of the bone (27,31).

Microscopic (SEM and light microscopy) analyses have been used recently to identify signature characteristics and features on the cut surface of the bone (2,27–31). These topographical features are marked by the parallel striations formed by characteristic qualities of the blade edge. Scanning electron microscopy (SEM) provides high-resolution three-dimensional surface images, an increased depth of field, and enhancement of topographical features on the cut surface of the bone that are not always visible with the naked eye or with light microscopy.

Wakely (27) discerned curved parallel striations on the cut surface (kerf) of a Bronze-Age axis (second cervical) vertebra from Covesea, Scotland. These striations are visible under a light microscope but are seen at a higher resolution under SEM. Wakely illustrated several other examples of these parallel striations, perpendicular to the kerf floor, occurring on the kerf walls of skull wounds from Anglo-Saxon cemeteries, Iron-Age war cemeteries, and a trophy head from Borneo. Wakely concluded that these parallel striations are ". . .clearly a general feature of bone that has been cleanly cut with a single blow from a thin, straight, metal blade" (Wakely, 1993:208).

The objectives of our study were:

1) To identify the characteristic signatures of specific weapons on the cut surface of the bone. Our study complemented the past research of Wakely (27) in identifying the topographical features on the cut surface of the bone caused by imperfections and individual characteristics of the blade edge.

2) To correlate the striations on the cut surface to specific weapon types. Symes et al. (25) were able to achieve a correlation between certain striation patterns on the cut surface of the bone and the class of saw blade responsible. This observation has enabled the identification of saw blade types used in forensic investigations. Houck (2) was able to demonstrate a similar correlation between knife marks and the microscopic patterning on the kerf wall. Our study tested the applicability of such a comparative baseline to hacking trauma.

3) To establish a reliable database from which comparative analysis may be performed. The recent success of saw mark iden-

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tification has opened an area of forensic science that had previously been thought to be too difficult or too variable for reliable identification of weapons. It is possible that systematic analysis of hacking weapon trauma may enable forensic investigators to accurately correlate specific weapon types, class, or individual to violent crimes.

Materials and Methods

The skeletal elements used were domesticated pig (*Sus scrofa*) limb bones ($n = 28$). The sample was comprised of mostly femora and tibiae (hindlimb bones), but also included one ulna and one humerus (forelimb bones). These elements were chosen for their size, in order to best approximate the tensile strength of human long bones, as well as their cortical bone surface area for analysis. The elements were semifleshed. The skin and a portion of the muscle had been stripped, but some muscle and connective tissue remained on the elements.

Three hacking weapons were used to inflict the trauma: machete, axe, and cleaver (32,33). These weapons were chosen for their varying size of head, differential wedge thickness of the blade, differential weight, and length of handle. Three weapons of each type were employed. The element was placed on a wooden block and the trauma was inflicted manually. The force of each weapon was not regulated. Justification for this methodology is evident in forensic cases as most trauma is not inflicted in a regulated manner. The variability of blows served to approximate the variation that is evident in forensic investigations. All of the weapons were previously used, and in most cases, several years old. Heavy use wear was evident in the form of visible scratches and dents along the blade surface. The one exception was Cleaver 1, which was never used prior to the experiment.

Two cuts were made to each element whenever possible: one perpendicular to the long axis of the element (at approximately 90°), and one oblique-angle cut to the long axis of the bone (at approximately 45°) (32,33). This series of two cuts per element was performed three times for each weapon, except in the cases where the blow completely fractured the bone, thus making another blow impossible, usually in the case of the axe-inflicted trauma. All attempts were made to aim for the middiaphysis region in order to impact the cortical bone surface which would result in a more promising surface for analysis, as opposed to the porous, cancellous bone nearing the epiphyses. The same weapon was used to inflict the trauma on any given element.

The elements were then defleshed by boiling, the method that we felt would least affect the cut surfaces. Alternative defleshing methods, such as maceration, chemical means, or carrion insects, were ruled out as potentially damaging to the delicate cut surfaces of the bone. Insect gnawing, for instance, might leave confusing marks at the microscopic level. Elements of each weapon type, or class, were kept separate. The elements were placed in a large cooking pot, and were boiled down in water with a domestic degreasing agent (household cleaner). Colored identification tags were attached to each element, marking the number and class of weapon that inflicted the damage, as well as its number in the series of blows.

