Chapter 4
The Role of Fractography in Forensic Pathology and Anthropology Examinations

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Introduction

The analysis of skeletal trauma is an important aspect of forensic death investigation. Often, skeletal fracture patterns and features are examined by pathologists or anthropologists to assess trauma type (for example, projectile, blunt, or sharp) as well as to understand other aspects of the trauma event (for example, timing, magnitude, and direction of force). These assessments have traditionally emphasized categorizing fractures into discreet types using features such as fragment shape and intersection of fracture margins. For example, the orientation of wedge-shaped fractures resulting from impact and bending forces in bone (such as when a pedestrian's leg is struck by a vehicle) have commonly been used to interpret the direction of force (see, for example, Cohen et al. [1], Holzhausen [2], Martens et al. [3], Messerer [4], Reber and Simmons [5], Tersinski and Madro [6]). It has been shown, however, that reliance on these fracture typologies can lead to erroneous or ambiguous conclusions [5, 7].

A better understanding of the bone failure event can be achieved by looking not only at these fracture types and fragment morphology, but by trying to understand the initial point of failure and its mechanical cause. In recent years, there has been a shift in skeletal trauma analysis from typological approaches to interpretation of

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the failure event based on bone's mechanical properties and its response to force and different loading regimes. One such example is the introduction of bone fractography in skeletal trauma analysis.

Fractography refers to the study of cracks and fractures in a material in order to understand the cause of failure. Fractography is often applied in the failure of engineering structures and products to help ensure future reliability and safety [8]. It is also widely used in forensic contexts to study failure in materials such as glass and ceramics (see, for example, Quinn [9]) as well as plastic and metals. The analysis of cracks and fractures in bone can reveal information about how, why, and where a failure occurred and a crack travelled.

The application of bone fractography in forensic investigations is relatively new. It is therefore not yet widely known or understood in the forensic pathology or forensic anthropology communities, nor regularly taught as part of academic or training programs. Although there are many aspects to fractography, here we emphasize the assessment of fracture surface features. We review some of the recent pertinent work in this area and discuss how bone fractography can be applied in forensic contexts using both visual assessments as well as computed tomography (CT) imaging.

Bone Fractography

One important aspect of bone fractography is the examination of fracture surface morphology, which will be the focus of this chapter. The fracture surface refers to the surface created by the separation of two portions of a material as a result of a propagating crack front. In theory, for simple fractures, the two fracture surfaces will be complements such that a ridge on one surface will correspond to a valley on the other. In practice, skeletal fractures are often complex, fragment may be missing, or surfaces may be contaminated or damaged in such a way that makes a thorough fractographic analysis challenging. However, a useful feature of fractography is that each fracture surface (even for small fragments) may have features that reveal information about the fracture event.

Fracture surfaces express features that reflect the mechanical properties of a material, as well as the speed and stability of the propagating crack front. These features can be used to determine the origin and direction of propagation of the fracture, identify the cause of the failure, and estimate stress levels at failure [8, 10]. The greater the stress in the fracture, the more stored energy, and the more prominent the fracture markings [9]. Glass tends to show fracture surface features very well due to its very fine microstructure. It therefore makes a useful introductory example. Three features in particular are well documented and usually very easy to identify: mirror, mist, and hackle (Fig. 4.1).

