Tubule orientation and the fatigue strength of human dentin

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Abstract

In this study the influence of tubule orientation on the strength of human dentin under static and cyclic loads was examined. Rectangular beams were sectioned from the coronal dentin of virgin extracted molars (N = 83) and then loaded in quasi-static 4-point flexure or 4-point flexural fatigue to failure. The flexure strength, energy to fracture and fatigue strength were evaluated for specimens with the dentin tubules aligned parallel (θ = 0°) and perpendicular (θ = 90°) to the plane of maximum normal stress. Results from monotonic loading showed that both the flexural strength and energy to fracture of dentin specimens with θ = 0° were significantly greater than those with θ = 90°. Furthermore, the apparent endurance strength of dentin with θ = 0° (44 MPa) was significantly greater than that of the dentin with θ = 90° (24 MPa). The ratio of apparent endurance strength (for fully reversed loading) to the flexure strength for θ = 0° and θ = 90° was 0.41 and 0.28, respectively. Although the influence of tubule orientation was most important to mechanical behavior, the flexure strength and energy to fracture also decreased with an increase in tubule density. According to differences in the fatigue strength with tubule orientation, restorative practices promoting large cyclic normal stresses perpendicular to the tubules would be more likely to facilitate fatigue failure in dentin with cyclic loading.

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Keywords: Dentin; Fatigue; Fracture; Tubule orientation

1. Introduction

Dentin is a hydrated hard tissue that comprises the majority of human teeth by both weight and volume [1]. The tissue serves as an elastic foundation for the hard, outermost enamel, and as a protective enclosure for the central pulp. Dentin is traversed by a network of tubules that are oriented radially outward from the central pulp towards the dentin-enamel junction. Both the tubule density and lumen diameter decreases within increasing distance from the pulp. A highly mineralized cylindrical cuff of apatite mineral surrounds the tubules and is regarded as the peritubular dentin. Intertubular dentin occupies the interstitial space between the peritubular cuffs and is comprised of a matrix of collagen fibrils that is bound by crystalline apatite. The collagen fibrils are distributed in planes essentially perpendicular to the lumens [2]. Based on this unique combination of constituents and their distinct orientation, dentin is structurally anisotropic. Furthermore, the hardness and elastic modulus of peritubular dentin are greater than that of intertubular dentin [3,4]. According to the differences in composition and properties of these two constituents, the bulk properties of dentin are expected to be dependent on the tubule orientation, size and density.

The influence of tubule orientation on the elastic modulus and strength of dentin have been studied in detail. Dentin exhibits the largest elastic modulus in the direction perpendicular to the tubule axis [5]. While studies on the elastic behavior of dentin have shown that tubule orientation is important, it is now believed that the collagen fibrils are responsible for the elastic anisotropy [6,7]. In comparison to the elastic response, the microstructure and tubule orientation appear to play a more important role on the strength of dentin. Both the ultimate tensile strength (UTS) [8–13] and shear strength [14] are dependent on the tubule orientation. The tensile strength is highest when the tubules are perpendicular to the direction of loading (i.e. when the tubules are aligned with the plane
of maximum normal stress) and is believed attributed to the orientation and increased participation of the collagen fibrils. The strength of dentin is also dependent on the anatomical location [8,10–12,15,16]. In general, the strength increases with distance from the pulp and the strength of coronal dentin exceeds that of the root dentin. Differences in strength with depth have been attributed to the increase in tubule density towards the pulp and differences between the crown and root have been attributed to tubule density as well. However, Miguez et al [17] compared the UTS of both crown and root dentin and also evaluated the collagen biochemistry in these two regions. Though the collagen content was equivalent in the crown and roots, the number of specific cross-links in root dentin was significantly higher. Thus, the relative significance of tubule orientation on the stiffness and strength of dentin could also be a function of the collagen and cross-link profile.

