Aging and Fracture of Human Cortical Bone and Tooth Dentin

Kurt J. Koester, Joel W. Ager III, and Robert O. Ritchie

Mineralized tissues, such as bone and tooth dentin, serve as structural materials in the human body and, as such, have evolved to resist fracture. In assessing their quantitative fracture resistance or toughness, it is important to distinguish between intrinsic toughening mechanisms, which function ahead of the crack tip, such as plasticity in metals, and extrinsic mechanisms, which function primarily behind the tip, such as crack bridging in ceramics. Bone and dentin derive their resistance to fracture principally from extrinsic toughening mechanisms, which have their origins in the hierarchical microstructure of these mineralized tissues. Experimentally, quantification of these toughening mechanisms requires a crack-growth resistance approach, which can be achieved by measuring the crack-driving force (e.g., the stress intensity) as a function of crack extension ("R-curve approach"). Here this methodology is used to study the effect of aging on the fracture properties of human cortical bone and human dentin in order to discern the microstructural origins of toughness in these materials.

INTRODUCTION

Fracture mechanics has long been used for the study of engineering materials;[1] however, its utility for the characterization of mineralized tissues, such as bone and dentin, has not been as broadly realized. In its most simple application, the stress intensity ahead of a sharp stress concentrator can be evaluated using linear-elastic fracture mechanics (LEFM) and used to obtain a single-value toughness measurement, such as the K_{Ic} fracture toughness. This method has been used for the past several decades to evaluate the fracture resistance of bone and dentin.[2–7] More recently, however, it has become apparent that bone and dentin principally derive their toughness during crack growth, and hence evaluation in terms of crack-growth resistance curves (R-curves) is more appropriate. Indeed, several recent studies on these tissues have described their toughness properties in terms of such R-curves.[8–11] There are also a few examples where nonlinear-elastic fracture mechanics (NLEFM), which allow for the presence of local plasticity (actually nonlinear elasticity), have been applied to measure the toughness of these materials.[12–14] In addition, cohesive-zone modeling has been utilized as an alternative nonlinear fracture modeling approach to account for toughening and damage behavior both ahead and behind the crack tip.[15] A critical issue is how such fracture mechanics evaluations can be related to the microstructural mechanisms of damage and toughening in human bone and teeth. The focus of this article is on the sources of fracture resistance in these biological materials, as dictated by the characteristic size scales of their structure.

How would you…

…describe the overall significance of this paper?

Here we try to describe the mechanistic origins of fracture resistance in human cortical bone and tooth dentin in terms of how they are affected by the hierarchical structure of these tissues. We further explain how these mechanisms can degrade with age, leading to the well-known increased risk of bone and teeth fracture in the elderly.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

We have attempted to use the structure vs. properties concept of materials science with a fracture mechanics analysis of failure to provide an understanding of how bone and tooth dentin fracture and how such brittleness is made worse with aging.

…describe this work to a layperson?

The fracture toughness of bone and tooth dentin is a measure of the applied loads necessary to break these tissues. Here we describe how to evaluate this property, examine what in the microscopic structure of these tissues can enhance the toughness, and explain why it degrades due to biological factors such as age.

STRUCTURE

Cortical bone, the dense outer shell of bones, is a hierarchical composite of an organic phase, type-I collagen, and a mineral phase, hydroxyapatite.[16] It is approximately 50% mineral salts, 25% collagen, and 25% water by volume. At the nanoscale, bone is comprised of the collagen molecules and nanocrystalline hydroxyapatite; the collagen molecules self-assemble into collagen microfibrils, which are impregnated with hydroxyapatite crystals. The plate-like hydroxyapatite crystals are approximately 4–6 nm × 30–60 nm × 100 nm. The collagen microfibrils then assemble into collagen fibers, which have a diameter of ~1 μm; these in turn are arranged into the lamellar sheets, which make up the cortical shell. The process of Haversian remodeling results in concentric lamella and Haversian systems (osteons) and is the process by which intercortical bone is renewed in some adult mammals, including humans.

