J Forensic Sci, March 2009, Vol. 54, No. 2
doi: 10.1111/j.1556-4029.2008.00976.x
Available online at: www.blackwell-synergy.com

TECHNICAL NOTE

Cris E. Hughes,[1] *M.A. and Crystal A. White*[1]

Crack Propagation in Teeth: A Comparison of Perimortem and Postmortem Behavior of Dental Materials and Cracks*

ABSTRACT: This study presents a new method for understanding postmortem heat-induced crack propagation patterns in teeth. The results demonstrate that patterns of postmortem heat-induced crack propagation differ from perimortem and antemortem trauma-induced crack propagation patterns. Dental material of the postmortem tooth undergoes dehydration leading to a shrinking and more brittle dentin material and a weaker dentin-enamel junction. Dentin intertubule tensile stresses are amplified by the presence of the pulp cavity, and initiates crack propagation from the internal dentin, through the dentin-enamel junction and lastly the enamel. In contrast, *in vivo* perimortem and antemortem trauma-induced crack propagation initiates cracking from the external surface of the enamel toward the dentin-enamel junction where the majority of the energy of the crack is dissipated, eliminating the crack's progress into the dentin. These unique patterns of crack propagation can be used to differentiate postmortem taphonomy-induced damage from antemortem and perimortem trauma in teeth.

KEYWORDS: forensic science, forensic anthropology, tooth, tooth fracture, postmortem changes, heat, dentin, enamel

A foundational goal of forensic anthropology is analysis and differentiation of antemortem trauma, perimortem trauma, and postmortem damage. While there is an abundance of literature on these matters for bone, there is little research on trauma differentiation in relation to human dentition. The structural and biomechanical differences between bone and teeth necessitate distinct research on each substance. The literature present on crack propagation in human teeth is abundant in dental research, covering topics such as the fracture properties of different tooth tissues (1,2), thermal stress and fatigue of enamel and dentin (3–5), fracture behavior at the microstructure level (6–10), and dentin-enamel junction mechanical properties (6,11,12). However, this research can only be applied to perimortem and antemortem trauma, as the goal of dental research is to simulate *in vivo* cracks in living humans with living teeth. Studies that are related to postmortem taphonomic damage such as those by Kishen and Asundi (13), and Kruzik et al. (14), examine the biomechanical strength of hydrated (peri- and antemortem) versus dehydrated (postmortem) dentin. While these articles are comprehensive in addressing the biomechanical differences in hydrated and dehydrated teeth, forensic anthropologists need a simple and quick method for differentiating antemortem or perimortem trauma from postmortem trauma of the dentition.

The present study examines the macro- and microstructural patterns of heat-induced taphonomic crack propagation in dentition. The temperatures to which the teeth are exposed represent the upper range (41–49°C) of temperatures in the natural environment of a decomposing body. This study has several objectives and applications to the field of anthropology. First, teeth are one of the most durable parts of the body and are prevalent in the forensic and archaeological context. Therefore, new techniques for discriminating perimortem trauma and postmortem damage in dentition are highly useful. Second, the use of realistic temperatures in this study allows for the results to be applied to human bodies that were exposed to a natural environment. Third, the appropriateness of using *Sus scrofa* dentition as an analog for human teeth is addressed in this study, which provides future researchers with the inherent potentials and cautions of using the dentition of *Sus scrofa* to explain crack propagation in humans.

Methods

Macroscopic Methods

A total of 36 permanent mandibular first, second, and third incisors and first premolars from fresh pigs aged 6 months (*Sus scrofa)* were removed from the bone. The 36 teeth were separated into three groups, with a representative number of each tooth type in the three groups. The groups were each exposed to a temperature range of 41–49°C for 9 h/day for a total of 14 days. Teeth were examined at 3-h intervals during their exposure to heat using a low-powered microscope. Information on presence and propagation pattern of cracks was recorded.

Microscopic Methods

Following macroscopic analysis, all teeth were embedded in epoxy and cut with a diamond saw (Buehler Isomet Low Speed Saw, Lake Bluff, IL) into 500-μm thick transverse and longitudinal sections. Each section was mounted onto a slide, ground and polished to a thickness 300 μm. Each tooth section was

[1]Department of Anthropology, Social Sciences 1 Faculty Services, University of California at Santa Cruz, 1156 High Street, Santa Cruz, CA 95064.