The tubule orientation is also important to the fracture properties of dentin. Rasmussen and Patchin [18] and Rasmussen et al. [19] examined the influence of structure on the work of fracture, which defined the work per unit area required for crack extension (i.e. fracture). For dentin the work of fracture was lowest when the dentin tubules were oriented perpendicular to the plane of fracture. Similarly, the fracture toughness of dentin has been found to be largest when the crack is oriented parallel to the dentin tubules and consistent with the plane of fracture [20,21]. In this orientation the collagen fibrils are perpendicular to the direction of crack extension and could be perceived as the critical structural element responsible for the dissipation of fracture energy. Indeed, Nalla et al [21] examined toughening mechanisms in the fracture of dentin from elephant tusk and found that both intrinsic (i.e. in front of the crack) and extrinsic mechanisms (i.e. at or behind the crack) contributed to the toughness. The extrinsic mechanisms of toughening consisted primarily of bridging forces posed by collagen fibrils and uncracked ligaments, which were estimated to have the largest contributions to toughness. These mechanisms are largely dependent on the microstructure and most active for cracks extending parallel to the tubules. Similarly, in an evaluation of fatigue crack growth in bovine dentin [22], preference for crack extension perpendicular to the dentin tubules implied that there are differences in the mechanisms of crack growth resistance related to tubule orientation.

Fatigue strength is an important aspect of mechanical behavior that is extremely relevant to the success of restorative dentistry. Cyclic loading of teeth arises through mastication and as a result of temperature changes in the oral environment. Recent evaluations on the fatigue strength of human dentin reported that the endurance limit ranged between 25 and 45 MPa [23] and that the fatigue strength decreases with an increase in mean stress [24]. The fatigue strength of dentin has also been found dependent on age, and that the fatigue strength decreases significantly with patient age [25]. Interestingly, the influence of tubule orientation on the fatigue strength of dentin has not been examined. Consequently, in this investigation the mechanical behavior of human dentin was evaluated under both quasi-static and fatigue loads. The primary objective was to determine the influence of tubule orientation on the fatigue strength of human dentin.

2. Materials and methods

Human second and third molars (N = 83) were obtained from participating clinics within the state of Maryland according to an approved protocol issued by the Institutional Review Board of the University of Maryland. Both the age and gender of the patient were obtained with each tooth. The teeth were placed in Hank’s balanced salt solution (HBSS) immediately after extraction and then carefully inspected for the presence of flaws or decay. Those without defects were cast in a polyester resin foundation and sectioned using a numerically controlled slicer/grinder with diamond impregnated slicing wheels (#320 mesh abrasives) and continuous flood coolant. Rectangular beams with nominal cross-section of 0.4 x 1.4 and 6 mm length were obtained from the coronal dentin. The primary sections were 1.4 mm and made in the bucco-lingual plane; secondary sectioning was then performed to obtain specimens with the dentin tubules aligned perpendicular or parallel to the length of the beam. For specimens with tubule orientation ($\theta$) of 0°, the beams were obtained such that the dentin tubules were parallel to the plane of maximum normal stress in bending (i.e. perpendicular to the length of the beam as evident in Fig. 1a). Conversely, specimens with tubule orientation of 90° were obtained such that the tubules were perpendicular to the plane of maximum normal stress in bending (i.e. parallel to the length of the beam as shown in Fig. 1b). When possible, the relative location at which the beam was obtained with respect to the dentin–enamel junction (DEJ) was documented. Subsequent dressing of the beams was performed to obtain specimens with orthogonal edges. After machining, the beams were stored in HBSS at room temperature (22°C) for an average of 4 days. The total time elapsed from extraction to the day of testing ranged between 1 and 12 days.

The dentin specimens were loaded to failure in quasi-static four-point flexure or four-point flexural fatigue (Fig. 1c). The specimen test geometry and flexure apparatus conforms to a scaled version of ASTM D790 M for flexural testing of materials [26]. For the quasi-static evaluations, 61 dentin specimens were obtained from the molars of 27 different patients (Table 1). The average patient age for specimens with $\theta = 0°$ and $90°$ was 24 ± 3 and 23 ± 3, respectively. Flexure loading was conducted using an EnduraTEC Elf Model 3200 testing system2, which has a load capacity and sensitivity of 225 and ±0.01 N, respectively. The beams were immersed in a HBSS bath at room temperature during loading to maintain hydration. Quasi-static loading was applied using displacement feedback control at a crosshead rate of 0.001 mm/s. The instantaneous load and load-line displacement were monitored through the load cycle at a frequency of 4 Hz. The flexural modulus, flexural strength, and energy to fracture of the dentin beams were quantified according to established methods [25].