Haversian remodeling occurs by a cutting cone of osteoclasts resorbing

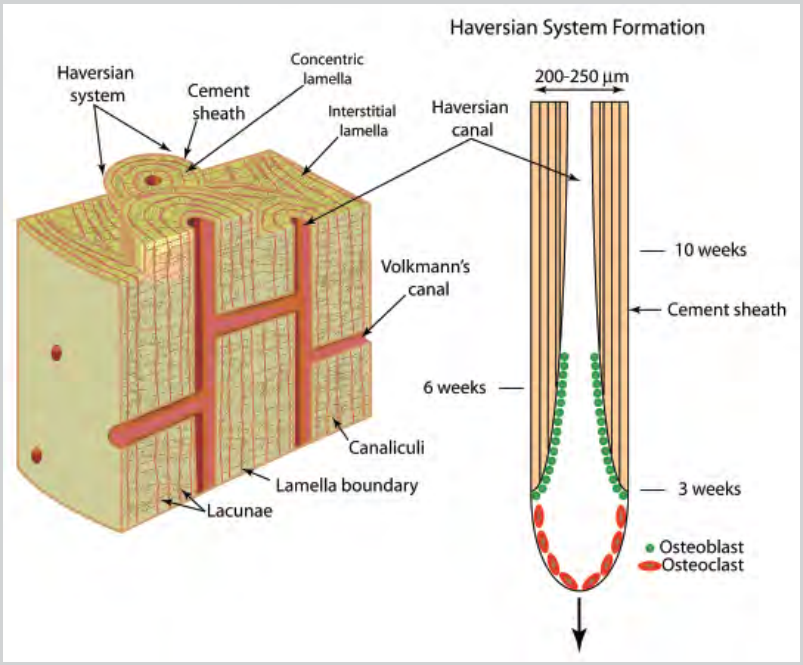


Figure 1. Diagrams of the structure of human cortical bone and of Haversian system formation. The schematic of the structure of human cortical bone shows the important microstructural features which could interact with a propagating crack. The diagram of Haversian system formation shows a cutting cone as it moves through bone and how osteoblasts follow in its wake to deposit new bone. The cutting cone advances at a rate of ~40 μm per day.

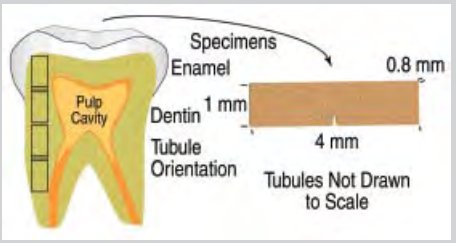


Figure 2. A schematic diagram of a human tooth (left) and of the notched three-point bend specimens of dentin (right) which were sectioned from the interior of the tooth. The nominal tubule orientation can be seen in the schematic to run from the exterior of the tooth to the pulp cavity.

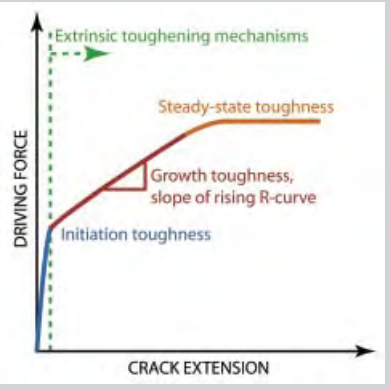
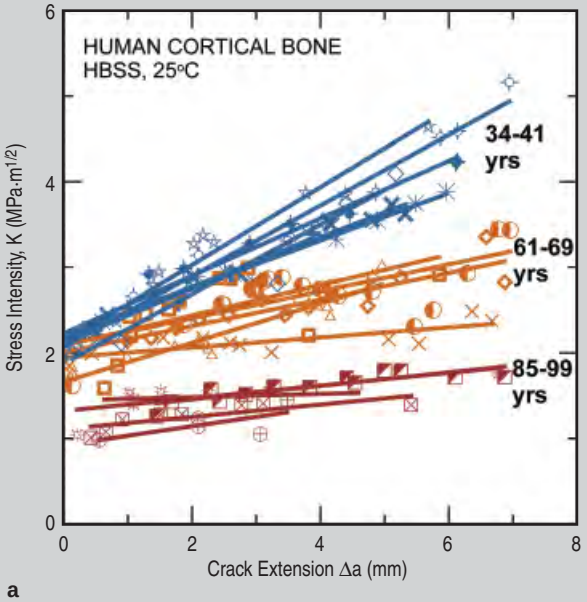
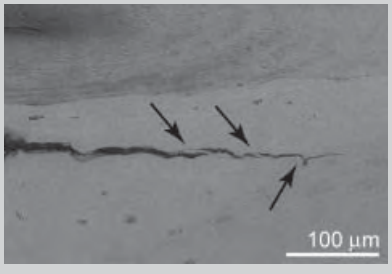