*Presented at the 2007 Mountain, Desert, and Coastal Forensic Anthropology Annual Meeting, May 2007, in Boulder City, NV, and the 60th Annual Meeting of the American Academy of Forensic Sciences, February 18–23, 2008, in Washington, DC.

Received 17 Jan. 2008; and in revised form 21 Mar. 2008; accepted 19 April 2008.

examined using a high-powered microscope for the origin, distribution, and variation of cracks.

Results

Macroscopic Results

Four general types of cracking patterns were present after exposure to the heat: transverse, longitudinal, contour, and sporadic (Fig. 1). All 36 teeth demonstrated at least one crack after exposure to heat. First premolars and third incisors were the first to exhibit cracks in all three runs. The presence and frequency of the four patterns can be seen in Table 1.

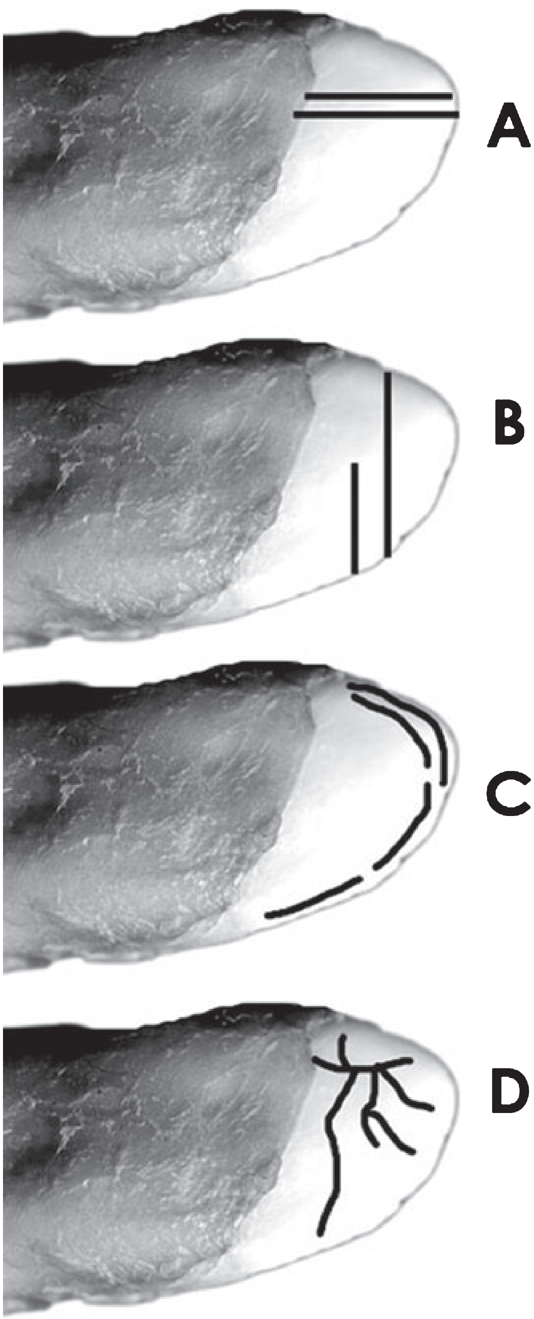

FIG. 1—*Different types of cracks affecting macromorphology of teeth: longitudinal (A), transverse (B), contour (C), and sporadic (D).*

TABLE 1—*Frequency of types of cracks for each tooth type in Batch 1.*

Crack/Tooth Type	First Incisor	Second Incisor	Third Incisor	First Premolar
Longitudinal	9	5	15	4
Sporadic	1	0	1	1
Contour	0	0	9	0
Transverse	1	0	1	0

Microscopic Results

All cracks viewed under the microscope originated from the most structurally strained portion (most acute three-dimensional angle) of the pulp cavity and propagated through the dentin toward the dentin-enamel (DE) junction. Not all cracks reached the DE junction. It was also noted that the closer the section was taken to the root, the less distance the crack would propagate from its origin at the pulp cavity. Those that reached it continued in one of two patterns, (i) directly crossing the DE junction and propagating out through the enamel, cracking completely through the external-most enamel, or (ii) entering the DE junction and running along it until eventually propagating out through the enamel, cracking it completely through the external-most enamel.