The elements were prepared for final analysis using scanning electron microscopy (SEM). Negative impressions, or casts, were taken of the cut surfaces of the bones using Mikrosil Forensic Casting Material. Negative impressions were also taken of the weapons' edge, in order to compare the striations on the cut surfaces to the features of the weapon edge. These negative impressions were then sectioned and mounted on aluminum stubs and coated with 90 Å of gold/palladium alloy. Specimens were analyzed on the East Carolina University Biology Department scanning electron microscopes: an *International Scientific Instruments 40* operating at 10 Kv, and a *Phillips 501* operating at 10 Kv. Micrographs of specimens that represented typical characteristics of weapon class, both of the blade and of the cut bones, were taken on *Polaroid Positive/Negative 55 Film* for the ISI. Final images were acquired from the Phillips 501 using *Gatan Digital Micrograph 2.5.*

Analysis was guided by past researchers in identification of parallel striation patterning on the cut surface of the bone. Houck (2), Wakely (27), Wakely and Bruce (28), and Wenham and Wakely (30) identified parallel striations on the cut surface of the bone, resulting from the use of hacking weapons. Additionally, Symes et al. (25) were successful in demonstrating the correlation between saw-mark striations on the kerf wall and floor and class of saw. With this research in mind, visual analysis was performed at varying magnifications, ranging from 20× to 160×, depending upon the specimen. After identification of which bone samples consistently revealed characteristics that best reflected the characteristics of that weapon class, those particular weapon casts were sectioned and prepared for SEM analysis. Due to the length of the blades on these weapons, reasonable estimates of the portion of the blade used to inflict wounds were necessary. Observations of used tools and weapons indicate that the midsection of the blade typically acquires the most use wear in any given hacking weapon. Therefore, the samples prepared for SEM analysis were taken from this area. This technique also served to reduce the number of samples into a more manageable range. Samples of the weapon edges consisted of 1 to 2 cm sections in a series of the blade midsection. Visual comparisons were then made of the blade edge topography and the striation patterns on the cut surface of the bone.

Initial analysis was performed on the ISI 40, and micrographs were taken to facilitate rudimentary comparison. Those specimens that best reflected the characteristics of this type of trauma across weapon class were reconfigured on the Phillips 501 operating at 10 Kv, with a 500 Å spot size and a 34 mm working distance. These images were then analyzed using Gatan Digital Micrograph 2.5 to produce a higher quality image and were printed on plates using a *Codonics NP-1600 Photographic Network Printer.* The analysis was performed at a consistent working distance, high voltage, spot size, and magnification in order to provide a baseline for comparison. When deemed necessary, additional micrographs were taken at differing magnifications in order to clarify or enhance detail.

Results

Microscopic Observations of the Bones

Comparisons of the microscopic appearance of the weapons and of the bones they cut are presented in Figs. 1–6. All but one of the cleaver specimens revealed at least one cut surface (kerf) with parallel striations. Cleaver-induced trauma consistently produced a kerf wall that exhibited parallel striations that are perpendicular to the kerf floor. This wall is typically the smooth obtuse-angled side of the wound. Parallel striations produced by cleavers are highly visible under SEM and typically do not require extremely high magnification to be discernible. The cut surface of the bone resulting from cleaver-induced trauma is characterized by thin, fine, distinctive striations that are relatively close spaced. The overall surface (of the striations) is smooth.

