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Individualization of Toolmarks in Bone: A Scanning Electron and Light Incident Microscopy Study of Metal Knife Dynamics in Bone

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INDIVIDUALIZATION OF TOOLMARKS IN BONE: A SCANNING ELECTRON AND LIGHT INCIDENT MICROSCOPY STUDY OF METAL KNIFE DYNAMICS IN BONE.

By

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ABSTRACT

INDIVIDUALIZATION OF TOOLMARKS IN BONE: A SCANNING ELECTRON AND LIGHT INCIDENT MICROSCOPY STUDY OF METAL KNIFE DYNAMICS IN BONE.

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The forensic discipline of toolmark analysis has focused on the identification of toolmarks produced on inanimate media. While some attention has been given to the process of identification of toolmarks made in bone, it has been limited to implements with gross defects which allowed expedient individualization. Use of the usual methodology of striation pattern matching to evaluate a mark by class and individual characteristics has not been attempted.

Applying techniques of paleoanthropologists and taphonomists of stone tool cutmarks on bone, and developing new standardized techniques, human and non-human bone was affected with commercially available knives. The resulting cutmarks were viewed with a light incident microscope and a scanning electron microscope. The two microscopic techniques were compared. Using traditional methods of striae pattern matching, the cutmarks were evaluated for class and individualizing characteristics. Significant criteria for matches, inconclusive comparisons and exclusions based upon class and individual characteristics is discussed.

To Janet Patricia and Max W. Houck,
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INTRODUCTION

Although Simpson (1982) probably did not have the forensic sciences in mind when he pointed out that all historical sciences have as their goal retrodiction, speaking about events in the past, the statement nevertheless directly applies to that investigative field. Forensic science may be considered an historical science since, like archaeology and paleoanthropology, it attempts to explain past behavior within a specific context, although it is more similar to the former than the latter. This is because, in contrast to the aforementioned disciplines, the time period between commission of an event of interest and the actual study of that event is exceedingly brief. Unlike paleoanthropology, the forensic sciences do not address the enormity of human prehistory and the growth of civilization. They are, however, able to be more specific concerning the actions, participants and items involved in the studied situation.

As with all historical sciences, certain limitations and constraints are imposed on the methodologies appropriate for addressing questions about the past behavior under study. For paleoanthropologists the explicit underlying theoretical justification for the methods used is a variation on the principle of uniformitarianism. Originally proposed by James Hutton in 1785 and expanded on by Lyell in the 1930's, the principle states that processes which are not currently observable in the world cannot be thought of as instrumental in the earth's formation (Knudsen, 1978). Currently observable geologic processes may be employed to explain past geologic events since these processes are assumed to operate in a uniform way through time. Paleoanthropologists apply this idea to all physical processes; if we cut a bone with a flint tool today, it will yield a result comparable to a bone cut with a flint tool 2 million years ago. The forensic sciences, however, use this theoretical underpinning implicitly and, for the most part, unconsciously. Historical sciences rely on this conceptualization of the primary causal mechanisms, and their concomitant effects, by which past events of interest are manifested in contextually-oriented information and use it to deduce affinities between these and corresponding present-day events. In the forensic sciences, the past events under study may have occured only a few months or days ago, as opposed to millions of years.

Caution must be exercised in the interpretation of the data and the ensuing conclusions, however, so that one does not overstate the case. Conclusions of this nature should have a structure that allows for a distinction between statements such as "this windowsill displays characteristics that best correspond with marks produced by a tool with a flat, chiseled edge 1/2" in width" rather than "this windowsill was gouged by a a 1/2" flathead screwdriver". As Shipman (1981) points out, given the intrinsic constraints of historical sciences, this is an acceptable and, in fact, optimal level of resolution. Otherwise, the observer may unintentionally bias the methods used or results obtained or even exclude from consideration potential avenues of research.

This thesis applies techniques of paleoanthropology and taphonomy of stone tool cutmarks on bone to the forensic discipline of toolmark examination. To this end, it stands as a link between these disciplines and it is hoped will initiate continued interdisciplinary research with traditionally "non-allied" disciplines. New standardized methods and devices were developed to affect human and non-human bone with commercially available metal knives. The resulting cutmarks were viewed with a light incident microscope and a scanning electron microscope. The quality of the two systems to image the specimens was compared. The cutmarks were evaluated with traditional forensic methods of class and individual characteristic comparison. What constitutes significant criteria for matches, inconclusive comparisons and exclusions based upon class and individual characteristics and the scientific and legal ramifications of these evaluative designations are discussed.

LITERATURE REVIEW AND BACKGROUND

The analysis of toolmarks and firearms are often considered analogous processes; while this may be true in a theoretical sense, it is not necessarily so in practice. When two bullets of the same caliber are sequentially fired from the same gun, they should exhibit characteristics which are very similar in quality and expression. The width, depth and general character of the striations transferred from the barrel will not differ significantly, unless extenuating circumstances arise. This "standardization" is due to the mechanical and physical limitations imposed upon the bullet/gun interaction by the precise nature of the chemical charge, the gun's particular dimensions, etc. When a tool is used, however, to produce two sets of sequential toolmarks, the results may be very different. The angle of the tool at impact, the force with which the tool is applied, the medium used to record the tool's surface and the action of the tool upon the medium, whether it creates an imprint or slides thus transfering striations, all vary with each interaction. These variables and others lead inevitably to difficulty in replicating toolmarks; thus, a practical distinction exists between the production of firearms and toolmark test standards.

To use information interchangibly between these two processes can cloud this issue much in the same way that a infrared spectrum may be referred to as a "fingerprint" of a particular substance. While the spectrum indeed may be indicative of a substance, it in no way bears resemblance to fingerprint identification. It is a correlation intended for descriptive purposes; the two systems of comparison are conceptually distinct and discrete. In practice, toolmark examination and the analysis of fired bullets are not equivalent methods because the former must account for certain traits associated with respect to their production. For firearms analysis, this matter is mostly pro forma.

When, in the course of this thesis, a reference which has firearms examination as its basis is cited, it is used only within a theoretical framework which compares two or more sets of transferred tooling and/or usage marks. Furthermore, a practical distinction is recognized between the production of test standards for firearms and toolmarks and no comparison between the two processes is made in that regard.

The major concern of the forensic subdiscipline of toolmark analysis is to individualize marks made by a specific tool or object involved in the commission of a crime (Flynn, 1957). This involves the recognition and matching of class and individual characteristics of the "impressions and striations imparted by a suspected tool with the markings on relevant objects found at the crime scene" (Bisbing, et al., 1988;

Flynn, 1957: 95). Class characteristics are the measurable details of a specimen which indicate membership in a restricted group or group source (Davis, 1958). Individual characteristics are those which have structures or combinations of structures that are "unique and distinctive of just one specific implement" (Burd and Gilmore, 1968: 390). Identifying toolmarks as having been made by a particular tool requires a significant correspondence between the suspected tool and the toolmark from the crime scene (Burd and Gilmore, 1968) together with "the absence of significant differences which cannot be explained" (Burd and Greene, 1957: 309) by subsequent alteration. Individual characteristics are random in production and generally result from manufacturing devices, grinding and finishing processes (Burd and Gilmore, 1968; Metals Handbook, 1964), and normal wear and usage (Burd and Gilmore, 1968; Cassidy, 1980). These processes produce surface phenomena, called striations, that are characteristic of only that tool; each tool's particular production and utilization history places it in a category of one, e.g., individualization (Cassidy, 1980).

The most common method of individualizing toolmarks is by comparing test marks made using the suspected item with the markings from the crime scene (Flynn, 1957). Comparison, categorization and subsequent matching of a toolmark with a particular tool is contingent upon two dynamic factors. First, the ability of the substrate to receive and record the surface phenomena of the tool, and, second, the quantity and significance or magnitude of the phenomena on the tool itself (Rao and Hart, 1983).

As a substrate, bone demonstrates compositional regularities similar to inanimate materials (Bonte, 1959) such that instances of tools leaving both class and individualizing criteria upon in vivo hard tissues have been documented (Bonte, 1959; Burd and Greene, 1957; Mittleman and Wetli, 1982), thus satisfying the first criteria for potential analysis (Rao and Hart, 1983). Rao and Hart (1983) and Bonte (1959) state that most cases of identifications involving cut bone almost always involve a tool that has gross defects of the cutting edge. Rao and Hart also mention, however, that cartilage, because of its softer texture, may record characteristics that bone might not and would ease identification of tools with "less prominent individualities" (1983: 798). In contrast, Bonte (1959: 321) states that in his experience, "bone...shows traces (of tool marks) better than wood". For example, rills produced by toothed implements, such as a carpenter's saw, may be found in the bottom of an incompletely sawed portion of a bone. With this information one may be able to determine the inter-tooth distance, the number of engaged teeth and estimate the length of the saw blade (Bonte, 1959).