Discussion

Several assumptions of the researchers prior to the microscopic analysis were contradicted: (i) cracks originate at the outermost enamel in response to the dehydration of the dentin, and (ii) these enamel cracks do not penetrate past the DE junction into the dentin due to the crack resistant nature of the DE junction. An alternative model than that of *in vivo* teeth can explain the internal origin and complete propagation of most cracks to the external surface of enamel. Exposure to heat in the ovens catalyzed a dehydration event. *In vivo* dentin has a much higher percentage of water than enamel, and therefore undergoes the largest amount of dehydration and shrinking, while the brittle enamel undergoes minimal, if any shrinking. The dentin is secured to the shape of the enamel by the DE junction, and must therefore shrink "out," not "in." This process of the dentin shrinking out away from the pulp cavity incites dentin intertubule tensile stresses (Fig. 2*A*). Dentin becomes more brittle as the material properties change and reorganize under water loss, causing intertubule areas of stress to give out under strain more easily, causing cracks to form (Fig. 2*B*).

It is important to conceptualize stress in a three-dimensional model for a tooth. Local stresses in materials are amplified by the presence of holes. Additionally, the smaller the radius of curvature of the hole or material, the greater is the stress. The pulp cavity represents a hole in the dental materials, which is larger nearest the root and smallest near the occlusal surface. Therefore, the combination of the (i) smallest radius of curvature nearest the occlusal surface in both the pulp cavity and the macrostructure of the tooth, (ii) the intertubule stresses, (iii) the lack of a stabilizing material like the DE junction on the innermost boundary of the dentin, and (iv) the lower tensile strength of the DE junction as a result of dehydrated collagen, stimulates crack propagation to occur from the pulp cavity outward toward the enamel (Fig. 3). This occurs in a planar fashion, seen as cracks in both longitudinal and transverse sections of teeth. While this is a preliminary explanation for the *mechanisms* of crack propagation and direction, the *characteristics* of the crack propagation can be applied to forensic analysis.

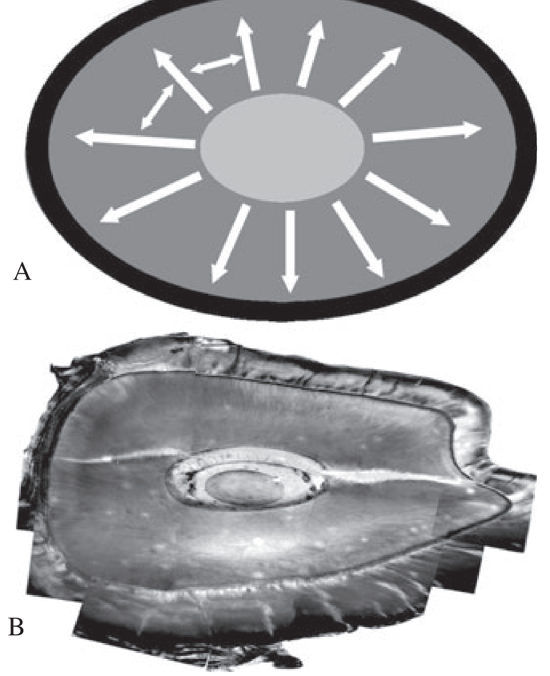

FIG. 2—*(A) Single arrows indicate alignment of dentin tubules. Double arrows indicate direction of intertubule tension. (B) Image of a transverse section of tooth exhibiting two cracks radiating from pulp cavity toward enamel.*