Flexural fatigue of the dentin beams was conducted using load control actuation with frequency of 5 Hz and stress ratio (R = ratio of minimum to maximum cyclic load) of 0.1. Fatigue testing of the dentin specimens with each tubule orientation was initiated using a maximum cyclic stress of approximately 90% of the flexural strength identified from the quasi-static experiments. For successive specimens the maximum cyclic load was decreased in increments ranging from 5 to 15 MPa according to the staircase method of evaluation [27]. The process continued until reaching the bend stress amplitude at which specimens did not fracture within 107 cycles. Beams with $\theta = 0°$ were subjected to maximum bending stresses

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1. K.O. Lee Model S3818EL, Aberdeen, SD.
2. EnduraTEC Model ELF 3200, Minnetonka, MN.
ranging between 90 and 160 MPa and specimens with \( \theta = 90^\circ \) were subjected to maximum cyclic stresses ranging from 50 to 130 MPa. The stress–life (S–N) response was obtained for each tubule orientation by plotting the cyclic stress amplitude in terms of the number of cycles to failure. In the evaluation of fatigue properties, 92 dentin beams were prepared from extracted molars of 56 patients (Table 1). The average age of the patients for the beams with tubule orientations of 0 and 90\(^\circ\) was 24.7 and 24.7 years, respectively. No more than three specimens were obtained from a single tooth and specimens obtained from the same tooth were not examined at the same cyclic stress level to minimize potential for bias associated with a patient.

The fatigue-life distribution of the dentin specimens with each tubule orientation was modeled according to a power law distribution in the form,

\[
\sigma = A(N)^B,
\]

where \( A \) and \( B \) are the fatigue-life coefficient and exponent, respectively. The power law parameters for the fatigue strength of dentin were obtained directly from a regression of the fatigue responses plotted on a log-normal scale. The apparent endurance strength was estimated using the power law models for a fatigue limit defined at 10^7 cycles and the equivalent fully reversed apparent endurance strength was estimated using the Goodman model [28].

The fracture surface of each dentin specimen was inspected using a scanning electron microscope\(^3\) (SEM) in secondary electron imaging (SEI) mode to confirm the tubule orientation and estimate the tubule density. Prior to this analysis the beams were sputtered with gold palladium to enhance conductance of the dentin. Both the tensile and compressive sides, as well as the fracture surfaces, were inspected to identify differences resulting from static and fatigue loading, and also to identify differences related to the tubule orientation.

### 3. Results

Typical flexure responses for dentin beams with \( \theta = 0^\circ \), which were sectioned from a single molar are shown in Fig. 2(a). In general, the specimens with \( \theta = 0^\circ \) exhibited linear elastic behavior at the onset of loading followed by a region of non-linear (and potentially inelastic) deformation to failure. Typical flexure responses for specimens with tubules aligned perpendicular to the plane of maximum principal stress (\( \theta = 90^\circ \)) are shown in Fig. 2(b). In contrast to specimens with \( \theta = 0^\circ \), the responses for beams with \( \theta = 90^\circ \) remained essentially linear elastic to failure. The flexure specimens with \( \theta = 90^\circ \) displayed lower flexural strength and strain to failure than those with \( \theta = 0^\circ \) as evident in Fig. 2. A summary of the flexural strength, energy to fracture and flexural modulus resulting from quasi-static loading are listed in Table 2. While there was no significant difference in age between the two groups of specimens, the average flexural strength (\( p < 0.0001 \)) and

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\(^3\)JEOL Model JSM-5600.
energy to fracture ($p<0.0001$) of dentin specimens with $\theta = 0^\circ$ were significantly higher than those of dentin with $\theta = 90^\circ$. The largest difference in mechanical behavior with tubule orientation was evident in the energy to fracture where specimens with $\theta = 0^\circ$ absorbed more than three times the energy to fracture of specimens with $\theta = 90^\circ$. There was also a significant difference ($p<0.002$) in the flexural modulus with tubule orientation in which the specimens with $\theta = 0^\circ$ exhibited the highest average elastic modulus (Table 1). Despite similar sample sizes and average age, the coefficient of variation for properties of the specimens with $\theta = 0^\circ$ was consistently larger than that of the specimens with $\theta = 90^\circ$.