In brittle materials, fractures begin as a single origin point, propagating at first relatively slowly. The propagating crack front expands and accelerates outwards. This increasing speed is responsible for the changing pattern of the markings on
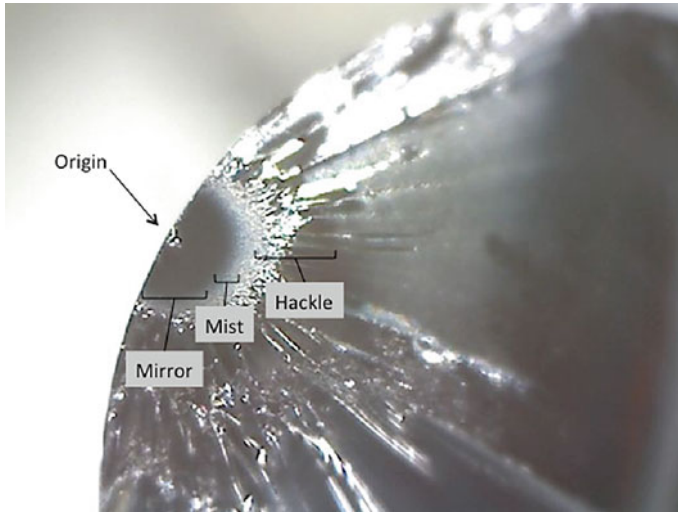
Fig. 4.1 Mirror, mist, and hackle shown on the fracture surface of a 5 mm glass rod; the fracture origin is indicated with an arrow (reprinted from Christensen AM, Hefner JT, Smith MA, Blakely Web J, Bottrell MC, Fenton TW. Forensic fractography of bone: a new approach to skeletal trauma analysis. Forensic Anthropol. 2018;1:32–51)

the fracture surface. Near the fracture origin, planar crack growth is associated with a relatively smooth fracture surface. As the crack accelerates away from the origin, microsteps and deviations begin to develop. These become rougher and more pronounced as the crack increases in speed and instability. The relative "roughness" of a fracture surface therefore indicates the direction of crack propagation, with smoother surface being associated with the fracture origin, becoming increasingly featured as the crack accelerates.

Features of bone fracture surfaces have been noted in a number of studies, including difference in the fracture surface appearance between fractured wet and dry bone [12, 13], and differences related to the postmortem interval [14]. Many researchers have also noted changes in fracture surface morphology across individual fracture surfaces, with the side of the fracture surface experiencing tension being noted as smooth or mottled, while compressive sides of bones are more jagged or sharp [13, 15–19]. While not described as such at the time, these observations were a form of bone fractography.

Forensic bone fractography, specifically the observation of fracture surface features and their relationship to fracture propagation and force direction, has been addressed in several recent papers beginning with Christensen et al. [11], and have found the approach to be reliable and easy to apply. The terminology used to refer to fracture surface features is somewhat standard in material science literature, but some variation exists between material types. Christensen et al. [11] developed terminology specific to the assessment of bone, noting that fractographic features in bone

Table 4.1 Fracture surface features commonly observed in bone (based on Christensen et al. [11], modified from Love and Christensen [20] and Christensen et al. [21])

| Feature	Description
Bone mirror	A region at the fracture origin in bone that is relatively flat or featureless compared to the rest of the fracture surface due to relatively more stable crack growth
Bone hackle	Angular or rounded hackle on a bone fracture surface produced by increased crack speed and instability
Wake feature	The offset alignment of features on the following side of a large inclusion
Arrest ridges	Pronounced peaks aligned approximately perpendicular to the direction of crack propagation resulting from drastic changes in crack propagation velocity on the compressive side of the fracture
Cantilever curl	A curved lip just before terminal fracture of a body loaded in bending; also called *compression curl*
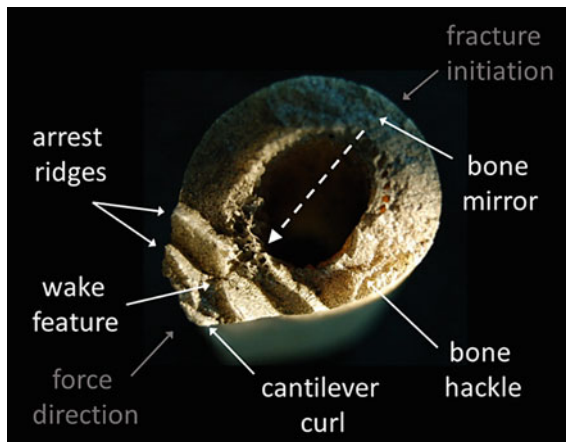
Fig. 4.2 Features of fracture surface morphology for a femur fractured in 3-point bending; solid white arrows indicate bone mirror, bone hackle, arrest ridges, wake feature, and cantilever curl; the dashed white arrow indicates the direction of crack propagation; grey arrows indicate force direction and fracture initiation (reprinted from Christensen AM, Decker SJ. Forensic fractography of bone using CT scans: a case review series. Forensic Anthropol. 2022;5(1):53–6)

appear somewhat differently in both quality and degree of expression than those previously described for other materials (Table 4.1 and Fig. 4.2).