Figure 3. A schematic diagram of a crack-resistance curve (R-curve) (i.e., the crack-driving force) as a function of crack extension Δa, for a material that exhibits linearly rising R-curve behavior and in which stable cracks can be grown to sufficient lengths to measure the steady-state toughness.



a



b

c

Figure 4. (a) Crack-growth resistance curves for human cortical bone tested in HBSS at 25°C, with corresponding scanning electron microscopy images of cracks in Young bone at (b) low and (c) higher magnification. The R-curves illustrate that both the initiation toughness (intercept at Δa = 0) and the growth toughness (slope) are degraded with age.

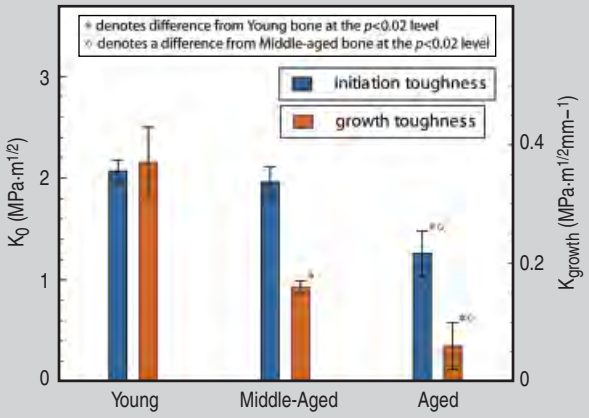


Figure 5. Means and standard deviations for the crack-initiation toughness and growth toughness, obtained from R-curve measurements, are shown for human bone for the three groups in the study (Young = 34–41 years, Middle-aged = 61–69 years, Aged = 85–99 years). It was found using ANOVA and "t" tests that the deterioration in initiation toughness and growth toughness with age was statistically significant.