Representative micrographs of the fracture surface from specimens with tubule orientations of $0^\circ$ and $90^\circ$ are shown in Fig. 3(a) and Fig. 3(b), respectively. In each of these micrographs the top of the beam represents the tensile surface. In Fig. 3(a) the dentin tubules are aligned parallel

![Figure 2](image1.png)

**Table 2**

<table>
<thead>
<tr>
<th>Property</th>
<th>Orientation</th>
<th>Student’s t-test</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta = 0^\circ$</td>
<td>$\theta = 90^\circ$</td>
<td></td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>$160 \pm 22$</td>
<td>$109 \pm 10$</td>
<td>$p&lt;0.0001$</td>
</tr>
<tr>
<td>Energy (MPa)</td>
<td>$1.9 \pm 1.0$</td>
<td>$0.5 \pm 0.2$</td>
<td>$p&lt;0.0001$</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>$18.7 \pm 3.5$</td>
<td>$15.5 \pm 2.8$</td>
<td>$p&lt;0.002$</td>
</tr>
<tr>
<td>Age</td>
<td>$24 \pm 3$</td>
<td>$23 \pm 3$</td>
<td>$p&lt;0.23$</td>
</tr>
<tr>
<td># Specimens</td>
<td>26</td>
<td>21</td>
<td>n/a</td>
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</tbody>
</table>

![Figure 3](image2.png)

**Fig. 3.** Typical fracture surfaces of the dentin specimens resulting from quasi-static flexure loading to failure. The tensile surface of the beam is located at the top of each micrograph. Both micrographs were obtained with magnification of 75 x. (a) $\theta = 0^\circ$; note the presence of a shear lip that developed at overload. (b) $\theta = 90^\circ$; note the absence of a shear lip and a rougher fracture surface.
to the majority of the fracture surface ($\theta = 0^\circ$) and perpendicular to the length of the beam. Conversely, the dentin tubules in Fig. 3(b) are oriented perpendicular to the fracture surface ($\theta = 90^\circ$) and parallel to the beam length. Interestingly, most specimens with $\theta = 0^\circ$ displayed an overload shear lip on the compressive side of the neutral axis, which is clearly evident in Fig. 3(a). The shear lip was oriented such that continuation of fracture occurred on a plane perpendicular to the dentin tubules. Specimens with $\theta = 90^\circ$ generally displayed no evidence of a shear lip (Fig. 3(b)) which is consistent with the failure characteristics of a brittle material in flexure. Based on the microscopic inspection, fracture surfaces of specimens with $\theta = 0^\circ$ generally appeared smoother than those with $\theta = 90^\circ$ and were consistently perpendicular to the beam’s length. Profiles of the fracture surfaces were not obtained for quantitative comparison due to physical limitations posed by the cross-section geometry.

Fatigue loading of the dentin beams was conducted using a maximum cyclic stress of between 0.3 and 0.9 the flexural strength identified from static loading. Fatigue life diagrams for the dentin specimens with $\theta = 0^\circ$ and $90^\circ$ are shown in Fig. 4(a). Each data point corresponds to the failure of a single dentin beam and data points with arrows identify beams that did not fail and the test was discontinued. As evident from both responses, the number of cycles required for failure increased with a reduction in the cyclic stress amplitude. There was also a marked difference in the number of cycles required for failure of the specimens with $\theta = 0^\circ$ and $90^\circ$ at all stress amplitudes as evident in Fig. 4(a). Most notably, specimens with $\theta = 0^\circ$ exhibited a fatigue life approximately two decades greater than that of specimens with $\theta = 90^\circ$ at the same cyclic stress amplitude. Power law models were developed to describe the mean fatigue responses and are presented in Fig. 4(b) along with the 95% confidence intervals, which highlight the significant difference in fatigue strength of dentin with tubule orientation. According to the power law model for $\theta = 0^\circ$, the apparent endurance strength at $10^7$ cycles is approximately 44 MPa. Similarly, for $\theta = 90^\circ$ the apparent endurance strength at $10^7$ cycles is 24 MPa.