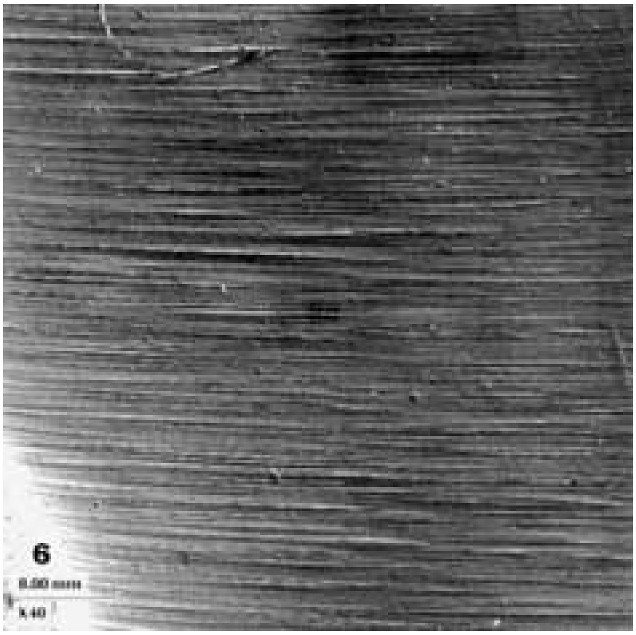

FIG. 1—*Digital micrograph of Cleaver 2 weapon edge (40×).*

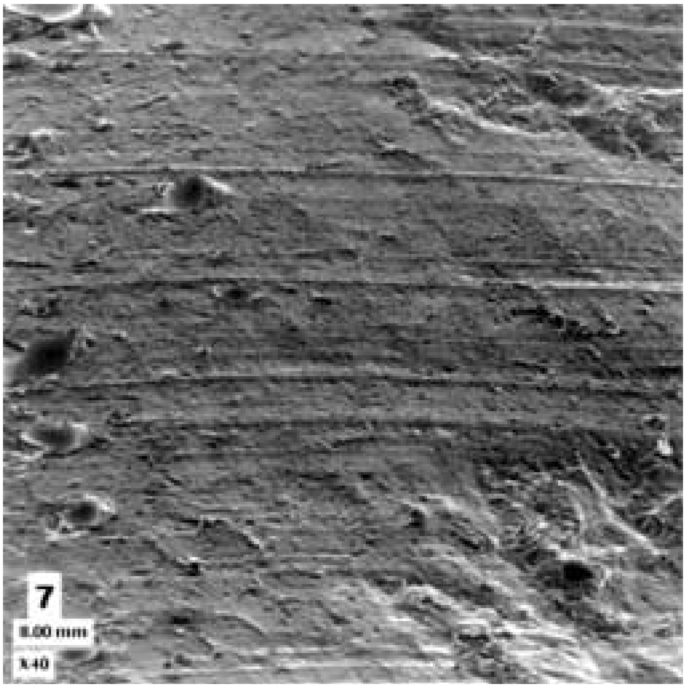

FIG. 2—*Digital micrograph of Cleaver 2C cut bone surface (40×).*

As reported in cleaver-induced trauma, trauma inflicted by machetes similarly produced a kerf wall that exhibited parallel striations that are perpendicular to the kerf floor or exit of the wound. This wall is typically the obtuse-angled side of the cut. The striations exhibited on the machete samples are coarse and more pronounced than those exhibited on the cleaver samples. The striations typical of machetes have a smoother, “rolling hills” appearance, rather than the sharp, fine lines of the cleaver striations. Machete striations are also slightly wider spaced than in specimens cut with the cleavers, and are discernibly more rugged in morphology.

No trauma inflicted by axes resulted in a striated cut surface on the bone. All specimens were shattered or otherwise broken by the weight and wedge action of the axe head. The bone was fractured and split apart, preventing any record of striations resulting from the blade itself.