Bonte (1959: 315) also mentions that knife wounds in rib cartilage "offer excellent opportunities for tool classification". Burd and Greene (1957) note that in one case, test marks were made on paraffin and these marks were compared successfully with a section of skull from the murder victim. As early as 1927, in the sensational Beernem murder case, DeRichter identified the murder weapon, a hammer, as having been the tool which caused the cranial depression fracture of the victim. He arrived at this conclusion by matching striations (DeRichter, 1929 cited in Thomas, 1967). Mittleman and Wetli report that "(w)hen used as bludgeons, [threaded metal pipes, bolts and dowels] may leave a characteristic pattern injury on the skin and underlying bone" (1982: 567) and recognition of this pattern could categorize the weapon to class or even possibly individual status (1982).

In forensic tool mark examination, the direction of the tool's progress is often apparent due to a ridge or spicule of the affected medium which is pushed ahead of the tool (Burd and Greene, 1957). Indications of foreign object/tissue interactions such as these may be used in determination of direction in soft tissue wounds. As noted by Dixon, "The so-called 'skin tags' located along lateral margins of the...wound trough point toward the weapon,...in a direction opposite the path of the projectile" (1980: 275). In a comparison situation, observations and interpretations of such trauma are facilitated if the experimental marks are made at as nearly the original angle of incidence as possible.

It is significant to note in this context that cut marks on bone or, by association, cartilage are definitive and direct evidence of human involvement or interference with the substance (Shipman and Rose, 1983). This is because "(n)o process has yet been discovered which produces marks that mimic slicing, chopping or scraping marks on a microscopic level" (Potts and Shipman, 1981: 577).

Within the field of paleoanthropology, several researchers have studied the problem of taphonomy, the study of the circumstances and events involving an organism from the time of its death until it is examined (Simpson, 1983), in a way that is methodologically relevant to the forensic discipline of tool mark examination. Work has been done to distinguish a variety of taphonomic marks on bone, such as carnivore tooth marks, stone tool cutmarks, preparator's marks (Potts and Shipman, 1981; Shipman, 1981; Shipman and Rose, 1983), directionality of cutmarks (Bromage and Boyde, 1984), sequence of cutmarks (Shipman, 1981) and effects of abrasion on forming bone surfaces (Bromage, 1984).

Tooth marks, stone tool cutmarks, and preparator's marks may appear similar at a gross level of visual examination and therefore only the distinctive characteristics of each taphonomic process should be considered diagnostic (Shipman, 1981); it is critical to distinguish the desired traits from the extraneous background information. Tooth scratches, most often made by a carnivore's canine tooth being dragged across the bone surface, are described as "elongate grooves that may vary from V-shaped to U-shaped in cross-section with the bottom of the groove being smooth" (Shipman, 1981: 365) and generally have a single groove at the nadir (Shipman and Rose, 1983). Occurring singly, as sets of parallel or subparallel marks, or as groups of marks, tooth scratches may vary widely in their orientation to each other (Shipman, 1981).

The functional equivalent of a tooth scratch, stone tool cut marks produce elongate grooves, V-shaped in cross-section, which may or may not be narrower than a tooth mark. Although once thought to be a useful demarcator of cutmarks (Potts and Shipman, 1981; Bunn, 1981), cross-sectional shape is now considered to be a poor criterion (Shipman, 1983). The distinguishing criteria of tool scratches are fine parallel striations within the original groove (Shipman, 1981) producing numerous distinct "tracks" at the bottom (Shipman and Rose, 1983). "These fine striations are drag marks or tracks made by the fine projections that deviate to one side or the other of the edge of the artifact" (Shipman, 1981: 365). Shipman and Rose (1983: 66) found that "without exception, all...tool slicing marks showed the typical, multiple, fine striations within and parallel to the long axis of the main groove". As might be expected, prehistoric cutmarks show the same microscopic traits as modern experimental cutmarks (Shipman and Rose, 1983). In their experimental production and subsequent examination of cutmarks, Shipman and Rose (1983: 70) also found that "many of the apparent features of any single cutmark are actually features on the periosteum rather than on the bone itself". Interestingly, one of Shipman and Rose's research conclusions was that little difference exists between the first mark made with a stone tool and marks made as late in the series as the 250th mark. To them this suggests that "the microscopic features of cutmarks might be used to identify the particular tool that made them" if the tool itself had not been significantly altered (Shipman and Rose, 1983: 74-75).

In order to more acutely evaluate the taphonomy of carcass processing by hominids, Bromage and Boyde (1984) did experimental research into the determination of the direction in which a cutmark is made. Looking at studies of smears in dental tissue, Bromage and Boyde noticed that the smears were lifted in the opposite direction of the cut and a fracture pattern similar to that seen in surface abrasion of glass (Gordon, et al., 1959). This pattern is termed a "Hertzian fracture cone", where the apex of the cone faces the direction of the abrasive movement, and is also evident in wear striations on teeth (Gordon, 1984). To test these phenomena in relation to toolmarks on bones, Bromage and Boyde (1984) experimentally produced over 200 cutmarks on bovine bones with stone tools. They found that bone smears, similar to dental enamel smears, were lifted in the opposite direction of the cut. Further, oblique faults of bone adjacent to slicing marks had the medial portions of the mark, those nearest the center, displaced in the direction of the cut ("forward", relative to the cut). These latter artifacts are hypothesized to result from the tool "chattering" building up pressure and then releasing it repetitively across the bone surface (Bromage and Boyde, 1984).

The sequence of overlapping cutmark production can be determined under certain conditions. "If the depths of the intersecting marks are reasonably similar, then the fine striations of the later mark will overlie and obscure those of the earlier mark" (Shipman and Rose, 1983: 89). Marks of different depths are difficult to evaluate in this context, as are poorly preserved cutmarks. In a forensic investigation, this type of evidence, accurately interpreted, could lead to the designation of primary causal trauma and the resultant hierarchy of trauma incidence, to an individual.

The successful application of the aforementioned evaluative criteria rests upon the assumption that the bone surface has not degenerated or been obliterated to a significant degree. After only brief contact with abrasive agents, stone tool and bone tool marks may lose some of their microscopic traits (Shipman and Rose, 1983). Bone abrasion, the result of any agent that erodes the bone surface through the application of physical force, has been defined and categorized by Bromage (1984). Any taphonomic inquiry into an osteological assemblage or forensic case where the depositional history is unknown needs to consider the possibility of abrasively altered or obliterated data.

Cut marks on bone, however, may persist for a very long period of time. The research on hominid butchering practices deals with cutmarks from the late Pliocene and Pleistocene epochs, which date to from about 2 million years ago (Jolly and Plog, 1987). An historic incident of toolmarks persisting in bone is an eighteenth century homicide at Fort Ouiatenon in Indiana (Sauer, et al., 1988). Under a scanning electron microscope, striations from a metal axe are clearly present on the cut surface of the victim's rib (Sauer, et al., 1988: figure 8, page 71) and, with restorative work, could possibly allow individual categorization. This knowledge could be crucial to the application of the proposed technique in cases of prolonged interment.

Pivotal to the success of these paleoanthropological and taphonomic studies of has been the use of the scanning electron microscope (SEM). Use of the SEM has several advantages when compared to conventional light microscopes, including superior resolution of three-dimensional structures, increased depth-of-field, and the capability for higher magnification of specimens, up to 200,000 x (Hayat, 1978; Watt, 1985). Although the SEM does represent sheer brute magnification superiority when compared to a conventional light microscope, at a working distance of about 10 mm from the specimen, a conventional SEM achieves a resolving power of about 4 nm while a light microscope achieves only about 200 nm (Watt, 1985). In practical application, this means,

> "(i)nspection of the same specimen with a light microscope and the SEM has shown that the latter often reveals features that are unclear or invisible under the light microscope even when the magnifications are the same" (Shipman, 1981: 360; original emphasis).