Differences in the topography and origin of fracture associated with tubule orientation or magnitude of cyclic stress amplitude were distinguished from an examination of the tensile and compressive surfaces, as well as the fracture surface. Magnified views of the tensile portion of the fracture surface from beams with $\theta = 0^\circ$ and $90^\circ$ are shown in Figs. 5(a) and (b), respectively. The tensile surface of the beams in Fig. 5 is located at the top of the micrographs. Features of the fractured specimens from fatigue and quasi-static loading were very similar. For example, beams with dentin tubules oriented perpendicular to the beam length ($\theta = 0^\circ$) displayed an overload shear lip on the compressive side of the neutral axis. An example of a shear lip initiating on a beam with $\theta = 0^\circ$ is shown in Fig. 6; the experiment was interrupted upon exhibiting an acute reduction in stiffness. Similar to observations pertaining to specimens that failed under static flexure, the shear lip was generally oriented such that fracture proceeded perpendicular to the tubules. The shear lip (Fig. 6) is posed to progress with orientation perpendicular to the tubules and would have enabled fracture within the next few load cycles. Specimens with $\theta = 90^\circ$ did not display a shear lip and the fracture surfaces extended essentially perpendicular to the length of the beam. Similar to the observations of beams that failed under quasi-static loading, the fractures surfaces of beams with $\theta = 90^\circ$ were generally rougher than those with $\theta = 0^\circ$ as evident from a comparison of Figs. 5(a) and (b).
4. Discussion

Several investigators have identified the importance of tubule orientation to the strength of dentin. Carvalho et al. [8] found that the UTS of human dentin with tubules aligned parallel (θ = 0°) and perpendicular (θ = 90°) to the plane of maximum normal stress was 80.0 and 57.6 MPa, respectively. Strength is also a function of anatomical location. Inoue et al. [12] reported that the average UTS of human dentin from the cervical and occlusal regions with θ = 0° was 65.0 and 99.8 MPa, respectively. For cervical and occlusal dentin with θ = 90° the UTS was 50.9 and 77.6 MPa, respectively. In the present study, the average flexural strength of specimens with θ = 0° and 90° was 160 ± 22 and 109 ± 10 MPa, respectively, which are significantly larger than the reported UTS. Differences between the flexure strength and UTS are expected due to the non-uniform stress distribution resulting from flexure. Both the average stress and population of flaws subjected to the maximum stress are far lower in the flexure specimens. Nevertheless, the ratio of UTS for θ = 90° and 0° in previous investigations was between 0.72 and 0.78. In terms of the orientation dependent flexure strength that ratio is 0.68. Thus, results of the present study are in general agreement and confirm that the flexural strength of dentin with θ = 0° is significantly larger than that for θ = 90° (p < 0.0001).

Interestingly, the variation in flexural strength and energy to fracture for specimens with θ = 0° was notable larger than that for θ = 90° (Table 2). The coefficient of variation (COV) in flexure strength for specimens with θ = 0°, and 90° was 0.14 and 0.09; the corresponding COV in the energy to fracture was 0.53 and 0.40. Although age has a significant influence on the mechanical behavior of dentin [25], consistency in the mean age for both tubule orientations (Table 2) was targeted to minimize contribution of this factor. Considering that the beams with θ = 0° were obtained sequentially with distance from the DEJ, the variation in mechanical properties is expected to be associated with the increase in tubule density with depth. Overall, specimens obtained closest to the DEJ exhibited the highest flexural strength and strain to fracture, whereas those from the cervical region exhibited lower strength and strain to failure. A comparison of responses for quasi-static loading of beams from the occlusal, middle and cervical regions (Fig. 7(a)) of a single molar are shown in Fig. 7(b). There is a reduction evident in both the flexural strength and strain to fracture for the dentin specimens obtained progressively closer to the pulp.