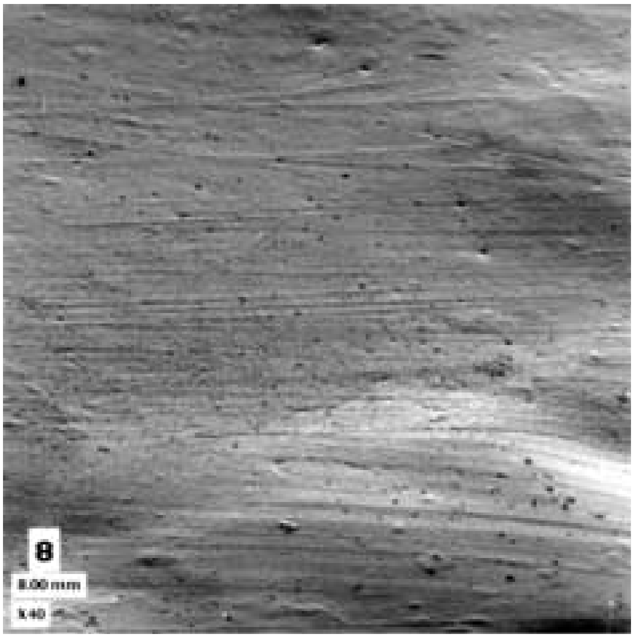

FIG. 3—*Digital micrograph of Machete 2 weapon edge (40×).*

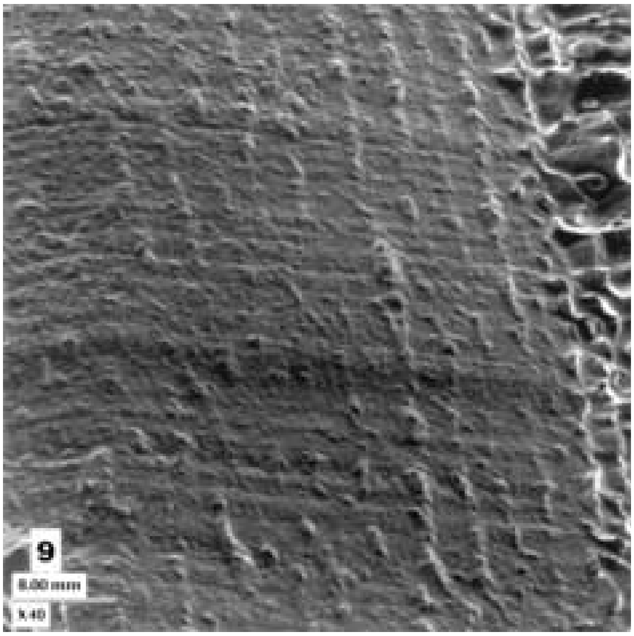

FIG. 4—*Digital micrograph of Machete 2C cut bone surface (40×).*

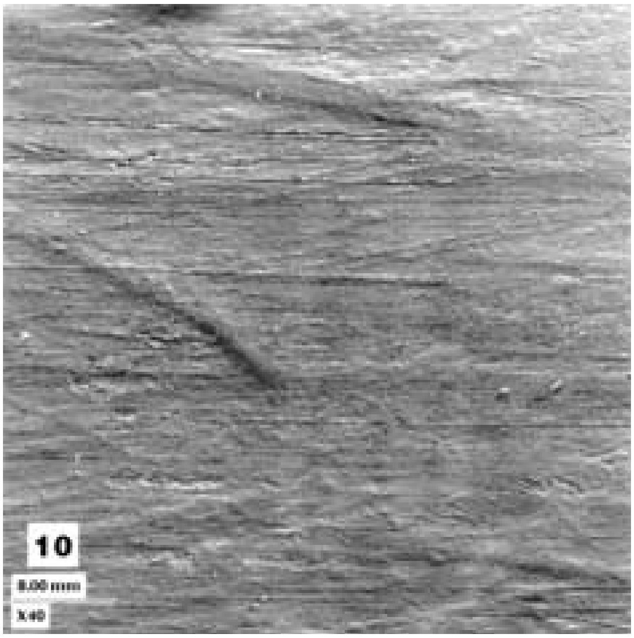

FIG. 5—*Digital micrograph of Axe 1 weapon edge (40×).*

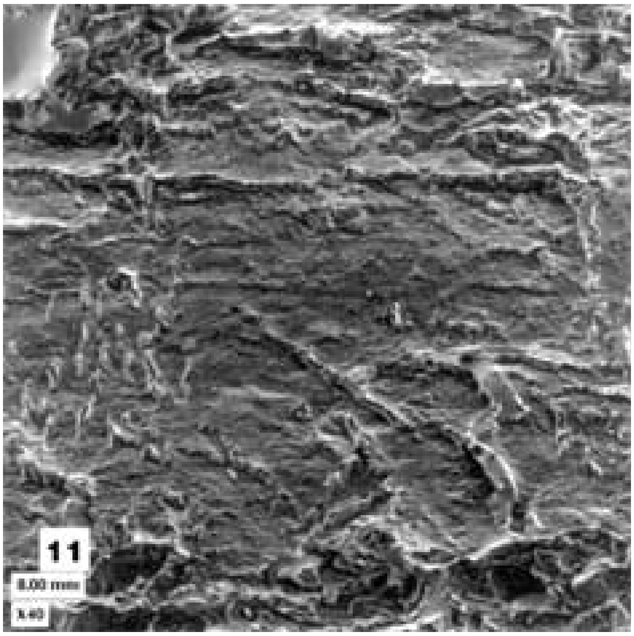

FIG. 6—*Digital micrograph of Axe 1C cut bone surface (40×).*

Microscopic Observations of the Weapons

Three weapons were initially analyzed: Cleaver 2, Machete 2, and Axe 1. The left side (if holding weapon by the handle) of the blade was prepared, thus preserving the right side for further analysis if necessary. All were previously used weapons. These three weapons were selected for initial analysis as specimens cut with these particular weapons exhibited characteristics that best represented that weapon class. The remaining six weapons (Cleavers 1 and 3, Machetes 1 and 3, and Axes 2 and 3) were visually assessed following this initial analysis. We determined that in all cases, blade topography and characteristics pertinent to the cutting edge were consistent across weapon class, thus eliminating the need for further analysis of the weapon edges.