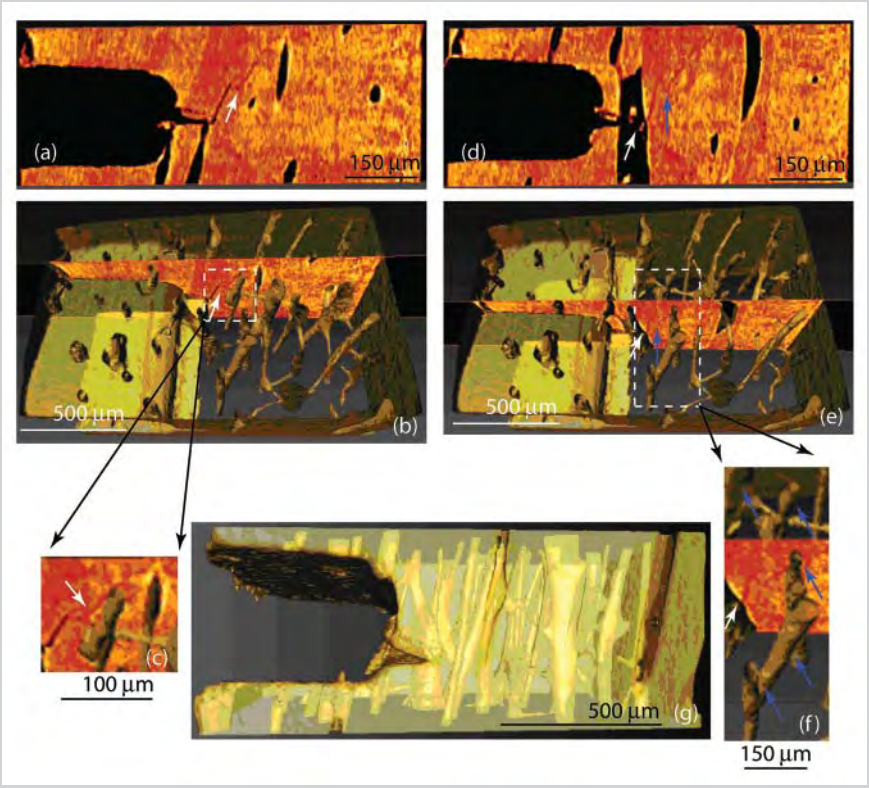


Figure 6. X-ray computed tomography images of a stable crack in human cortical bone in the transverse orientation. Panels (a–c) and (d–f) each show a two-dimensional (2-D) slice through the sample, a three-dimensional (3-D) image containing the slice, and a magnified view of a region of interest. A 3-D image of the entire volume of interest is shown in (g). In (a), a white arrow indicates a deflection that occurs before the crack encounters a Haversian canal, which appears as a black ellipse. The region of interest of this deflection is bounded by a box in (b) and the deflection is again highlighted with a white arrow. In (c), the deflection coincides with a Haversian canal at a different depth in the sample. Panels (d) and (e) show that at this depth the crack grows off of the notch at a different angle than the slice shown in (a), indicated by a white arrow, and that this angle corresponds to the edge of the Haversian canal at that depth. The crack undergoes three radical changes in direction in (d) and the blue arrow in (d) and (e) indicates two of these changes. The region of interest in (e) given by the white box is shown in (f). In (f) the white arrow again indicates that different angle of initial crack growth; the blue arrows indicate Haversian canals that could be exerting the influence to cause the multiple deflections of the crack as seen in (d).