Carvalho et al. [8] reported a linear trend between the UTS and tubule density. Though there was a definite decrease in strength with tubule density, the relationship was not statistically significant ($R^2 = 0.051$, $p > 0.05$).
Staninec et al. [29] and Giannini et al. [15] compared the UTS of dentin of the cervical and occlusal regions and while both groups found that occlusal dentin exhibited the largest strength and attributed the difference to tubule density, neither correlated the changes in strength with respect to depth or tubule density. Using micrographs taken from the fracture surfaces of the flexure specimens subjected to quasi-static loading (e.g. Fig. 7(a)), the tubule density was estimated from the area fractions. In the occlusal regions, the density ranged from approximately 11,000 to 30,000 tubules/mm² and for cervical dentin the density ranged from 50,000 to 70,000 tubules/mm². These estimates are very consistent with past measures as reported by Garberoglio and Brannstrom [30]. Utilizing this approach for estimating tubule density, the distribution in flexural strength with tubule density for specimens with $\theta = 0^\circ$ is shown in Fig. 8(a); the corresponding energy to fracture is shown in Fig. 8(b). Each data point in Fig. 8 corresponds to a single fractured dentin specimen. Both the average flexure strength and energy to fracture decreased with increasing tubule density. Despite a lower correlation, there was a 100% increase in the energy to fracture over the measured range in tubule density, indicating that there is a large decrease in the strain to fracture with increasing tubule density. Comparison of the reductions in energy to fracture related to tubule orientation (Table 2) and tubule density (Fig. 8(b)) indicates that the effect of tubule orientation was more significant. The same statement is true for the flexure strength. Although the flexural modulus appeared to decrease with higher tubule densities (Fig. 8(c)) there was no distinct trend.

There are many factors that could contribute to the mechanical properties of dentin and their variation with tubule orientation and density. For example, the net cross-section area decreases with depth and tubule density due to the increase in cross-section occupied by open tubules [10]. Consequently, the decrease in strength with increasing tubule density (Fig. 8(a)) is likely attributed, in part, to differences in the net area. It is also expected to be responsible for the larger COV for strength and energy to fracture of specimens with $\theta = 0^\circ$ (Table 2). Note, however, that simple estimates of the volume occupied by tubules over the range in density limits the change in cross-section area to within 15%. According to the location in which specimens with orientation of $\theta = 90^\circ$ were obtained (Fig. 1(b)), they exhibited lower range in tubule density than those with $\theta = 0^\circ$ and, thus, lower COV. The specimen gage section was nearly always at the same depth. Aside from contributions of the net area, Carvalho et al. [8] hypothesized that shear stresses develop at the union of the peritubular and intertubular dentin for $\theta = 90^\circ$ due to the difference in elastic properties [3,4], whereas when the load is applied perpendicular to the tubules ($\theta = 0^\circ$) stresses at the interface are strictly tensile. They suggested that the shear stresses promote debonding at the interface and enable failure at lower loads. While both of the aforementioned contributions are valid, the most plausible explanation would stem from the difference in contribution of the collagen fibrils, which should contribute more to the stiffness and strength in conditions where the plane of normal stress is perpendicular to the tubules [6,7]. Indeed, this is the orientation with highest strength and energy to fracture (Table 2). Fracture of specimens with $\theta = 90^\circ$ occurred primarily within the plane of the collagen network, whereas fracture of specimens with $\theta = 0^\circ$ required extension and fracture of the fibrils. The larger strain to fracture of the quasi-static flexure experiments with specimens of $\theta = 0^\circ$ must indicate contribution of the fibrils in providing damage tolerance. The role of extension...
and bridging of the collagen fibers has been identified in studies on the fracture properties of dentin [20,21]. If the fibrils are the primary contributor to differences in properties with tubule orientation, then the change in strength and energy to fracture with tubule density may be attributed to differences in the fibril properties and degree of cross-linking with depth [17]. Further speculation along this vein suggests that the reduction in strength and energy to fracture of dentin with age [25] is attributed to progressive changes in properties of the collagen fibrils and that occlusion of the tubules is apparent but not the most significant factor to the change in mechanical behavior. Although directed towards resin-dentin bonding, there is evidence that a progressive degradation of the collagen matrix can occur with age [31]. Further studies should be performed to quantify the individual contribution of collagen fibrils to the mechanical behavior of dentin.