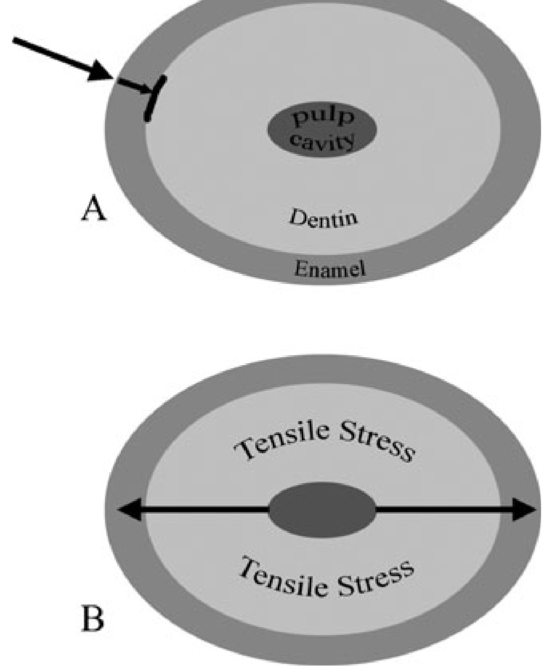

FIG. 4—*Models of crack propagation patterns in perimortem/antemortem trauma (A) and postmortem heat-related damage (B). Black arrows indicate initial direction of stress and subsequent crack propagation.*

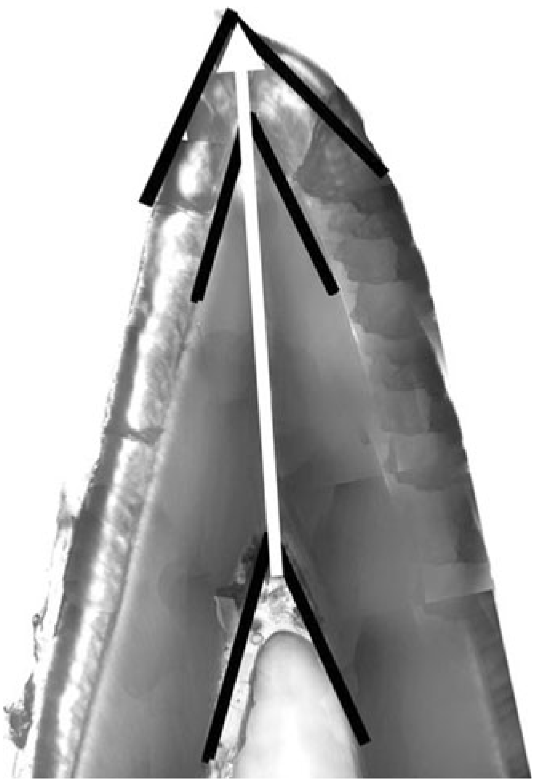

FIG. 3—*Longitudinal section of tooth showing smallest radii of curvature (black arrows) and direction of crack (white arrow).*

Perimortem and antemortem stress through trauma is applied to the exterior surface of the tooth and the compressive forces initiate cracks to propagate through the enamel to the DE junction. The DE junction is 5–10 times tougher than enamel, but 75% less tough than dentin (12). The DE junction can dissipate a large amount of force before allowing cracks to propagate into the dentin, or even completely arrest the crack prior to entering the dentin (6,11) (Fig. 4*A*). When and if a crack enters the dentin, the *in vivo* material properties of dentin allow for a quick dissipation of the remaining energy in the crack. Alternatively, this pilot study suggests that taphonomic heat-related damage allows for crack propagation in an opposite fashion from perimortem and antemortem trauma. Due to water loss and subsequent shrinking of dentin, stress is greatest in the intertubule areas closest to the pulp cavity, and the cracks originate here. The crack is then able to easily propagate through the dehydrated dentin, the dehydrated and structurally modified DE junction, and out toward the minimally modified enamel (Fig. 4*B*). This pattern is similar to that by Brown et al. (4) with the exception that none of the teeth in our study exhibited complete separation of the dentin from the enamel at the DE junction. Further testing using a larger, human dental sample will empirically confirm the preliminary results of this pilot study.

The use of *Sus scrofa* teeth as an analog for human teeth for this research necessitates a comparison of the structural characteristics of both. In general, humans have thicker enamel and a more complex enamel rod decussation pattern than pigs, which accounts for a greater stiffness in human teeth (9). Additionally, the percent ratio of mineral to organics to water in human and pig enamel is 92:2:6 and 95:2:3, respectively. While the majority of *Sus scrofa* teeth used for this experiment had completed enamel mineralization, several exhibited incomplete mineralization, which would increase the percent ratio of organic material such as collagen and decrease the percent ratio of inorganic material such as hydroxyapatite (15). Overall, the characteristics presented here predict that human teeth have a greater stiffness, greater fracture resistance, but less elasticity than the *Sus scrofa* teeth used in this experiment (8). While this should not affect the pattern of crack propagation, it means that the amount of force needed to induce crack propagation through the enamel could be greater.