Bone Mirror

Bone mirror is a region that occurs near the fracture origin prior to tilts and deviations from the original fracture plane and is relatively flat in comparison to the rest of

the fracture surface. Bone is a structurally complex material with a relatively large microstructure, so *bone mirror* will never be completely flat and smooth like in glass. It is generally the portion of the bone surface with the fewest features.

Hackle

Hackle is a broad category of fracture surface features, referring to any line on the surface of a fracture running in the local direction of cracking [9, 23], and resulting from increasing crack speed and instability. *Bone hackle* typically appears as rounded or angular ridges aligned in the direction of crack propagation. *Bone hackle* is sometimes sharp or angular and may also be more rounded.

Arrest Ridges

Arrest lines refer to lines on a fracture surface due to arrested or momentarily hesitated crack under an altered stress configuration [9]. *Arrest ridges* in bone result from drastic changes in crack propagation velocity as the crack reaches the compressive side of a bending fracture. They typically appear as pronounced ridges or peaks aligned approximately perpendicular to the direction of crack propagation, and are often very easy to identify.

Wake Hackle and Features

Wake hackle is a discreet line resulting from a split crack front passing an obstacle such as an inclusion or pore. When a crack wave reaches the other side of the obstacle, slight shifts in the angle may occur, with the two fronts of the crack wave ending up slightly out of sync on the following side. *Wake hackle* is aligned in the direction of crack propagation. *Wake features* in bone may be seen in the form of *wake hackle*, which has been noted in association with nutrient foramina or other small holes. *Wake features* may also present as the off-set alignment of larger features such as arrest ridges, which have been observed on the following side of large inclusions such as the medullary cavity.

Cantilever Curl

Cantilever curl forms at the terminus of a fracture of a structure loaded in bending, and presents as a curved lip (the positive portion of which is sometimes called a "breakaway spur" in anthropological literature). In fractured bone, it will be the final

feature in a fracture event. If there was a branching event (such as in the case of a "butterfly wedge") there may be two or more cantilever curls. *Cantilever curl* is typically associated with a load with a strong bending component, and may therefore not only be used to determine the direction of crack propagation, but also to interpret loading conditions.

A number of other fracture surface features have been documented and described for other materials, but are not seen (or are less often seen) in bone, including *Wallner lines* and other forms of *hackle*. These features may become more important and relevant as more is known about forensic bone fractography.

These features of fractured bone surfaces have been shown to be reliable indicators of the location of fracture initiation and therefore the direction of applied force in experimentally fractured bone [11]. Very strong agreement was found between assessors in identifying the point of fracture initiation and direction of crack propagation. It was also found that more experienced fractographers identified more features that those with less experience (even if those less experienced fractographers were highly experienced anthropologists). Visualization of fracture surface features were also noted to be enhanced through the use of aids such as oblique lighting, low-power microscopy, and the application of reversible coatings (such as fingerprint powder) on the fracture surface in order to decrease reflection and increase contrast. Overall, fractography was found to be a reliable, inexpensive, and user-friendly method for assessing fractured bone.

Other recent studies also support the reliability and utility of bone fractography. For example, Love and Christensen [20] retrospectively reviewed a series of blunt trauma cases from an autopsy sample, and found that fractographic features correlated well with autopsy findings (including soft tissue and radiologic findings) as well as with traditional skeletal trauma analyses. Isa et al. [24] studied complex fractures documented through high-speed video, and found that fractography findings were supported by ground truth. Fracture surface morphology was shown by Emerith et al. [25] to be more accurate for determining crack propagation direction than looking at wedge orientation in fractured sheep femora. While most studies have focused on blunt trauma, certain fracture surface features have also been noted in association with projectile trauma [26].