Although the SEM has been used widely in other areas of forensic science (Bohm and Bohm, 1983; Katterwe et al., 1980; Pfister, 1982; Taylor, 1973; Wong, 1982), and has shown great success in toolmark analysis (Devaney and Bradford, 1970; Grove et al., 1972; Haas et al., 1975; Judd et al., 1974; MacDonell and Pruden, 1971; Singh and Aggarwal, 1984) little has been done in the area of interpreting the results of assaultive and/or taphonomic processes on human remains in situations of legal concern. Clearly, electron microscopy has the potential to be an extremely helpful technique in the individualization of toolmarks on bone. This is especially true since microscopic characteristics are the most reliable means of categorizing marks of uncertain origin (Shipman and Rose, 1983) and there is no set amount of characteristics which constitute a positive identification of a tool mark (Davis, 1958). Maximization of data is paramount to tool mark analysis and the use of a SEM can increase the quantity and quality of recoverable data from an affected material. Despite such advantages, application of this technique to the usual methodology of striation pattern matching to evaluate a mark by class and individual characteristics has not been systematically attempted on bone trauma.

METHODS AND MATERIALS

In the preparation and production of the experimental equipment to be used in this study, several factors of the knife-bone dynamic needed to be addressed. The angle at which the knife was applied must be duplicated, force of application, or work, and the degree of hardness of the affected materials had to be addressed (Flynn, 1957), otherwise it might not have been possible to sort out the particular effects. Additionally, the process had to be reproducible to insure both intra- and inter-observer standardization.

More comparable results are achieved when the original material that was affected by the tool in question is duplicated; a less resistant material will also suffice (Burd and Greene, 1957). To this end, bovine tibial shafts were obtained from a local butcher and were quartered lengthwise to maximize usable surface area. As much adherent material as possible was removed without damaging the periosteum. Half of the tibiae quarters were placed in a venting hood at room temperature for 72-80 hours to dry. The remainder of the tibiae quarters were kept refrigerated at 34^{o}F until needed. For inter-species comparason, a human rib section removed during autopsy at Edward E. Sparrow Hospital was also refrigerated for later use.

To induce the trauma in the bone, a guillotine-like machine, the Impact Trauma Device (ITD), was built using the facilities at the Trauma Biomechanics Laboratory at Michigan State University (Figure 1). The ITD consists of an anodized aluminum drop tower with a single center piston guided by two sets of Thompson precision bearings. The knives were placed in a specially made chuck at the bottom of the piston and positioned with six centering bolts. The bones were placed horizontally, periosteal side towards the knife blade (upwards), in plastelene, a non-drying synthetic clay, on a sample base made of Lexan (Figure 2). The sample base was hinged so it could be set at an angle tangential to the center piston using supportive insets to produce the desired angle. The base of the ITD has guide holes every 1.25 cm so the sample base can be incremented linearly beneath the center line of impact in order to produce sequential cutmarks.

Originally, four commercially available knives were purchased for this study; one of them, knife 2, proved to be unsuitable for use with the chuck on the ITD because the blade was too narrow. Therefore, it was omitted from the study. Fifteen coded specimen interactions each with four characteristics were produced using the random number function of a Hewlitt Packard 33C calculator. The characteristics were chosen for ease of reproducibility, production of necessary components, and simplicity of interpretation. This last factor was considered to be of use because of the preliminary nature

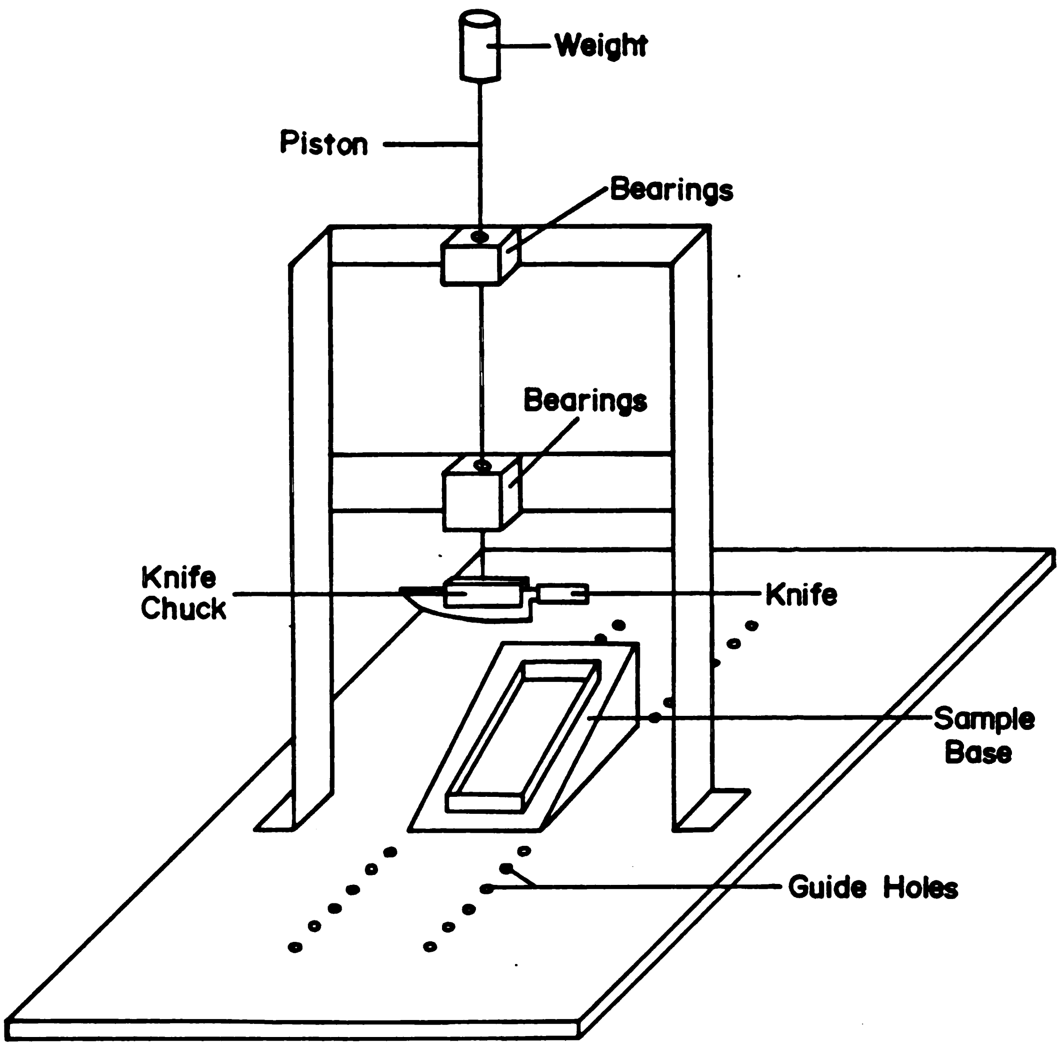


Figure I. Impact Trauma Device

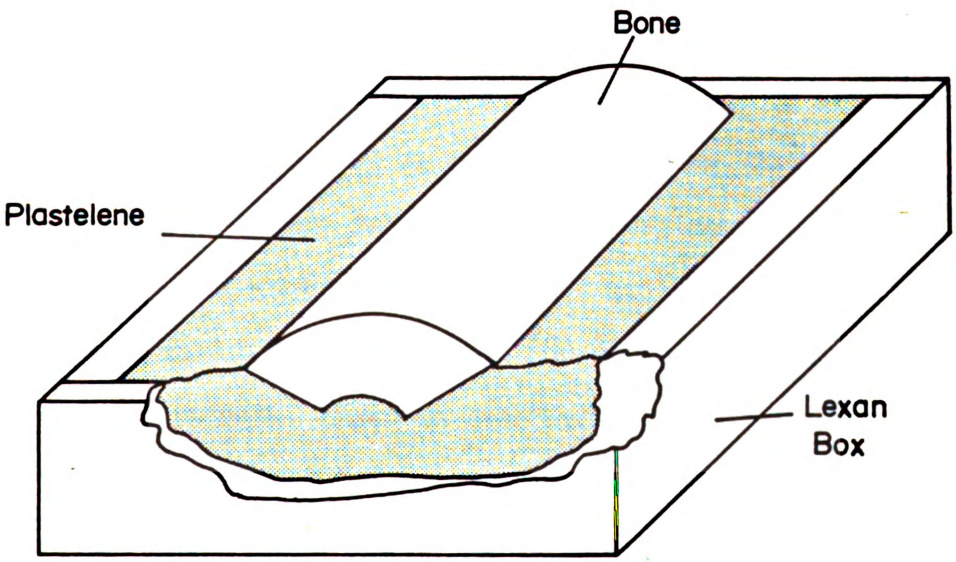


Figure 2. Cross-section of Specimen Base

of this research; it aided in sorting out "background noise" from potentially important observations.