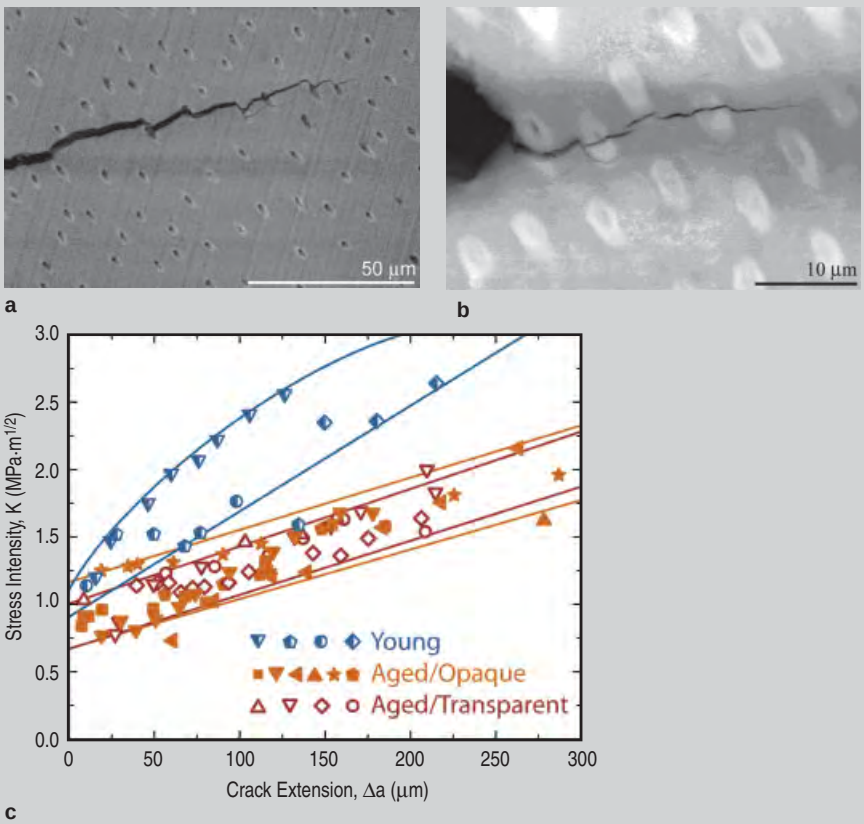


Figure 7. Crack-growth resistance curves for human tooth dentin (saturated in HBSS) grouped by age and fraction of occluded tubules. Environmental scanning electron microscopy images for the Young and Aged/transparent groups are shown in (a) and (b), respectively. It can be seen from (c) that all of the groups exhibit rising R-curve behavior.

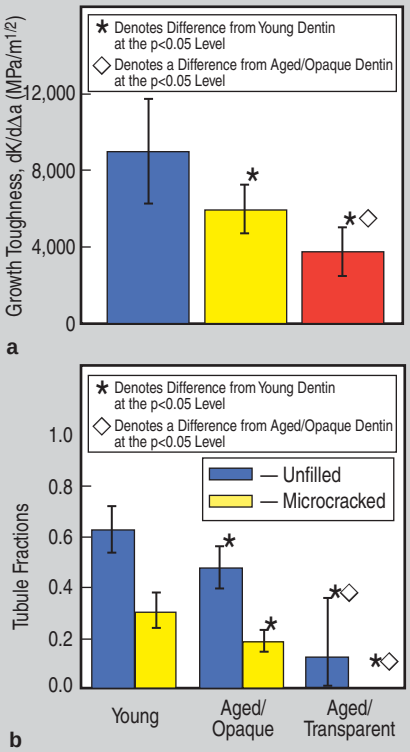


Figure 8. (a) Crack-growth toughness and (b) open tubule fractions (i.e., not occluded with mineral deposits) for the Young, Aged/Opaque, and Aged/Transparent human dentin groups. The growth toughness degraded as the fraction of unfilled and microcracked tubules decreased. This is because the unfilled and microcracked tubules are instrumental in the development of the extrinsic toughening mechanisms of crack deflection/branching and crack bridging.

bone and moving in the longitudinal direction of the bone. In the wake of the cutting cone, osteoblasts adhere to the wall of the resorbed cavity, termed the cement sheath, and begin to form new bone. The osteoblasts lay down new bone by excreting the organic extracellular matrix of bone, which is subsequently mineralized. The osteoblasts become trapped in their excretions so they do not move with the cutting cone but follow via a process of continuous recruitment. The trapped osteoblasts mature into osteocytes, and the cavity in which they reside is called the lacuna. The lacunae are connected to each other by a network of canaliculi. Figure 1 provides a schematic diagram of cortical bone and of the Haversian remodeling process.

Dentin is a somewhat similar mineralized tissue that comprises the bulk of the human tooth and as such determines its structural integrity. It is a hydrated composite of mineralized collagen fibers and nanocrystalline hydroxyapatite, with ~45% hydroxyapatite, 35% collagen, and 20% water by volume. The mineralized collagen fibrils form the intertubular dentin matrix, and are arranged in a felt-like structure oriented perpendicular to a series of channels, termed tubules. These tubules are ~1–2 μm in diameter, and extend from the pulp cavity to the exterior of the tooth; they are lined with a highly mineralized cuff of peritubular dentin (Figure 2 contains a schematic of the structure of a tooth).[17,18] In contrast to bone, there is no remodeling after tooth growth is completed. During aging, human dentin sclerosis causes the tubules to become occluded through deposition of carbonated apatite[19,20] leading to transparency to visual light of the dentin (termed "transparent" dentin). This leads to changes in the mechanical properties, most notably a loss in ductility, toughness, and cyclic fatigue resistance.[20–23]

FRACTURE RESISTANCE

Fracture can be considered to be a mutual competition between intrinsic damage mechanisms, which act ahead of the crack tip to promote cracking, and extrinsic shielding mechanisms, which act primarily behind the tip to inhibit cracking.[24,25] Intrinsic toughening mechanisms serve to limit microstructural damage; an example is the occurrence of plasticity ahead of the crack tip, which dissipates energy and locally reduces the stresses by blunting the crack tip. This is a dominant toughening mechanism in most ductile metallic materials.