Cleaver 2—Four samples from the midsection of the blade edge were prepared for SEM analysis. Each sample displayed a uniform and consistent striation pattern. As depicted in Fig. 1, numerous thin, fine parallel striations are clearly discernible at this magnification (40×). The other two cleavers, Cleaver 1 and Cleaver 3, share this class morphology. Cleaver 1 is a new, unused tool. The striations on the blade reflect this distinctiveness, as they appear to be "factory perfect" as well as widely spaced and distinct. Cleaver 3 reflects a different pattern that resembles machete class characteristics. This resemblance is not surprising, as this overlap was seen in the cut bone surface as well. This cleaver was a tried-and-true tool, having been used for many years. Repeated sharpening may have led to the intersecting striations seen in the micrograph. However, close inspection reveals the striations remain distinct and sharp-walled, characteristic of cleavers.

Machete 2—Five samples of the midsection of the blade surface of Machete 2 were prepared for SEM analysis. This area, the midsection of the blade, is perceived as the portion of the blade most likely to encounter the most usage. As evidenced by the cleaver samples, each sample displayed a similar pattern of striations; this uniformity was reflected all along the blade. As depicted in Fig. 3, the striations occurring on the blade of the machete seem to reflect its usage in clearing brush or grass. Archaeological studies of microwear analysis on stone tools have revealed a comparable pattern of striations (34,35). We postulated that due to the swinging motion involved in the harvesting or cutting of plants, random areas of the tool edge are in contact with the plant material at any given stroke. These tools typically exhibit a high level of "polish" (due to the biological components of plant matter) characterized by random striations resulting from grit on the stems and leaves of the plant. This striation pattern differs markedly from other tools that are used to cut meat, saw bone, or scrape hides (34,35). The topography of the machetes analyzed in this study is consistent with these microwear analyses and confirms the status of the machete as a garden tool prior to this experiment. The striations run in a parallel direction, with a 45° angle range. At some points, the striations do intersect one another. The blade of the machete also reflects the "rolling" topography seen in the cut surfaces of the bones with machete-induced trauma. It is also interesting to note the vast number of imperfections in the blade, seen as raised bumps in the image. As the casts are negative impressions, these "bumps" actually translate into dents and nicks in the blade edge. Conversely, the depressions witnessed in the micrograph are actually raised surfaces along the blade. The topography of the machete blade reveals a coarse, rugged surface, in sharp contrast to the smooth uniformity of the cleaver blade. The other two machetes, Machete 1 and Machete 3, share these class characteristics. Machete 1 displays a topography that resembles cleaver blades. This phenomenon was also observed on the specimens cut with Machete 1. Although some overlap between Machete 1 and Cleaver 3 might be perceived, closer examination reveals that the striations depicted on Machete 1 are characteristic of the striations made by the other two machetes in this study. These striations are pronounced and gently rolling. Machete 3 reveals a marked pattern of striation intersection. The overall appearance of the blade is very characteristic of machetes, with nicks and scratches across its surface.

Axe 1—Two samples of this weapon edge were taken from the midpoint of the blade (at approximately 6 cm from either end of the blade). Samples from this weapon were taken so as to provide a comparison with the other two weapon edges. Although none of the trauma inflicted by the axes resulted in a striated cut surface, it is interesting to note that the axe blade does exhibit parallel striations. Figure 5 clearly displays very distinctive parallel striations. We postulate that if an axe were to strike a surface that could withstand the force of the wedge and record a cut surface before fracturing, it is likely that the acute-angled surface would reflect parallel striations similar to those observed in the cleaver and machete specimens.