Each coded interaction contained four numbers which carried information regarding the specific parameters. The first number indicated the species of the osteological sample; a "1" or a "2" means the specimen was bovine and a "3" meant the specimen was human. The knife used to cut the bone, 1, 3, or 4, is represented by the second number. The third number indicated the angle at which the knife contacted the bone, 45^{o} or 90^{o}. The fourth number represents the amount of weight on the center piston, .68 kg (1.5 lbs.) or 1.6 kg (3.5 pounds). Fifteen cuts were made following the specifications in the coded sample interaction information. If, when making a cut, a specification was not followed or the piston release allowed a non-uniform release, that cut was removed and discarded. The ITD was then reset ad the cut attempted again. All impacts were made at a distance of 30 cm between the sample bone and the knife's edge. A spring-release system was employed to insure exact piston release. The same section of each knife blade was employed for all cuts to restrict the amount of cut surface needed to be searched for striations. After each cut was made, that portion of the bone with the mark on it was removed and numbered for specimen preparation.

After inducing the trauma, the moist refrigerated specimens were placed in a ventilated hood at room temperature for 72-80 hours to dry. All specimens were sonicated for 1 minute to remove adherent debris. In retrospect, sonicating for up to 3 minutes would be advisible due to consequent problems with particles building up a charge under the electron beam. The specimens were then mounted on stubs and coated with gold for four minutes using an Emscope Model EM 1200 sputter coater. Carbon-based paint, such as is used on television tubes, was applied at the point of connection between the specimen and the mounting stub to increase the conductivity of the specimens.

All cutmarks were evaluated for criteria which would constitute class membership and individualization of a toolmark to a particular tool (Biasotti and Cupertino, 1964; Cassidy, 1980; Davis, 1958; Burd and Gilmore, 1968; Haas, et al., 1975; Judd, et al., 1974; Singh and Aggarwal, 1984;) using an Olympus model BH light incident microscope and a CamScan Series 4 SEM.

The light incident microscope and the SEM were chosen for reasons specific to each instrument. The light incident scope was chosen because it is ubiquitous in forensic science labs and it is the instrument that most easily lends itself to the task of toolmark analysis (Tedeschi, et al., 1977) and because samples require no special preparation or environment. The SEM, while requiring special preparation and environmental control, namely a gold-coated specimen and a high vacuum, provides a depth of field and resolution not possible in a light microscope (Hayat, 1978; Watt, 1985). Studies have shown that the utility of the SEM in toolmark analysis far outweighs any special considerations its use may necessitate (Haas, et al., 1975; Judd et al., 1974; Matricardi, et al., 1974; Singh and Aggarwal, 1984; Speeter and Ohnsorge, 1973).

The use of the CamScan Series 4 was especially helpful because of its unique comparison abilities. A variable sized image window can be defined on one screen and the image contained within this window is substituted within the same equivalent location in the image on the other screen. This enables a direct comparison to be made between the two samples. This study employed a large stage capable of holding four specimens in the chamber at one time; thus, multiple conjoint comparisons were facilitated. In addition, a motorized stage was used which allowed for precise manipulation of the specimen.

MATCHES, NON-MATCHES, AND EXCLUSIONS

Most experts in toolmark or firearms analysis agree that what constitutes a match between two compared specimens is largely dependent upon the qualitative and quantitative criteria chosen by each individual examiner, gained through practical professional experience (Bisbing, et al., 1988; Biasotti and Cupertino, 1964). No rigid evaluative or statistical standards exist, such as proper magnifications (Flynn, 1957) or the necessary number of characteristics used to determine a match (Davis, 1958), and the specific techniques employed will vary depending on the class of tool involved, the orientation and physical traits of the mark and other factors (Burd and Greene, 1957). A match is a conclusion drawn from relevant observations by a person who is considered to be an expert in the field. The criteria of a match is generally understood to be a sufficient correspondence of individual characteristics (Biasotti and Cupertino, 1964; Bisbing, et al., 1988; Burd and Gilmore, 1968; Burd and Greene, 1957; Cassidy, 1980; Flynn, 1957; Singh and Aggarwal, 1984) between the test standard and the questioned sample without the presence of significant non-corresponding traits.

No single arbitrary standard for what consititutes "sufficient" criteria exists for toolmark analysis. Each individual examiner decides what quantity and quality of traits exhibited on a particular specimen is enough to warrant the resulting statement. The designation of the observer as an expert, therefore, is pivotal to the certainty of the conclusion. The expert needs to be aware of the range of variation of the toolmarks in question and what can or cannot be said about the relationship between the known and the questioned samples. The soundness of the results rests in large part upon the acquired experience of the examiner.

It should not be surprising, then, to find that researchers disagree as to the type of conclusions that can be drawn from toolmark comparisons. Burd and Greene (1957) list the following four conclusions:

I. "No opinion or conclusion can be reached due to alteration of either the tool mark or the tool, which has occurred since the commission of the crime" (1957: 308),

II. "The questioned tool can be eliminated as having been responsible for producing the tool mark under study" (1957: 309),

III. "The tool may have made the mark but a conclusive identification is not justified" (1957: 309),

IV. "The tool did produce the mark in question" (1957: 309).

The authors note that in the case of conclusion II, this decision can be reached on the basis of non-correspondence of the class-level characteristics of the test standard and the questioned specimen or, if the class traits do correspond, on the "lack of identifying detail...which it appears should be present if this particular tool did produce the mark" (1957: 309). Rowe (1988), on the other hand, lists only three possible outcomes of striations comparisons:

1. The questioned item made the mark (identification)
2. The questioned item did not make the mark (non-identification)
3. The results of the comparisons are inconclusive (Rowe, 1988: 430).

Rowe explains that conclusion 1 is based on observation of similar class features and matching striation patterns on the test standard and the questioned specimen, while conclusion 3 hinges on the correspondence of class characteristics but not on traits of an individual nature. Conclusion 2 indicates that the questioned specimen has different class-level characteristics than those found on the test standard. While it is generally accepted that a non-correspondence of class or genus characteristics necessarily implies exclusion (Biasotti and Cupertino, 1957; Bisbing, et al., 1988; Burd and Gilmore, 1968; Burd and Greene, 1957; Cassidy, 1980; Flynn, 1957; Rowe, 1988), most researchers in the field are hesitant to make a specific statement about a non-correspondence of individualizing traits. This level of conclusion, however, has been implied. In 1930, Goddard stated that

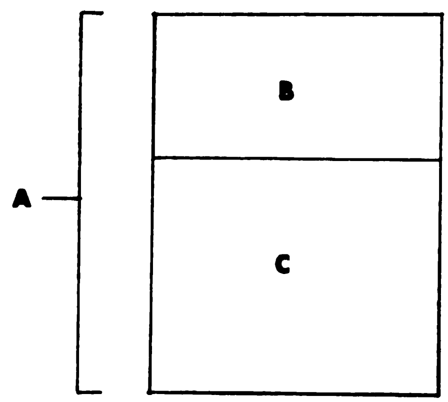
> "two arms of the same caliber and make will exhibit sufficiently pronounced characteristics of their own,...to make possible a determination as to which of them fired a given bullet. This is because a bullet in traversing a barrel acquires on its surface the <u>characteristic</u>

> markings peculiar to that barrel alone (emphasis added, 1930: 6)".

Buxton (1930: 212) also mentions that "if the (rifling) grooves correspond but the other distinguishing marks do not, it is shown that the two (bullets) were fired from different firearms of the same make". Watson found that, after comparing two different knives, "no correspondence was observed in the pattern of accidental [read individual] characteristics present" and "the identifying elements form a combination the coexistence of which is highly improbable in a toolmark produced by another knife" (1978: 45). In an SEM study of wire cutters, Singh and Aggarwal state that a "non-correspondence of the surface structures on the cut faces produced by different pliers affirms that they are characteristic of the cutting tool" (1984: 121). These studies clearly indicate that some experts consider it possible to exclude a tool mark based on the comparison of individual characteristics. Applying some of the more basic aspects of formal logic will facilitate a better understanding of the arguments used to bolster this kind of opinion.

Using a Venn diagram (Figure 3), "A" will represent all possible straight-edged knife cutmarks, "B" will represent all cutmarks made with knife number 1, which has a straight edge, and "C" will represent all cutmarks made with all straight-edged knives other than B.