Results from flexural fatigue loading showed that tubule orientation is also important to the mechanical behavior of dentin under cyclic loading (Fig. 4). The lowest fatigue strength of dentin results for conditions in which the tubules are parallel to the direction of cyclic loading. The apparent endurance strength for human dentin with \( \theta = 0^\circ \) and \( 90^\circ \) was estimated to be 44 and 24 MPa, respectively; these measures were obtained using a load frequency of 5 Hz and stress ratio (\( R \)) of 0.1. Nalla et al. [23] reported that the apparent endurance strength of human dentin at \( 10^6–10^7 \) cycles was between 25 and 45 MPa for frequencies of 2 and 20 Hz, respectively. At a frequency of 10 Hz the endurance strength decreased from approximately 30 to 20 MPa with an increase in stress ratio from \( R = 0.1 \) to 0.5 [24]. A comparison of these results with those of the present study is presented in Fig. 9 and shows that the previous results are bounded by the flexure responses obtained for \( \theta = 0^\circ \) and \( 90^\circ \). Based on the small sample sizes in [23] and

![Fig. 8. The influence of tubule density on the mechanical properties of dentin evaluated in quasi-static flexure to failure: (a) flexural strength, (b) energy to fracture and (c) flexural modulus.](image)

![Fig. 9. A comparison of experimental results for the two tubule orientations with existing data for the fatigue response of human dentin.](image)
[24], patient bias could contribute to differences in fatigue life. Also, the dentin specimens were subjected to a combination of normal stress and shear stress in the cantilever configuration in [23,24]. Yet, the most likely contribution to the difference in fatigue responses is tubule orientation. The beams were sectioned parallel to the height of the tooth, and due to the S-shaped path of the tubules from the pulp to the DEJ these beams would be expected to have an orientation between $\theta = 0^\circ$ and $90^\circ$. Thus, the experimental results are in agreement with those of the only previous study of human dentin and provide a more distinct indication on the importance of tubule orientation to the fatigue response. Collectively the investigations confirm that the fatigue strength of dentin decreases with increasing cyclic stress amplitude. Certainly, the difference in fatigue properties with tubule orientation is also related to contribution of the collagen fibrils for $\theta = 0^\circ$ in maintaining damage tolerance with cyclic loading through fibril extension and bridging of microracks that develop with fatigue loading [25].

The four-point flexure arrangement resulted in a gage section of uniform normal stress, but the nature of cyclic loading ($R = 0.1$) resulted in a non-zero mean stress. Using the maximum flexural strength for both tubule orientations (Table 1) and the Goodman model [28] to correct for mean stress effects, the equivalent endurance strength for fully reversed loading ($\sigma_e$) of dentin with $\theta = 0^\circ$ and $90^\circ$ is 64.3 and 31.0 MPa, respectively. The ratio of fully reversed endurance strength to the flexure strength ($\sigma_e/\sigma_f$) for specimens with $\theta = 0^\circ$ and $90^\circ$ is 0.41 and 0.28, respectively. Although dependent on many factors, the ratio of the endurance strength and UTS ($\sigma_e/\sigma_{uts}$) for most engineering materials ranges from 0.30 to 0.60 [32]. While the ratio of $\sigma_e/\sigma_f$ for dentin falls well within this range, the smaller ratio for dentin with $\theta = 90^\circ$ emphasizes the larger sensitivity to fatigue and potential for fatigue failure in this orientation. Fatigue cracks in restored teeth are typically oriented perpendicular to the dentin tubules [33] and appear to be attributed to the higher sensitivity to fatigue damage. Differences in the fatigue life diagrams (Fig. 4) for dentin with $\theta = 0^\circ$ and $90^\circ$ clearly indicate that tubule orientation played an important role on the response of dentin to cyclic loading.