Comparison of Cut Bone Surface with Weapon Blade

Cleavers—Discernible similarities are apparent on both the weapon edges and the cut surface of the bone. All specimens cut with cleavers exhibit fine, thin parallel striations in varying degrees of distinction. The same parallel striations are seen on the weapon edges—fine, thin, and distinctive. Figures 1 and 2 are digital micrographs of the blade surface of Cleaver 2 and the cut bone surface of Cleaver 2C, respectively. The weapon edge displays higher resolution and more numerous striations than are recorded on the cut surfaces of the bones, due to the malleable properties of metal versus the cellular structure of bone. Overall, the striking similarity in morphology of the striations seen on the cut bone surfaces when compared to the topography of the blade edge enables class correlation of cleavers to cleaver-induced trauma.

Machetes—Machete-induced trauma is characterized by coarse, thick striations that, under SEM, are reminiscent of “rolling hills” and are in marked contrast to the striations displayed on both cleaver blades and the cleaver-cut bones, which display sharp-walled, distinct striations. Figures 3 and 4 are digital micrographs of the blade of Machete 2 and the cut bone surface of Machete 2C, respectively. The parallel striations observed on the machete-induced trauma can be relatively widely spaced or tightly packed against one another. A similar pattern is apparent on the blade edge. The striations are thick, coarse, and not sharply defined, but rather “gently rolling.” It is important to note the high degree of blade imperfections evident under higher magnifications. Dents and nicks in the blade edge characterize the blade surface of machetes. These imperfections likely contribute to the overall coarseness and rugged topography seen in the cut bone surface, in the form of “tracks” left during the passage of the blade through the bone. Due to the consistency in the overall topography of the blade edges in all three machetes, as well as the uniformity of striation morphology across all of the bone specimens, it is possible to correlate weapon class to these specimens.

Axes—Axe-induced trauma consistently resulted in complete breakage of the bone, sometimes resulting in marked shattering and fragmentation. This breakage occurred as a result of the wedge-action of the blade, in that the bone is forced or split apart by the thickness of the blade and weight of the axe head, and not as a result of the cutting edge. Consequently, no cut surface exhibiting parallel striations or distinguishing marks of any kind was observed in the axe specimens. Figures 5 and 6 are digital micrographs of the blade edge of Axe 1 and the cut bone surface of Axe 1C, respectively. The axe blade, however, does display parallel striations of distinct character. These striations share characteristics of both machetes and cleavers, in that the striations, although widely spaced, are sharp-walled and thin. Axes also display numerous imperfections on the blade, although not to the extent exhibited by machete blades. Due to the presence of these striations and imperfections, it is possible that axes have the potential to leave distinguishing characteristics on cut surfaces of some mediums. However, in terms of axe-induced trauma on bone, it is most likely that the axe will consistently cause the bone to break and prevent any sort of cut surface from exhibiting these striations. Thus, it is the *absence* of any cut surface, in conjunction with the violence of the wedge action of the blade resulting in complete shattering of the bone, that most characterized axe-induced trauma. Based on this observation, class correlation of hacking trauma inflicted by axes is possible.

Discussion and Summary

Visual comparison of the cut surfaces of the bones to the cutting edges of the hacking weapons reveals that correlations of class characteristics are possible. The plastic response of the organic constituents of bone enables the cut surfaces to show evidence of the weapon edge. Trauma inflicted by cleavers is characterized by fine, thin striations that are distinct and sharp-walled. Striations observed in cleaver-induced trauma range from widely spaced to closely spaced, however, it is the overall quality of striations that is consistent. The blade edge of the cleavers shares this overall morphology. Upon close examination of the blade edges, these distinct striations are readily seen. It is apparent that striations observed on the cut surface of the bone result directly from the topography of the cutting edge. Although the resolution and number of striations differ between the blade edge and the cut bone surface, it is the common characteristic of the striations that enable class association.