From this relationship we can immediately infer that while either B or C are sufficient conditions for A, they are not necessary. The conditions for A could be met by either B or C. Therefore, A is a necessary but not sufficient



Venn Diagram (Figure 3)

condition for B or C. In relation to each other, the statements "If A, then B" and "If A, then C" are contraries; they offer alternate competing responses to a situation (Emmet, 1981). This is a similar situation to comparing "That tree is a birch" and "That tree is a pine"; at most, one statement is true. It is important to remember that it is entirely possible for both statements to be false; the tree in reality may be an oak. This is why phrasing is important to the interpretation of "historical" data; if a set of tool marks is identified as having been made by a screwdriver, all other tool marks are eliminated from the researcher's consideration. If, on the other hand, the statement is phrased to connote that the marks are consistent with having been produced by a screwdriver, the possibility of their production by some other object remains available to investigation.

We may say that the terms B and C are contradictory in that one is true and one is false and they may be neither true together nor false together (Emmet, 1981). In this sense, B is equivalent to "not-C" and C is equivalent to "not-B". When we say "If either B or C, then A", either B or C, but not both, are sufficient but not necessary criteria for A. We are therefore not entitled to infer from this statement, "If A, then B" or "If A, then C". We may, however, infer "If not-A, then not-B" or "If not-A, then not-C" (Emmet, 1981); this is the logical basis for a class exclusion. In a more manageable format, our first statement would read like this,

> If this mark has traits similar to knife 1 or some other straight-edged knife, then it was made by a straight-edged knife.

And the valid inferences we could draw from it would be as follows,

> If this mark was not made with a straight-edged knife, then it was not made with knife 1 (a straight-edged knife);
>
> If this mark was not made with a straight-edged knife, then it was not made with any other straight-edged knife.

Individual exclusions have been based on a non-correspondence or lack of individual characteristics (Biasotti and Cupertino, 1964; Bisbing, et al., 1988; Burd and Gilmore, 1968). This comparative process is based upon the disjunctive syllogistic form:

Either B or C
<u>Not-B</u>
Therefore, C.

The terms B and C are called the disjuncts of the syllogism and are its component propositions (Copi, 1982). If one premise is a disjunction, in this case the first line, and the other is the denial or contradiction of one of the two disjuncts, the second line, then to infer the truth of the other disjunct is valid. Disjunctive syllogisms are valid only when the categorical premise contradicts one disjunct of the disjunctive premise and the conclusion affirms the other disjunct of the disjunctive premise (Copi, 1982). This argument expressed in words would be:

> Either this mark has traits similar to knife 1 or some other straight-edged knife
> <u>It does not have traits similar to knife 1</u>
> Therefore, this mark has characteristics similar to some other straight-edged knife.

This is the same systematic evaluation made in fingerprint analysis; assuming that no technical errors were made in the production of the test standard,

> "should an unexplained dissimilarity occur, as for example the appearance of a clearly defined ridge characteristic in a latent print which does not exist in the inked impression, the conclusion is inescapable that the prints were not made by the same finger" (Moenssens, et al., 1986).

More prosaically, this process is analogous to comparing a photograph of a person's face with a number of photographs of people of a similar class category, for instance, white males between 25 and 35 years of age. An observer would be able to state whether or not the person in the reference photograph was in the pile of comparison photographs. If the person's photograph was not, then the observer would have excluded the subject on the basis of personal or individual characteristics.

The validity of non-matches as a possible conclusion permits certain categories of observations to be used in a statistically legitimate manner. Since the population of observations is finite, this allows for a greater range of statements about the accuracy and independence of the observations. More will be said about this in the next chapter.

For purposes of this thesis, "exclusion" will define a situation where two items do not belong to the same class category. "Non-exclusion" denotes a indeterminable, possibly similar, class relationship. The word "match" will mean a sufficient number, to be determined by the examiner of corresponding individual characteristics and the phrase "non-match" will indicate a non-correspondence or lack of otherwise individualizing striations patterns; a non-match therefore necessarily implies exclusion based upon individualizing characteristics. "Not possible" denotes that insufficient criteria exist for making a reasonable judgement about the class or individual relationship of the specimen in question.

RESULTS

Fifteen specimens were produced which allowed for a population of 105 independent-pair comparison observations, after removing same sample and reflexive comparisons after the formula used by Flynn (1957):

$$S = \frac{a + l}{2} \times n \qquad (1)$$

where S is the sum of the terms, a is the first term, l is the last term and n is the number of terms.

$$S = \frac{1 + 15}{2} \times 15$$

$$S = \frac{16}{2} \times 15$$

$$S = 8 \times 15$$

$$S = 120 \text{ (-15 reflexive comparisons)}$$

$$S = 105$$

The breakdown of the actual relationship of these 105 comparisons is that 50 were class exclusions, 24 were non-matches, and 31 were matches.

<u>Scanning Electron Microscopy</u>

With the CamScan Series 4 SEM, the estimation of the population's make-up was divided into exclusive and non-exclusive categories. Of the 105 comparisons, 39 were excludable by class characteristics alone while the other 66 were assigned unknown class category relationships. This latter group were then subjected to microscopic analysis to determine if striations sufficient to evaluate a match or a non-match were present. This type of categorization made no allowance for an equivocal response; observations were a match, a non-match or, if either of these designations were not possible, left at the class level of information.

Of the 66, 39 were determined to have striations which would allow individualizing comparisons; the other 27 had insufficient characteristics for this type of observation.

Of the 39 which were usable, 26 were classified as matches and 13 as non-matches. Three of the 26 matches were in fact false positives or a type II error (B); that is, they were actually non-matches (Table 1). Type II errors carry greater ethical consequences than do type I (a) errors since type II errors would result in wrongly incriminating evidence whereas an inconclusive comparison does not necessarily imply either innocence or lack of association (Gaudette, 1987).

A major concern of the current thesis is the relationship between the accuracy of the technique and the nature of the observations upon which the accuracy is

Scanning Electron Microscopy Estimates (Table 1)

	Match	Non-match	Class Exclusion
Correct	23	13	39
Incorrect	3	0	0
Totals	26	13	39

Insufficient Characteristics = 27

predicated. These topics were explored with Fisher's Exact Test of Independence, where the working hypothesis is that whether a observational unit is a success or a failure is dependent on its classification as an observational unit (Bradley, 1976). The results with the light microscope do not meet the requirements for statistical analysis and merit discussion only. The scanning electron microscope data matrix set-up is seen in Table 2; "C" indicates a correct estimate, "I" indicates an incorrect estimate, "M"

SEM Data Matrix (Table 2)

	C	I	T
M	23	3	26
N	13	0	13
T	36	3	39

stands for an estimated match and "N" represents an estimated non-match or individual exclusion. "T" indicates the totals for each column and row. Using this tabular array, the accuracy percentages were derived by division of totals into the estimates and are shown in Table 3. While it is apparent that these accuracy values show the method to be quite accurate, they would be meaningless unless it

Accuracy Percentages For SEM (Table 3)

	C	I	T
M	.885	.115	1.0
N	1.00	0.00	1.0
T	.923	.077	1.0

could be demonstrated that the estimations are independent of each other; whether an estimate is a success or a failure should have nothing to do with the type of estimate that was made.

The formula for Fisher's test is obtained from the matrix shown in Table 4; observation units A and B are

Formula Matrix for Fisher's Exact Test (Table 4)

	S	F	T
A	r	n-r	n
B	R-r	(N-R)-(n-r)	N-n
T	R	N-R	N

either a success S or a failure F. A random sample of n observations was drawn from the infinite subpopulation of units that are A's and a random sample of N-n observations from the infinite subpopulation of units that are B's. Suppose that r of the units in the A sample and R-r of the units in the B sample are successes; when combined, a pooled sample of N units, R of which are successes is obtained.

The working hypothesis for this test using the SEM estimates is as follows: the success or failure of an observation is dependent upon how the observational unit is classified, in this case as either a match or non-match, with alpha set a .05. If this hypothesis is rejected, the subpopulations of A and B are homogeneous in terms of the proportion of successes. Whether a sample unit was a match or a non-match would have no influence upon its success or failure (Bradley, 1978). If the hypothesis is confirmed, then the observational categories would be preferentially correct or incorrect due to their classification; for example, matches would be correct more often than non-matches. Because it is a standard value and a 95% accuracy rate would be acceptable, alpha is set a .05.