Bone Fractography Using Computed Tomography

In cases where remains are discovered or received skeletonized, the application of bone fractography is rather straightforward, since the bone fracture surfaces can be directly observed. Indeed, many of the previously mentioned studies involved the direct examination of defleshed, dry bone surfaces which were isolated and processed/macerated prior to assessment. In other contexts, such as autopsy cases involving skeletal trauma, remains are typically fresh with significant associated soft tissues. Direct examination of bone surfaces may be impossible or impractical, and assessment may be expedited if the fracture surfaces could be assessed without

maceration. Scheirs et al. [27] found that certain gross morphological features typically associated with perimortem fractures (including, for example, layered breakage, bone scale, flake defect, tension lines, and plastic deformation—some of which are similar to fracture surface featured described in bone fractography) could be identified using CT scans. Several studies and reviews have also specifically investigated the use of CT scanning to assess fracture surface features.

Christensen et al. [11] present several examples of bone fracture surfaces imaged using high-resolution micro-CT scanning. Perhaps unsurprisingly, the resolution of this imaging technology is sufficient to visualize many fracture surface features (Fig. 4.3). However, such instruments are not widely used and cannot be used for whole body imaging.

Christensen and Hatch [28] investigated whether fracture surface features could be observed using traditional medical CT scanners such as those commonly used in postmortem imaging. They reviewed postmortem CT scans performed at a large, high volume, centralized state medical examiner's office which were taken as part of routine forensic examinations. A single case was presented of an individual involved in a motor vehicle accident with a fractured femur. Imaging was performed using a large bore, 16 detector row CT, with thin slide data obtained of the lower extremities using a bone algorithm. The fracture surface was isolated using proprietary software to create a volume rendering, with surface details accentuated using lighting and shading tools. Fractographic features were found to be readily apparent, though the resolution was notably less than for fracture surfaces examined directly. Specifically, bone mirror, arrest ridges, and cantilever curl were all observed, and crack propagation direction could be easily determined (Fig. 4.4).

Christensen and Decker [22, 29] present a review of several clinical CT scans taken of patients with traumatic lower extremity injuries. Scans were performed with a 64-slice CT scanner using a standard trauma scan protocol. Scans had a

Fig. 4.3 High-resolution micro-CT scan of fractured femur surface; bone mirror, arrest ridges, and cantilever curl are all apparent (reprinted from Christensen AM, Decker SJ. Forensic fractography of bone using CT scans: a case review series. Forensic Anthropol. 2022;5(1):53–6)
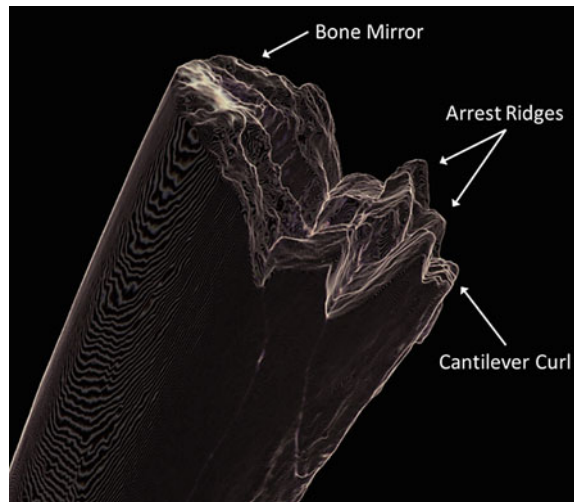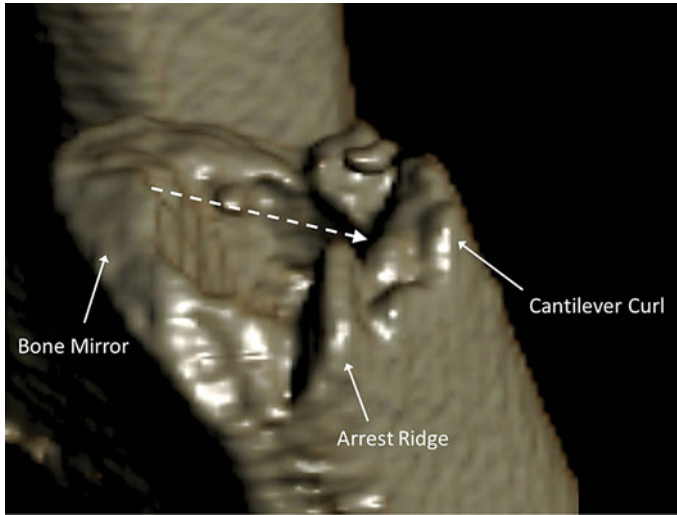
Fig. 4.4 Fracture surface features as seen in a postmortem CT scan; solid arrows indicate bone mirror, arrest ridge, and cantilever curl; dashed white arrow indicates direction of crack propagation (reprinted from Christensen AM, Hatch GM. Forensic fractography of bone using CT scans. J Forensic Radiol Imaging. 2019;18:37–9 with permission from Elsevier)