Extrinsic toughening is quite different. Unlike intrinsic mechanisms, these mechanisms do not increase the inherent resistance to fracture but instead shield the crack tip from the applied driving force for crack propagation. As they primarily operate in the wake of the crack tip, they require the presence of a crack and consequently result in crack-size dependent behavior. An example of an extrinsic toughening mechanism is crack bridging, where material bridges (e.g., intact fibers in fiber-reinforced composites or interlocking grains in monolithic ceramics) span the crack and carry load that would otherwise be used to further crack propagation (crack-tip shielding).

Bone and dentin are primarily toughened extrinsically; although intrinsic mechanisms, such as viscoplastic flow,[26] have been identified, the principal source of fracture resistance arises from microcracking,[9,11,27] crack deflection,[11,13,28,29] and crack bridging.[8,10,11,30,31] Due to the fact that extrinsic toughening mechanisms can only develop after some amount of crack extension, these mechanisms have no influence on the crack-initiation toughness (Figure 3). Rather, they are associated with crack-growth toughness and naturally result in R-curve toughness behavior where the driving force for cracking (e.g., K, the stress-intensity factor, G, the strain-energy release rate, and J, the J-integral) increases with crack extension. Figure 3 shows a schematic diagram of an R-curve and the parameters one obtains from this type of analysis. (J is the nonlinear-elastic strain-energy release rate.)

As shown in the figure, the crack-initiation toughness is the value of the driving force at where $\Delta a \rightarrow 0$, and in principle corresponds to values (e.g., K_{Ic}) obtained by single-value fracture toughness parameter measurements. In the presence of extrinsic toughening mechanisms, such as crack bridging, the R-curve begins to rise with crack growth; these mechanisms require crack extension to become active. After some degree of crack extension, the toughening from these mechanisms may reach steady state such that the toughness of the material reaches a constant value. It should be noted that in bone and dentin it is not always possible to reach steady state due to physiological limitations on the size of the samples, as compared to the characteristic microstructural size scales associated with the prevalent toughening mechanism.

FRACTURE AND AGING IN HUMAN BONE

To evaluate the effect of aging on the mechanical properties of human bone, macroscopic R-curve fracture toughness tests were performed on cortical bone taken from the humerii of nine cadavers (donor age: 34 to 99 years).[32] Seventeen (N = 17) compact-tension specimens were fatigue-precracked and tested in simulated body fluid—Hanks' Balanced Salt Solution (HBSS). Samples were divided into three age groups—arbitrarily named Young [age: 34 (N = 1), 37 (N = 4), and 41 (N = 2) years], Middle-Aged [age: 61 (N = 1), 69 (N = 2) and 69 (N = 2) years], and Aged [age: 85 (N = 1), 85 (N = 2), and 99 (N = 2) years]. The samples were all oriented with the starter notch and the nominal crack-growth direction along the proximal-distal direction of the humerus (in the longitudinal direction) (i.e., parallel to the long axis of the Haversian systems and hence, long axis of the humerus). Procedures for measuring resistance-curves are detailed elsewhere.[10,32,33]

Resistance curves for cortical bone, shown in Figure 4a, give a clear indication that aging causes both the initiation toughness (intercept of the curve at zero crack extension) and the growth toughness (slope of the curve) to decrease in human cortical bone. Mean crack-initiation toughness values of 2.07 (S.D. = 0.11), 1.96 (S.D. = 0.15), and 1.26 (S.D. = 0.22) $MPa{\cdot}m^{1/2}$, and mean slopes (crack-growth toughness) of 0.37 (S.D. = 0.06), 0.16 (S.D. = 0.01), and 0.06 (S.D. = 0.04) $MPa{\cdot}m^{1/2}$ were obtained for the Young, Middle-Aged, and Aged groups, respectively.