To determine the probabilty of the test statistic r, the hypergeometric probability law is used:

$$P(r) = \frac{\binom{R}{r}\binom{N-R}{n-r}}{\binom{N}{n}} \qquad (2)$$

By substituting the values in Table 3, the formula appears as:

$$P(r) = \frac{\binom{26}{23}\binom{3}{3}}{\binom{39}{36}}$$

$$P(r) = \frac{\frac{4.0329^{26}}{2.5852^{22}} \quad 1}{\frac{2.0398^{46}}{3.7199^{41}}}$$

$$P(r) = \frac{15,600}{54,834}$$

$$P(r) = 0.28449$$

Rounding up, the value of P(r) is .285. Using Fisher's Exact as a test statistic (Bradley, 1978), if the test value is less than the set level of alpha, then the observational units are dependent upon each other; if greater, the units are independent (Bradley, 1978). Since .285 is greater than .05, the test rejects the null hypothesis; the success or failure of a match or a non-match of a knife mark is independent of their classification as a match or a non-match. For these observations to be dependent, the alpha level would need to be set at .286 or higher; clearly this would not be a useful statistic. Since the observational units are independent, the accuracy values can be accepted with confidence that no non-observer biases are intrinsic to the method.

One of the strengths of this technique is the clarity with

which the visual characteristics present themselves. In Figure 4, the background is a known cutmark and the two vertical windows are the questioned specimen. A similar comparison at 50x also yields a positive match (Figure 5). Fracture lines perpendicular to the direction of cut (Figure 6) are present in most cuts, although their exact cause is not understood. These may be related to the "chattering" oblique fractures observed by Bromage and Boyde (1984). Due to the ITD's single impact, as opposed to the continual build-up of a slicing mark, one or two severe fractures might be expected rather than multiple fractures at regular intervals. Even at 150x, as shown in Figure 7, matches were possible; in fact, increased magnification was necessary for the cuts made by the serrated knife. Individualizing characteristics were visible only at higher magnifications. The direction of the knife cut was discernible as is shown in Figure 8; as the blade passes through the bone, it
crushes the nascent surface of the cut and produces "lifts" in the opposite direction. This is the phenomenon noted by Bromage and Boyde in their research on of directionality of stone tool cutmarks (Bromage and Boyde, 1984). In Figure 9, the knife is traveling from the bottom to the top of the photograph. Here the lifts are more clearly seen. In conjunction with gross visual examination and anatomical orientation of a cutmark, microscopic determination of cutmark directionality could be of great assistance in victim/assailant