Microcracks were present on the tensile surfaces of specimens with $\theta = 0^\circ$ while they were far less evident in specimens with $\theta = 90^\circ$. Intrinsic defects are undoubtedly present in dentin and contribute to the initiation of damage with fatigue. The fatigue life of dentin should be considered a summation of the initiation and propagation of damage. The propagation stage in the current investigation would be small with relation to initiation due to the use of load control feedback. Therefore, the difference in fatigue strength between dentin with $\theta = 0^\circ$ and $90^\circ$ is likely attributed to the difference in rate of damage initiation rather than the rate of damage propagation. According to the larger exponent of the power law model, dentin with tubule orientation of $\theta = 90^\circ$ is more sensitive to the presence of damage that develops with cyclic loading. This may suggest that a cavity floor is more susceptible to damage and failure with function than the walls.

Results of the present investigation have established that the fatigue strength of dentin is dependent on tubule orientation and that restorative practices that increase the magnitude of cyclic stresses in restored teeth are detrimental. Conditions that pose cyclic stresses parallel to the dentin tubules are most likely to cause fatigue of the dentin. Despite the value of this new understanding there are several recognized limitations to the study. For example, the experiments were conducted at room temperature using a cyclic stress frequency that is greater than that of standard mastication (1–2 Hz). According to results of previous studies on the mechanical behavior of dentin, differences in the flexural responses resulting from temperature are expected to be small [34,35]. The fatigue strength of dentin increases with frequency [24] and rate of loading [36]. Therefore, the fatigue strength of dentin resulting from oral activities would be expected to be lower than the estimates presented herein. It is important to note that the evaluation was conducted with coronal dentin of extracted virgin molars and did not consider the potential differences between root and coronal dentin or the potential differences between the tissues of restored and unrestored teeth. There are other relevant clinical factors that likely contribute to the changes in fatigue life, namely mean stress, hydration and other physiological factors. Thus, further research on the fatigue properties of dentin appears warranted.

5. Conclusions

An experimental evaluation on the effects of tubule orientation to the mechanical behavior of human dentin was conducted. Rectangular beams were prepared from the coronal dentin of virgin molars and subjected to quasi-static four-point flexure or four-point flexural fatigue to failure. The specimens were prepared with the dentin tubules aligned either parallel ($\theta = 0^\circ$) or perpendicular ($\theta = 90^\circ$) to the plane of maximum normal stress. Based on results from this study the following conclusions were drawn:

(1) The mean and standard deviation in flexural strength of dentin with tubule orientations of $\theta = 0^\circ$ and $90^\circ$ was $160 \pm 22$ and $109 \pm 10$ MPa, respectively. Similarly, the energy to fracture for specimens with $\theta = 0^\circ$ and $90^\circ$ was $1.9 \pm 1.0$ and $0.5 \pm 0.2$ MPa, respectively. Both the flexural strength ($p<0.0001$) and energy to fracture ($p<0.0001$) for the two tubule orientations were significantly different.

(2) The fatigue life of the dentin beams with $\theta = 0^\circ$ was approximately two orders of magnitude larger than dentin with $\theta = 90^\circ$ over all cyclic stress amplitudes. The apparent endurance strength (defined at $10^6$ cycles) of dentin with $\theta = 0^\circ$ and $90^\circ$ was 44 and 24 MPa,
respectively. The ratio of equivalent fully-reversed endurance strength to the flexure strength ($\sigma_e/\sigma_f$) for the dentin specimens with $\theta = 0^\circ$ and $90^\circ$ was 0.41 and 0.28, respectively.

(3) There was a non-linear decrease in both the flexure strength and energy to fracture of dentin with increasing tubule density. The decrease in the energy to fracture with increasing density was more significant than the decrease in strength. Nevertheless, the influence of tubule orientation on the mechanical properties of dentin was more significant than the influence of tubule density.

(4) Fracture surfaces of the dentin beams with $\theta = 0^\circ$ exhibited a large overload shear lip in which unstable fracture progressed perpendicular to the dentin tubules. Dentin specimens with $\theta = 90^\circ$ exhibited little or no such feature. The observation confirms that the fatigue crack growth resistance of dentin is anisotropic and that the lowest resistance is for crack growth perpendicular to the tubules.

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References