The R-curves shown in Figure 4a illustrate that both the initiation tough-

ness (intercept at $\Delta a = 0$) and the growth toughness (slope) are degraded with age. However, the more pronounced effect is on the growth toughness, which is caused by the decreasing efficacy of the extrinsic toughening mechanisms in bone with age. This in turn can be related to increased density of Haversian systems with age and the consequent reduced fraction of crack bridges in the wake of the crack. Figure 4b shows the development of bridging (indicated by the arrows) for a crack propagating in the longitudinal direction. As the crack is still quite short (~200 μm), the bridges are still relatively small. Figure 4c shows a collagen fiber bridging the crack faces. These images illustrate the dimensionality of the bridging mechanism. For example, the size scale of the phenomenon can range from sub-micrometer to hundreds of micrometers, depending on the size of the crack and the microstructural origin of the bridging features (adapted from Reference 32).

Differences of the means of the measured parameters (initiation toughness and growth toughness) between the groups were assessed with the one-way ANOVA statistical test and, when appropriate, one-tailed "t" tests were used to make comparisons between the groups. These data are shown graphically in Figure 5, where it is apparent that while aging affected both the initiation and growth toughnesses, the deterioration in properties with aging was most evident during crack growth.

With progressive aging, the bone is remodeled; in human bone, this occurs in the interior of the cortex by Haversian remodeling. The process of Haversian remodeling changes the microstructure of the bone, which must be understood in terms of how this may affect, or interact with, a growing crack. Most notably, the Haversian systems have cement sheaths ("cement lines"), which have a different composition than the bulk of the bone[34] and act as weak interfaces, thus serving as sites for preferential microcracking. The process of Haversian remodeling stimulates additional remodeling due to the fact that the cement sheaths sever the canaliculi of the interstitial bone leading to the death of the osteocytes; therefore, the Haversian systems are not randomly distributed through the bone but are predominately located in the vicinity of each other.[16] As expected, the density of the Haversian systems in the current study was higher in the Aged bone than in the Young bone.[32]

The toughness of bone (in the longitudinal direction) deteriorates with aging due to these changes in the microstructure, which the authors believe inhibit the formation of uncracked-ligament bridges, one of the dominant toughening mechanisms in bone. Because the cement sheaths are "weak interfaces" in bone, a crack advancing in the longitudinal direction of bone will tend to follow these features. As bone ages the density of Haversian systems increases and there is a greater chance that a crack can follow a lower resistance path along these interfaces through the material. These cement sheaths also play an important role in the formation of uncracked-ligament bridges. This occurs during crack propagation by a new crack initiating, generally at a cement sheath, ahead of the main crack tip; the region between the original and the new crack can then act as a bridge (the so-called "mother and daughter" crack configuration, as shown in Figure 4b), and carry load that would otherwise be used to promote cracking. This mechanism is suppressed with aging because of the higher osteon density, whereby the distance between cement sheaths is reduced, resulting in a corresponding decrease in the size of the bridges. Crack initiation can occur along a low toughness path, such as a cement sheath, and this could be the reason that the initiation toughness also decreases with aging. However, the principal effect of aging is on the growth toughness as the extrinsic toughening (crack bridging) mechanisms are directly affected by the age-related changes in the bone-matrix structure.

Microcracking along the cement sheaths also gives rise to toughening in the transverse (breaking) orientation of bone by providing locations for crack arrest and macroscopic crack deflections; this is shown in the x-ray computed tomography image in Figure 6. This extrinsic mechanism of toughening is particularly effective in cortical bone and is the primary reason that bone is substantially tougher in the transverse than in the longitudinal directions.

FRACTURE AND AGING IN HUMAN DENTIN

Human molars (N = 7), extracted according to protocols approved by the University of California San Francisco, Committee on Human Research, were used as the source of dentin. Three-point bend samples (4 mm long, 1 mm wide, 0.5 mm thick), two or three per tooth, were wet sectioned from the central portion of the crown and root (Figure 2) using a low-speed saw, and stored in 25°C HBSS. The molars were divided into three groups as determined by the fraction of the occluded tubules: Young dentin (19–30 years old) with 3–7% filled tubules (N = 4), Aged/opaque dentin (40–70 years old) with 12–32% filled tubules (N = 5), and Aged/transparent dentin (40–70 years old) with 65–100% filled tubules making them transparent to visible light (N = 5).