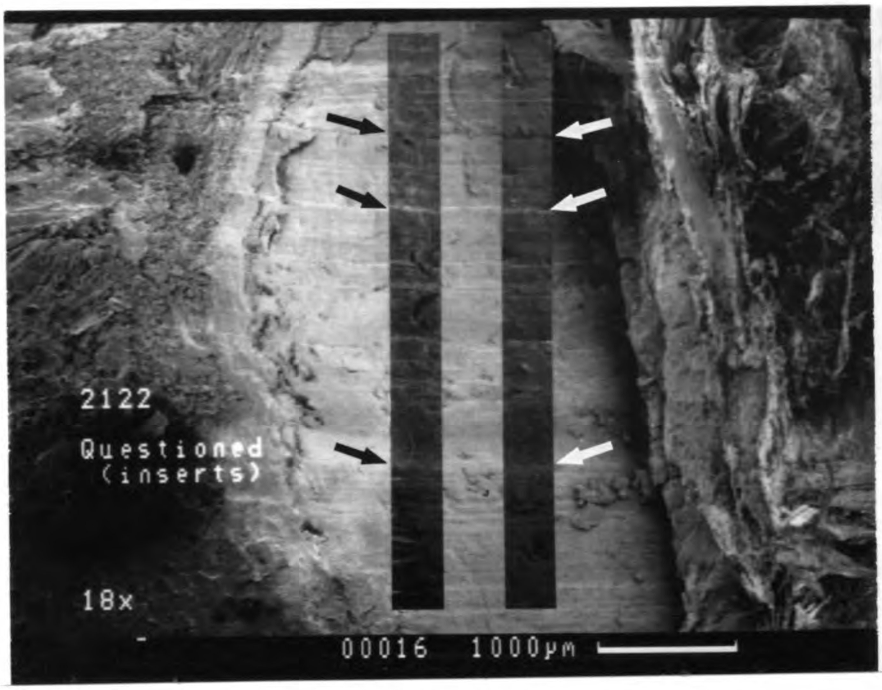


Figure 4

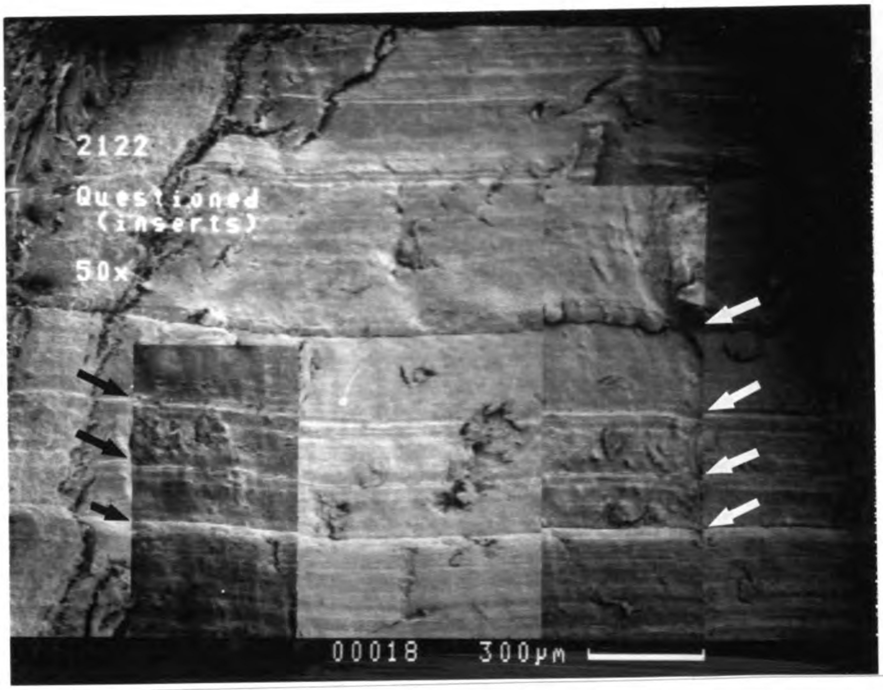


Figure 5

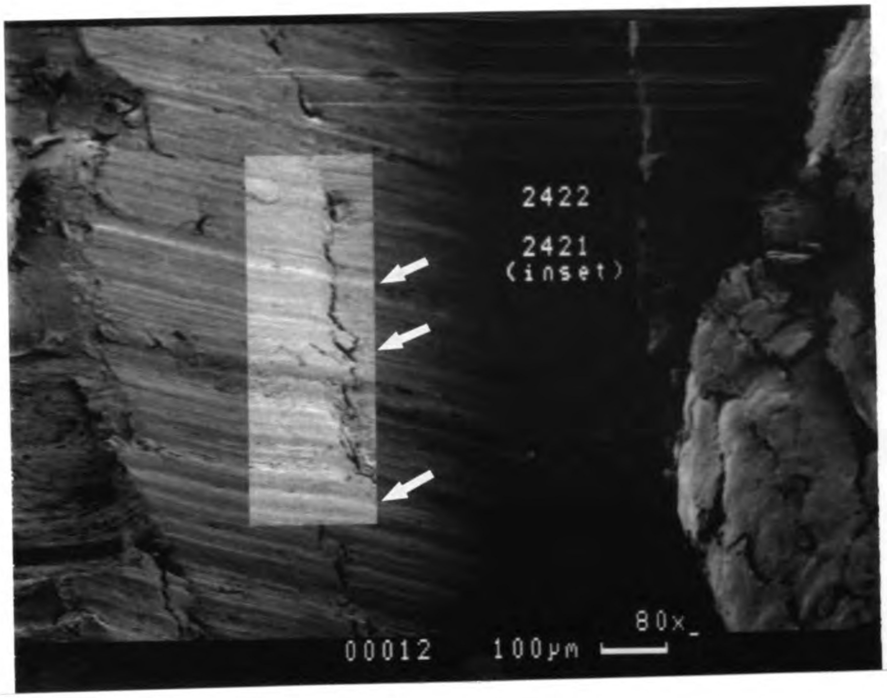


Figure 6

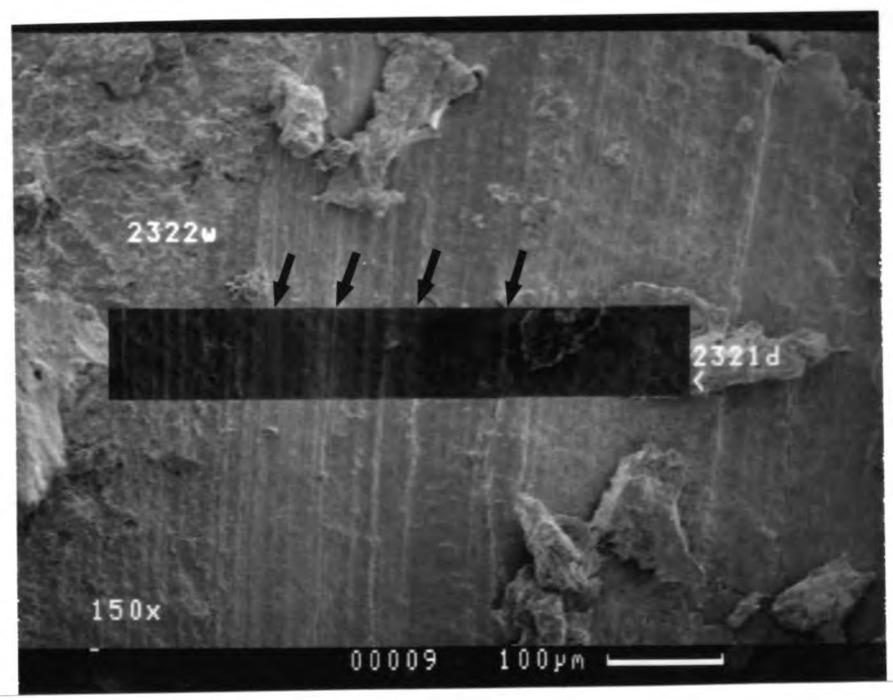


Figure 7

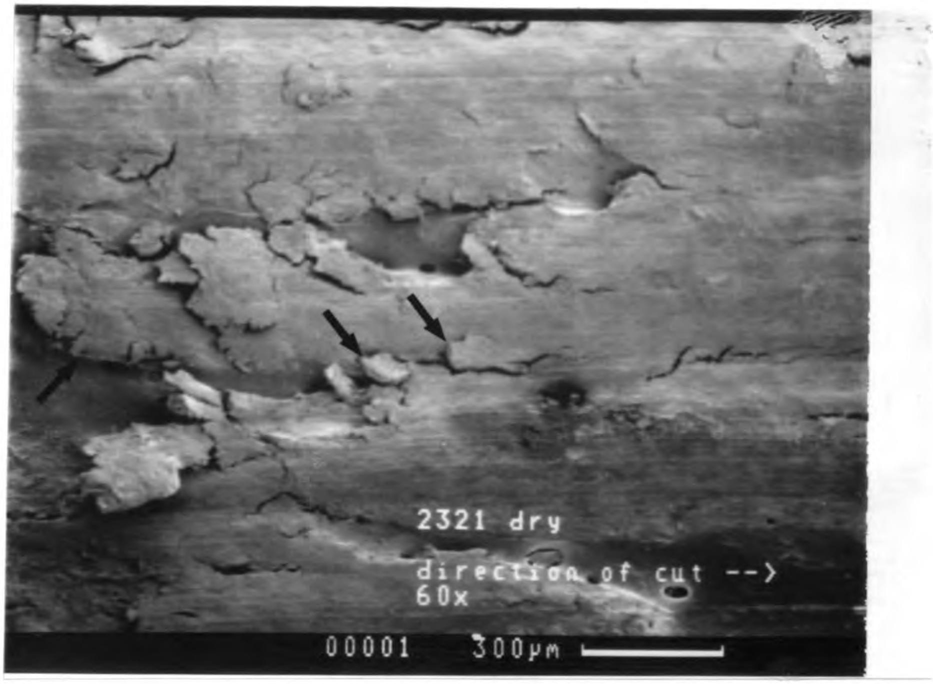


Figure 8

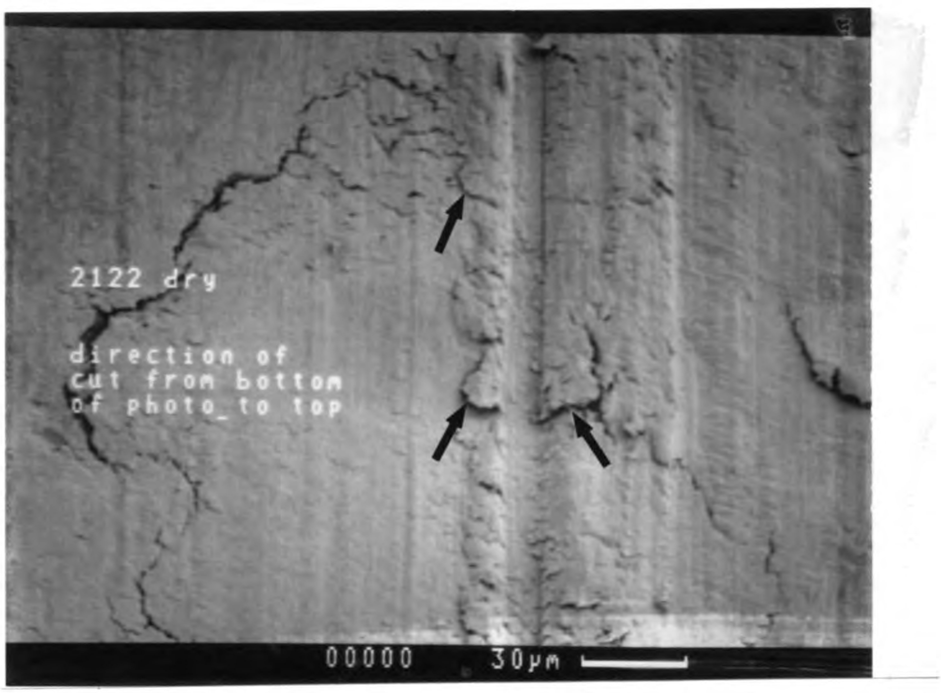


Figure 9

positioning at the time of the assault. Also, directionality can narrow the examiner's range of test marks for comparison by eliminating from comparison impossible or difficult stab wound trajectories.

Of special concern to forensic anthropologist and pathologists is the question of whether cutmarks should be associated with the victim peri- or post-mortem. In a broad time frame, this type of estimation is possible using the SEM. Figure 10 shows a cutmark made when the bone was still fresh; the bone was subsequently air-dried over a period of 72-80 hours at room temperature. The line of cut, the location where the knife first contacted the bone, is separate from the line where the periosteum was first cut. As the periosteum dried and shrank, it pulled back from the initial line of cut. This is contrasted in Figure 11 where a cut made after the bone had already been air-dried. The line of cut for the bone and the periosteum are equal; no post-cut shrinkage of the periosteum has taken place. These results could be of use in instances where a general time orientation of trauma and order of events is desired.

Light Incident Microscopy

Using the comparison light incident microscope, of the 105 comparisons in the actual population, 33 were excluded on the basis of class characteristics. Of the remaining 72, 63 had no individualizing characteristics that were visible under the