Inferences from the current study's results are limited by several aspects: the sample is small, only four types of teeth were used in the study, the sample consists of nonhuman teeth, and there is no testing of antemortem contexts such as endodontic treatments (14,16,17) or exposure to extreme temperature fluctuations that could simulate similar results as described in this study (3). Questions such as how postmortem crack propagation in human teeth is affected by perimortem trauma, or the mildest temperature at which postmortem crack propagation induced by dentin dehydration will occur still need to be answered. Future research on crack propagation is already underway, and will include a larger sample of human teeth to address the defined limitations. In addition, the research will explore how postmortem crack propagation patterns may vary when variables such as the presence of perimortem trauma, tooth macromorphology variations, dental restorations, and different temperature ranges are introduced. The results from future research will refine the current study's goal to differentiate temperature-induced postmortem crack propagation patterns from alternative forms of trauma.

Acknowledgments

The authors thank Dr. Alison Galloway for her insights and critiques. We also thank Dana Carpenter for sharing his knowledge and references of hard tissues biomechanics with us.

References

1. Rasmussen ST, Patchin RE, Scott DB, Heuer AH. Fracture properties of human enamel and dentin. J Dent Res 1976;55(1):154–64.
2. Rubin C, Krishnamurthy N, Capilouto E, Yi H. Stress analysis of the human tooth using a three-dimensional finite element model. J Dent Res 1983;62(2):82–6.
3. Brown WS, Jacobs HR, Thompson RE. Thermal fatigue in teeth. J Dent Res 1972;51(2):461–7.
4. Jacobs HR, Thompson RE, Brown WS. Heat transfer in teeth. J Dent Res 1973;52(2):248–52.
5. Lloyd BA, McGinley MB, Brown WS. Thermal stress in teeth. J Dent Res 1978;57(4):571–82.
6. Xu HHK, Smith DT, Jahanmir S, Kelly JR, Thompson VP, Rekow ED. Indentation damage and mechanical properties of human enamel and dentin. J Dent Res 1998;77(3):472–80.
7. Kinney JH, Balooch M, Marshal GW, Marshall SJ. A micromechanics model of the elastic properties of human dentine. Arch Oral Biol 1999;44:813–22.
8. Popowics TE, Rensberger JM, Herring SW. The fracture behaviour of human pig molar cusps. Arch Oral Biol 2001;46:1–12.
9. Popowics TE, Rensberger JM, Herring SW. Enamel microstructure and microstrain in the fracture of human and pig molar cusps. Arch Oral Biol 2004;49:595–605.
10. Wang R. Anisotropic fracture in bovine root and coronal dentin. Dent Mater J 2005;21:429–36.
11. Lin CP, Douglas WH. Structure-property relations and crack resistance at the bovine dentin-enamel junction. J Dent Res 1994;73(5):1072–8.
12. Imbeni V, Kruzic JJ, Marshall GW, Marshall SJ, Ritchie RO. The dentin-enamel junction and the fracture of human teeth. Nat Mater 2005;4:229–32.
13. Kishen A, Asundi A. Experimental investigation on the role of water in the mechanical behavior of structural dentine. J Biomed Mater Res 2005;73(A):192–200.
14. Kruzik JJ, Nalla RK, Kinney JH, Ritchie RO. Crack blunting, crack bridging and resistance-curve mechanics in dentin: effect of hydration. Biomaterials 2003;24:5209–21.
15. Kirkham J, Robinson C, Weatherell JA, Richardson A, Fejerskov O, Josephsen K. Maturation in developing permanent porcine enamel. J Dent Res 1988;67(9):1156–60.
16. Huang TG, Schilder H, Nathanson D. Effects of moisture content and endodontic treatment on some mechanical properties of human dentin. J Endodon 1992;18(5):209–15.
17. Sedgley CM, Messer HH. Are endodontically treated teeth more brittle? J Endodon 1992;18(7):332–5.

Additional information and reprint requests:
Cris E. Hughes, M.A.
Department of Anthropology
Society Sciences 1 Faculty Services
University of California at Santa Cruz
1156 High Street
Santa Cruz, CA 95064
E-mail: cehughes@ucsc.edu