KVP of 120, mA was variable to patient size, all scans had a slice thickness of 1.25 mm and a slice increments of 0.75 mm. Data sets of the lower extremities were acquired using bone and soft tissue algorithms. Fracture surfaces were visualized as 3D computational models (volume and surface) in volume rendering software with a Hounsfield value of $\geq$226HU used to generate the initial surface models. Fragments were hand separated but maintained the same threshold value. The renders were overlain with a bone volume rendering. One case (Fig. 4.5) involved a motorcyclist struck by a car who suffered a fractured femur. Fracture surface features including bone mirror, arrest ridges, and cantilever curl are seen in the surface rendering, and clearly indicate the direction of crack propagation.

Machin [30, 31] examined the agreement between assessment of fracture surface morphology performed using CT scans and direct visual examination of the same bone specimens. Pig femora fractured in 3-point bending with axial loading were macerated and CT scanned. Bones were scanned using a 64-side scanner at 120 kV and 300 mA using 0.5 mm slices reconstructed with an interval of 0.33 mm. Recon-struction was performed using both a sharp "bone" kernel and a soft tissue kernel. CT images were assessed by a radiologist using a medical imaging viewer, and bones were examined directly by an anthropologist using a light and conventional light microscope. Both assessors examined the specimens for the presence of frac-ture surface features and interpretation of impact side/direction. Assessments were compared between the two groups as well as to ground truth for impact direction. The results showed perfect agreement between assessors and with ground truth for impact direction. There was also strong agreement between the assessors regarding the presence of arrest ridges (Fig. 4.6). There was less agreement between assessors
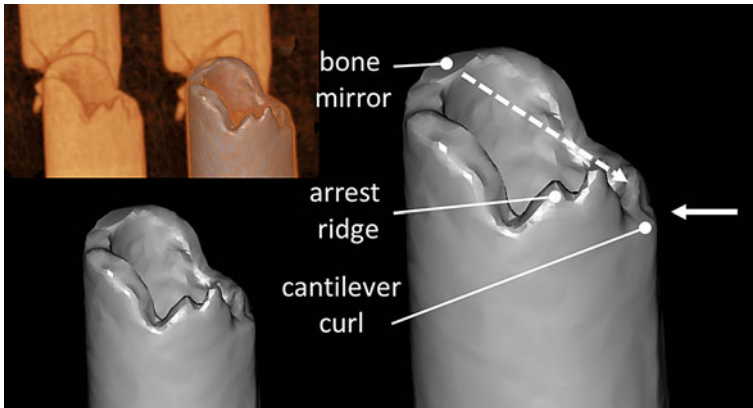
Fig. 4.5 Fracture surface features as seen on a clinical CT scan including volumetric rendering (top left), combined volumetric and surface rendering (top middle), and surface rendering (bottom left); several fracture surface features are apparent (far right); direction of crack propagation is indicated with a dashed arrow and the general direction of impact or loading (not necessarily a specific impact location or angle) is shown with the solid arrow (reprinted from Christensen AM, Decker SJ. Forensic fractography of bone using CT scans: a case review series. Forensic Anthropol. 2022;5(1):53–6)