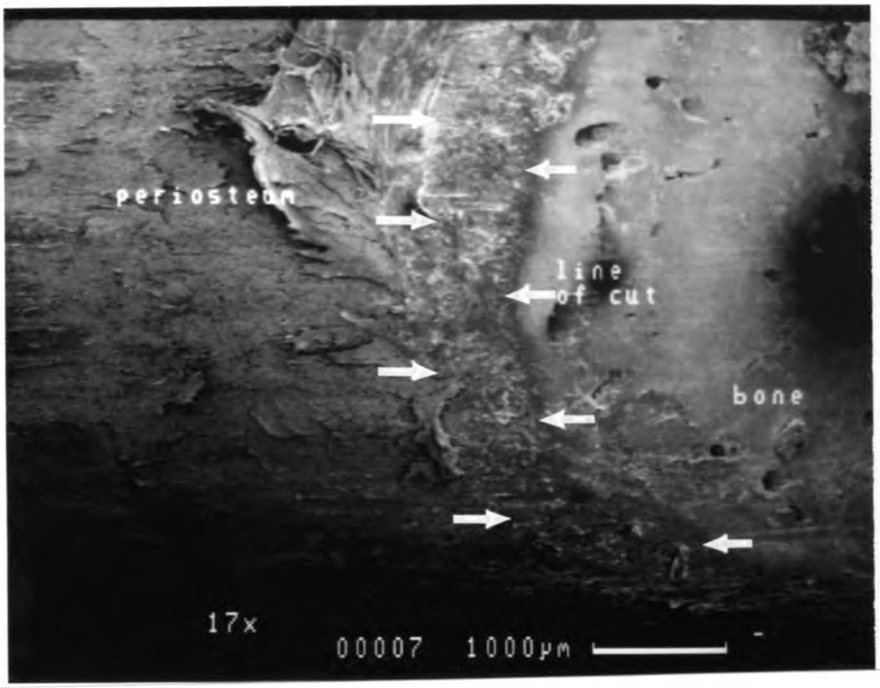


Figure 10

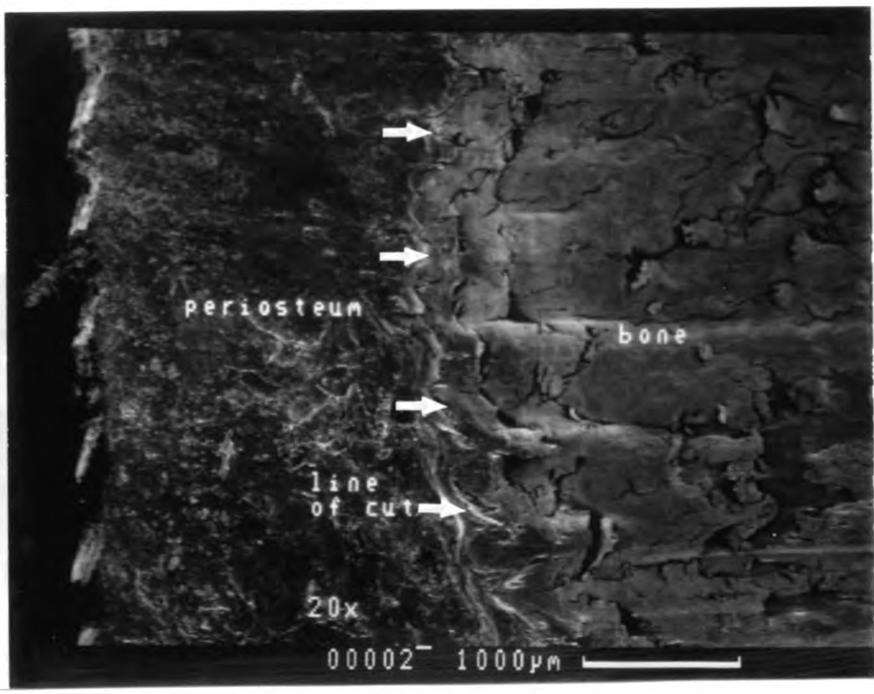


Figure 11

light microscope. Only 3 positive identifications and 6 non-matches were made (Table 5). Directionality was not possible to determine, although whether the bone had been cut when wet or dry was evident in certain instances. Overall, the light incident microscope performed poorly relative to the SEM. This is due in large part to the light microscope's shorter depth of field and weaker resolution (Figure 12). Although

Light Incident Microscopy Estimates (Table 5)

	Match	Non-match	Class Exclusion
Correct	3	6	33
Incorrect	0	0	0
Totals	3	6	33

Insufficient Characteristics = 63

possible, achieving definitive results with a light incident microscope is greatly dependent upon the specimen cutmark's characteristics such as angle, depth and force used to make the cut. Cuts which are deep and vertical are more difficult to evaluate than are shallow, more obliquely angled cuts. Making a replica might be of assistance with difficult to observe cutmarks.

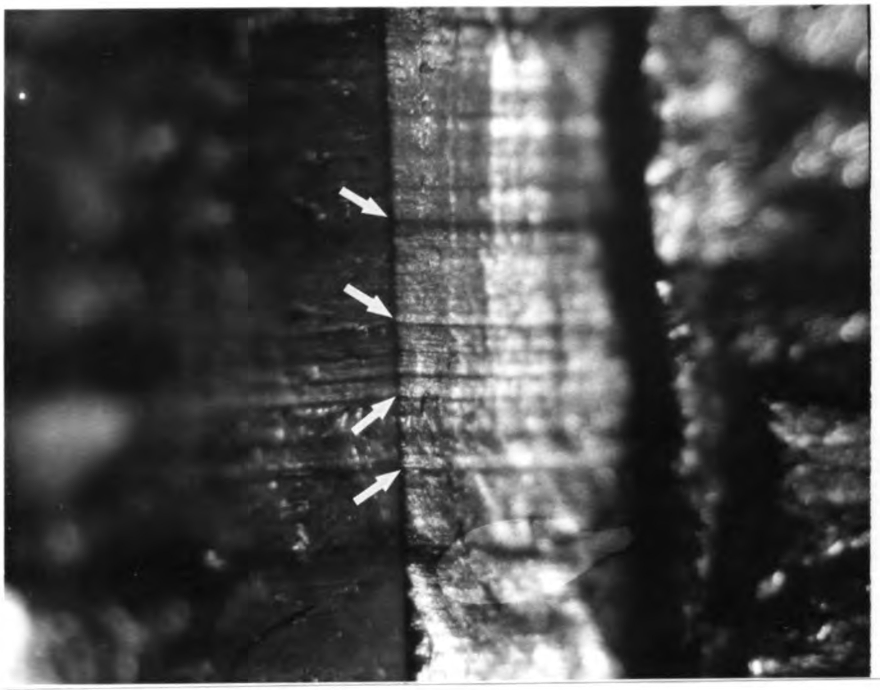


Figure 12

SUMMARY AND CONCLUSIONS

The results of this study should be taken as preliminary but very positive. Borrowing techniques from paleoanthropological and taphonomic studies of stone tool cutmarks on bone, and developing new standardized techniques, a novel method of identifying knifemarks made in bone was developed. Cutmarks were made on human and non-human bone with commercially available knives. The resulting cutmarks were prepared for and viewed with a light incident microscope and a scanning electron microscope. The ability of the two microscopic techniques to image the cutmarks was compared. Using methods common to the forensic discipline of toolmark analysis, the cutmarks were evaluated for class and individualizing characteristics. A working definition for an inclusion (match) and exclusion (non-match) based upon individual traits was developed and implemented. What constitutes significant criteria for drawing various conclusions concerning the relationship between two sets of toolmarks was discussed.

Toolmarks from knives do transfer to bone and thus matches and exclusions are possible with the methodology developed in this thesis. No visible difference exists between affected bovine or human bone at the magnifications employed in this study. Non-human bone is an adequate medium for research of this type. The use of the SEM provides quantitatively and qualititatively superior data with which to make comparisons. The accuracy rate with the conditions set forth in this thesis was 89% for matches and 100% for non-matches. Only 3 errors were made using the SEM and these were false positives. These may be attributed to difficulty in aligning the two specimens due to differences in the sample angle. Four samples were placed in the chamber at a time and each was clamped into place on the stub holder. Therefore, as the stub holder turned, so did the individual specimens; they retained their position relative to one another. This meant that unless each specimen position was changed, the observer would always view the same side of the specimen. Although not a significant problem in relation to the sample under study, since the relationships were set and the population finite, a type II error can create serious problems in a real-world situation within the realm of the legal system. This potential source of error could conceivably be corrected for by an alternate mounting method which would allow for a wider range of specimen manipulation. No bias concerning the accuracy was attributable to the designations of observational units as matches or non-matches; the success or failure is independent of their classification.

In application, a researcher would do well to examine potential cutmarks with a light incident microscope before utilizing an SEM. This "screening" could save time and difficulty in narrowing down the actual knife edge areas to be searched. Since it is possible to compare cutmarks on a light microscope, this stage of analysis could obviate the use of an SEM for that specimen. The process outlined here is possible with an SEM that does not have the comparison window capabilities of the CamScan SEM; microphotographs are compared instead of images and documentation is of greater concern. Sample preparation requirements for the SEM may be greater as compared to the light microscope; the results are, however, of a much higher level of resolution.

Turning to the legal acceptance of this study, that is, having the results of such comparisons as these accepted as evidence in a court of law, several precedents exist. The Washington Supreme Court remarked "the edge on one blade differs from the edge of another blade as the lines on one human hand differ form the lines on another." (State v Clark, 1930). In Commonwealth v. Bartolini, a cleaver and testimony that marks on the victim's skull could have been made by such a cleaver were admitted into evidence (1938). Also, in State v. Churchill, a knife was connected to marks on a homicide victim's sternal cartilage (1982). Similar analyses have been performed with knifemarks in cartilage (Bonte, 1959; Galan, 1986; 1987; Rao and Hart, 1983). And in 1927 an examiner was required to identify the weapon, a hammer, which was responsible for a depression fracture of the skull. He achieved his goal by the matching of striations DeRichter (1929). With further research and experimentation, to produce a more standardized and reliable test standard replication technique, it seems reasonable to expect that this method could become a reliable, legally acceptable method of identifying knives used as homicide weapons.

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