Resistance curves for human dentin as a function of aging are shown in Figure 7. The crack-initiation toughness is ~0.75-1.1 $MPa{\cdot}m^{1/2}$ and appears to be the similar for all groups. However, after ~100 μm or more of crack extension, the toughness of the Young samples is higher than that of the Aged samples. This again represents an aging-related decrease in the crack-growth toughness, which can be quantified in terms of the slope (least-squares fit) of the R-curve. For each of the groups tested, the initiation toughness was difficult to determine accurately, but it was clearly similar for all groups, ranging from ~0.75 $MPa{\cdot}m^{1/2}$ to 1.1 $MPa{\cdot}m^{1/2}$. The crack-growth toughness of the dentin, however, was found to degrade with age as the dentinal tubules became progressively occluded, which is attributed to a reduced potency of crack deflection and crack bridging toughening mechanisms (adapted from Reference 11).

Results, shown in Figure 8a, indicate that young dentin has a significantly higher ($p<0.05$) growth toughness than aged/opaque and aged/transparent dentin; for aged dentin, the opaque group also has a significantly higher ($p<0.05$) growth toughness than the older transparent group. Statistical differences of

the means of the measured parameters (crack-growth toughness, unfilled and microcracked tubule fractions) between the groups were evaluated with the one-way ANOVA test and, when appropriate, one-tailed "t" tests were used to make comparisons between the groups. The decreased growth toughness with age is paralleled by a similar decrease in the fraction of unfilled and microcracked tubules involved in the crack path (Figure 8).

The effect of aging in dentin is that the principal microstructural features, the tubules, become occluded with apatite mineral with age; such tubule sclerosis is thought to be the result of the in-vivo loading in the mouth.[19] Once the tubules have become occluded with mineral, their interaction with a propagating crack changes; specifically, the increased fraction of filled tubules in older dentin is less effective in developing extrinsic toughening mechanisms.

Most notably, the unfilled tubules tend to initiate microcracks, whereas the filled tubules, presumably because they offer a reduced stress concentration, do not. Akin to bone, microcracking is important in dentin as it is a precursor to the other more potent toughening mechanisms. As cracks tend to follow a low modulus phase, the presence in young dentin of a larger fraction of empty tubules, many of which have several microcracks radiating out from them, leads to significant crack deflection and branching. Moreover, the microcracked tubules cause an increased incidence of crack bridging, particularly at larger crack sizes. This arises when a crack propagating in the intertubular dentin activates a microcrack of a tubule, which then becomes the active crack tip leaving an uncracked-ligament bridge in its wake. (This is similar to the bridging mechanism in bone where the microcracks initiate primarily at the cement sheaths). With the progressively diminished fraction of open, and hence microcracked, tubules with aging, all these extrinsic mechanisms degrade. This results in the deterioration in the crack-growth (but not necessarily crack-initiation) toughness of human tooth dentin with age.

CONCLUSION

"Hard" mineralized tissues such as human bone and tooth dentin have evolved to effectively resist fracture. However, their enduring strength and toughness invariably degrades with age. This brief review has attempted to show that in both biological materials, resistance to fracture arises primarily from crack growth (rather than crack initiation), which is evident by their rising crack-resistance curve toughening behavior. Such crack-growth toughening results from extrinsic (crack-tip shielding) mechanisms, principally associated with crack deflection and crack bridging. Both processes are induced by the formation of microcracks, which predominate at the cement sheaths in bone and at the tubules in dentin. However, with age, the increased density of Haversian systems in cortical bone and sclerosis of the tubules from mineral deposition in dentin leads to degradation in the potency of these mechanisms, which is manifest in a reduced slope of their resistance curves.

ACKNOWLEDGEMENTS

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