regarding the presence of bone mirror (Fig. 4.7), bone hackle, wake features, and cantilever curl. Overall the results suggest that crack propagation direction can be reliably interpreted from CT scans although fewer fracture surface features are observed. Computed tomography images in combination with freeware such as Blender (see
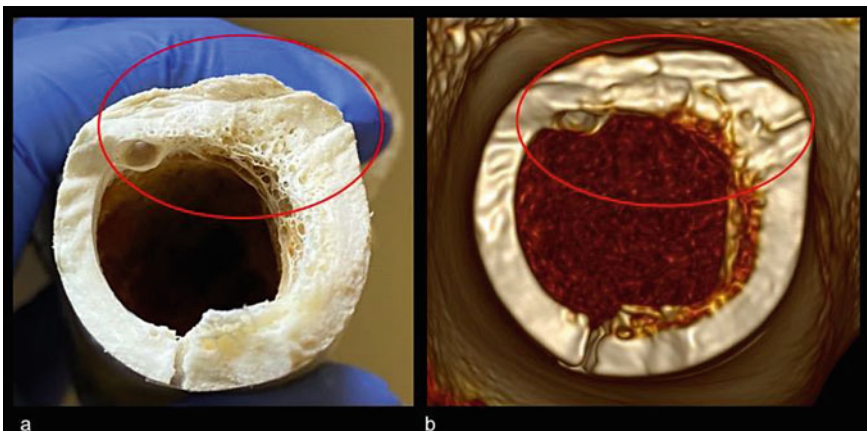

Fig. 4.6 Comparison of arrest ridges (indicated with red circles) between direct examination of the bone surface (left) and in a CT scan (right) (reprinted from Machin R. Can Computed tomography fracgtography determine the direction of fracture propagation? [MS Dissertation], University of Leicester; 2020)

Fig. 4.7 Comparison of bone mirror (indicated with red circles) between direct examination of the bone surface (left) and in a CT scan (right) (reprinted from Machin R. Can Computed tomography fracgtography determine the direction of fracture propagation? (reprinted from Machin R. Can Computed tomography fracgtography determine the direction of fracture propagation? [MS Dissertation], University of Leicester; 2020)
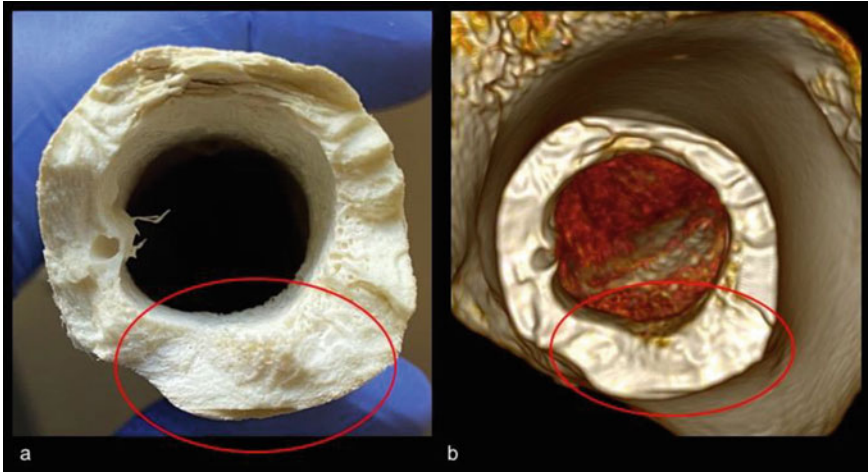
Chap. 1; https://www.blender.org/ last visited March 2022) can also be used to virtually deflesh a fracture site and isolate individual fractured bones for fractographic analysis (Fig. 4.8).
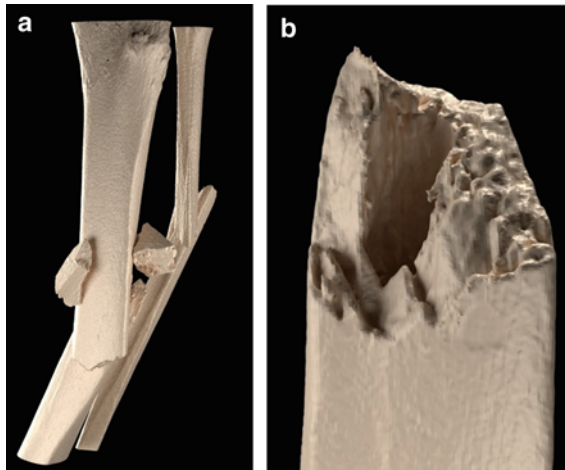