Trauma induced by machetes resulted in a cut surface displaying striations ranging from very closely to very widely spaced. However, as observed in cleaver-induced trauma, it is the overall quality of the striations that is consistent. These striations are typically coarse and reflect a rugged topography. This pattern is in sharp contrast to the relatively smooth overall appearance of the striated surface observed in cleaver-induced trauma. Striations resulting from machetes are also more pronounced and less distinct than in cleaver-induced trauma—the machete corresponds striations appear to be gently rolling, while cleaver-induced trauma results in distinct, defined sharp-walled striations. The blade edge of the machetes correspond to this morphology in character: the overall granularity and coarse topography in conjunction with coarse striations enable class correlation in this instance. It is important to note the high degree of imperfections on the machete blades. These dents and nicks contribute to the overall rugged topography of the striated surface on the cut bone and contribute coarse striations in the form of “tracks” left on the surface of the cut. It is also possible to conclude, based on the results of the new and unused cleaver, that an unused machete may exhibit similar results to that of the cleaver. The character of the blade edges of these weapons becomes more defined with use. However, it is important to note that even in the case of the unused cleaver, striations resulting from this weapon nonetheless shared the overall quality of cleaver striations. It is our opinion that while new or unused weapons may result in a less defined striated surface on the bone, class characteristics will be consistent, and class association remains possible.

Axe-induced trauma characteristically did not result in any cut surface on the bone—the wedge action of the blade broke or shattered the bone completely. Despite the presence of striations visible under SEM on the cutting edge of the blades of the axes, these striations were never recorded onto the cut bone surface. Thus, it is the *absence* of any cut that most represents axe-induced trauma. The characteristic shattering of the bone caused by a weapon with a blade thickness like that of axes enables class association.

Identification of individual characteristics, that is, the association of specific weapons to specific elements, proved to be an immense endeavor. Although the possibility of achieving such an identification was not ruled out, the practicality of embarking on such a mission requires: 1) time, both human and microscope, and 2) if possible, prior knowledge of the area of the blade used to inflict damage. The potential of individual correlation certainly does exist. Specific imperfections along the blade edge of a given weapon are undoubtedly recorded as signatures on the cut surface of the bone. It is simply a matter of resource availability whether a researcher would be willing and/or able to search for the match and whether two or more investigators could arrive at the same conclusions. It was our opinion that the time and resources required to make such an identification, as well as the research design of the present study, could not adequately address the issue of individuation, despite our initial goals and objectives. However, the potential of associating weapon edge defects and their resulting striations on bone is not denied.

Microscopic analysis of hacking trauma provides a more reliable identification of weapon class than macroscopic analysis of this type of trauma. For example, macroscopic inspection of machete-induced trauma that did not sever the bone may be mistaken for cleaver-induced trauma, as in the case of trauma inflicted by Machete 1 and Cleaver 3. Similarly, trauma induced by cleavers that did sever the bone may be interpreted as machete-induced trauma. The macroscopic appearance of such trauma is very similar. In the interest of providing a valid and reliable interpretation of hacking trauma morphology, we recommend that microscopic analysis be performed following a macroscopic assessment. It is important to recognize that a macroscopic assessment is necessary prior to microscopic analysis. In the interest of reducing the number of suspect weapons, a macroscopic assessment may save time and resources, particularly in the case of axe-induced trauma. In this instance, a microscopic analysis would prove to be futile, while a macroscopic assessment may be all that is required to identify class of weapon.

The nature of this investigation and of this technique involves a high degree of observer training. Although the time and energy involved in performing the SEM analysis of the cut bones and weapons were extensive, once a certain point of familiarity was achieved, the time involved was greatly reduced. The initial process of becoming familiar with the specimens and figuring out the most useful topographic landmarks comprised the most time consuming aspect of this study. After that point, it became a simple operation of processing the samples. Thus, it is our opinion that this technique is viable in forensic investigations, especially to an investigator familiar with scanning electron microscopy. Of chief concern is access to the microscope and related machinery (i.e., sputter-coater), as well as a knowledge of the SEM and cut mark morphology. It is of critical importance that a very fine casting material be used in order to record microscopic features on the bone and/or weapon edges. It is also recommended that a precursory knowledge of scanning electron microscopy be established in order to minimize time and resources. An additional recommendation is the use of the "tilt" feature on the microscope; the majority of specimens analyzed in this study were tilted at 40 to 65° in order to best highlight the desired features.

The results of this investigation indicate that it is possible to correlate class of hacking weapon to trauma inflicted by these weapons. An important reason for undertaking this study was to provide a baseline from which future comparisons of this type may be performed. The systematic analysis of hacking weapon trauma provided in this study enables forensic investigators to accurately correlate specific weapon types to violent crimes. The existence of characteristics unique to each class of weapon in this study provides a baseline that may assist in narrowing the field of suspect tools in forensic investigations. SEM analysis of hacking weapon trauma may be employed to corroborate additional evidence in criminal cases.

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