Fig. 4.8 **a** Postmortem computed tomography image of a fractured lower leg sustained in a pedestrian verses car incident using Blender (https://www.blender.org/.last visited March 2022) **b** The fracture through the tibia is then isolated for fractographic analysis

The amount of fracture surface detail is notably less in CT scans than direction observation of the bone (or using micro-CT) due to resolution limitations. However, features that are highly diagnostic of crack propagation direction, such as arrest ridges and cantilever curl, are still readily apparent. Smaller surface features such as hackle may be less likely to be observed due to this reduced resolution, though it is still considered possible. It may also be possible to increase the resolution of the scan in a region of interest if it is known prior to the scan that fractography may be utilized. The reduction in overall surface detail/resolution has also been noted to actually clarify the location of certain features such as bone mirror [28].

Scanner settings can impact the quality of the resulting model [22], which could potentially impact the detail expressed in the fracture surface. A CT slice thickness of $< / = 1.25$ allows for better visualization of the fractured region in 3D [32]. The selection of 3D modelling software may also affect results [22].

Although there are currently only a few studies that have addressed the use of bone fractography using CT scans, results strongly suggest that even with lesser surface detail available compared to direct examination, fracture surface features can be seen, and crack propagation direction can be reliably interpreted. This is significant because it not only potentially eliminates the need to macerate remains in order to apply fractography, but it also means that fractography may be applicable to a broader range of context than dry bones. Fractography may also have applications in clinical contexts, or forensic investigations involving the living. For example, fractography could be used to confirm or refute the circumstances of an injury incident such as an accident or abuse [28]. Moreover, CT scanners are now available in most clinical contexts, and increasingly in postmortem examinations, making it a practicable option in many settings.

Fractography in Practice

Forensic bone fractography is still a relatively new field. Few educational or training programs address it directly, and more research is needed to better understand the relationship between fracture surface features and skeletal trauma events. Notably, fewer fracture surface features are typically observed when evaluated by less experienced examiners [11]. Practitioners are therefore strongly encouraged undertake significant practice and study prior to applying fractography in casework.

Researchers have noted that features are less often identified when cortical area is smaller, and comminuted fractures also make feature identification more challenging. Caution should therefore be used in these potentially more challenging cases.

It is typical in anthropological examinations to physically re-fit fractured segments in order to reconstruct original bone dimensions or visualize overall fracture patterns. However, physical reconstruction of fragments for many other materials is discouraged because of the risk of altering or obliterating fine surface details through contact or abrasion. If physical reconstruction is to take place in an examination, it is recommended that fracture surface features be examined and documented first.

Based on what is known from fractography of other brittle materials, it is expected that higher energy events will have more features and be easier to interpret. Low energy fractures such as thermal fractures result in fewer surface features. Very porous or course-grained materials (such as bone) can also mask surface markings. More research is needed to fully understand the applications of fractography to forensic bone fractography.

Summary

Bone fractography has been shown to be an easy and reliable method for assessing skeletal trauma, specifically by observing the presence and orientation of fracture surface features. These features reveal information about the direction of crack propagation, and often correspondingly the direction of the impact or force. The presence of even one or two features, viewed directly on the bone surface or using CT scans, can be sufficient to interpret crack propagation direction.

It is hoped that the information presented here can be used by forensic practitioners to improve skeletal trauma analyses through the use of an additional method to interpret trauma patterns and better understand trauma events.

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