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ABSTRACT

The objective of this investigation was to distinguish whether the instruments commonly used for cutting dentin cause degradation in strength or fatigue behavior. Beams of coronal dentin were obtained from unrestored 3rd molars and subjected to either *quasi*-static or cyclic flexural loading to failure. The surfaces of selected beams were treated with a conventional straight-sided bur or with an abrasive air jet laden with glass particles. Under monotonic loading, there was no difference in the strength or Weibull parameters obtained for the control or treated beams. However, the fatigue strength of dentin receiving bur and air-jet treatments was significantly lower ($p \leq 0.0001$) than that of the control. The bur treatment resulted in the largest overall degree of degradation, with nearly 40% reduction in the endurance limit and even more substantial decrease in the fatigue life. The methods currently used for cavity preparations substantially degrade the durability of dentin.

KEY WORDS: cracked-tooth syndrome, dentin, fatigue, fatigue crack growth, tooth fracture, cutting.

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Degradation in the Fatigue Resistance of Dentin by Bur and Abrasive Air-jet Preparations

INTRODUCTION

There are many instances that require the cutting of tooth structure, including the removal of caries, trauma repair, preparation for bridges, repair of failing restorations, etc. In cases involving the removal of demineralized tooth tissue, a careful balance is needed among prevention, conservation, and the investment of time. While the removal of compromised material is essential, minimizing damage to the remaining hard tissue is equally important. An introduction of defects could diminish the structural integrity of the tissues (Kinney *et al.*, 2003), thereby reducing the durability of the restoration and increasing the likelihood of tooth fracture.

Several studies have examined the material removal process and the prepared surfaces resulting from cavity preparations (Charbeneau *et al.*, 1957; Leidal and Tronstadt, 1975; Watson and Cook, 1995; Xu *et al.*, 1997), but the results have been inconclusive. Though cracks have been found in enamel prepared with carbide and diamond abrasive burs, flaws are generally not found in dentin. Banerjee *et al.* (2000) did not find cracks in dentin resulting from the use of burs, but reported that sono-abrasion and Carisolv gels caused flaws. Sehy and Drummond (2004) introduced Class I or Class II MOD preparations into molars using either coarse diamond burs or an Er:YAG laser, followed by placement of a resin composite, bulk curing to maximize interfacial stresses, and evaluation of the tooth-composite interface *via* microscopy. Neither the laser nor coarse diamond burs were found to cause visible evidence of microcracking in dentin.

While direct examinations of the tissue after bur treatments have not identified flaws within dentin, Yan *et al.* (2009) showed that flaws resulting from material removal could serve as the origin of fracture. An evaluation of the strength of dentin after laser preparations showed that cracks exceeding 100 μ m in length were introduced within the dentin under some treatment conditions (Staninec *et al.*, 2009). Thus, flaws introduced with dental burs are potentially too small to see in direct evaluations (*i.e.*, microscopy), but they could cause degradation in strength if they reach an adequate size. Of note, previous studies were limited to *quasi*-static loading of the tissue to failure. Dentin is susceptible to degradation by fatigue (Arola *et al.*, 2010), and small flaws may propagate by fatigue crack growth (Arola *et al.*, 1999; Nalla *et al.*, 2003). No study has examined whether the methods of cavity preparation are important to the fatigue behavior of coronal dentin.

The primary objective of this study was to evaluate the influence of commonly used methods for cutting cavity preparations on the mechanical behavior of coronal dentin. The null hypothesis was that the methods of cutting do not cause a reduction in strength of dentin evaluated by *quasi*-static loading or by cyclic loading.

MATERIALS & METHODS

Caries-free third molars were obtained from participating dental practices in Maryland according to a protocol approved by the Institutional Review Board of the University of Maryland Baltimore County (Approval Y04DA 23151). All teeth were from individuals between 17 and 25 yrs of age. The teeth were maintained in Hanks Balanced Salt Solution (HBSS) with 0.2% sodium azide as an antimicrobial agent at 4°C, then cast in a polyester resin foundation and sectioned by means of a high-speed programmable grinder (Chevalier Smart-H818II, Chevalier Machinery, Santa Fe Springs, CA, USA) and diamond-impregnated slicing wheels (#320-mesh abrasives) under a water-based coolant bath. Primary sections were made in the bucco-lingual plane, and secondary sectioning was performed to obtain beams as shown in Fig. 1(a). All specimens were prepared to ensure that there were no pulp horn intrusions, enamel end-caps, or other non-uniformities.

The dentin beams were subdivided into a nominally flaw-free control group evaluated directly “as-sectioned” and two other groups further modified by a surface treatment. One of the treated groups was processed with a 6-flute tungsten carbide straight fissure bur (Model FG 57, SS White, Lakewood, NJ, USA) [Fig. 1(b)] with water spray irrigation. The second treated group involved the use of an abrasive air jet with 50- μ m abrasive particles and with treated surfaces oriented perpendicular to the incident jet [Fig. 1(b)]. Details regarding each method of material removal are described in the Appendix. Following either method of treatment, the specimens were returned to the HBSS for a period of at least 2 hrs prior to being tested for rehydration. In total, 209 beams were prepared from over 200 teeth, which included 99 control beams and 55 beams from each of the two methods of preparation.

The average surface roughness (R_a) and peak-to-valley height (R_v) resulting from sectioning were assessed by contact profilometry (Model T8000, Hommelwerke, Jena, Germany). Profiles were obtained with direction parallel to the long axis of the beams and a 10- μ m-diameter probe. This profile orientation characterized the scratches and surface defects that would be subjected to tension (*i.e.*, Mode I) loading. The surface roughness was calculated according to the standard ANSI B 48.1, with a traverse length and cutoff length of 4.8 mm and 0.8 mm, respectively.

Quasi-static and cyclic four-point flexure testing was conducted at room temperature (22°C) within a HBSS bath in a universal testing system (Model 3200, BOSE ElectroForce,

Figure 1. Specimen preparation and flexure loading of the dentin beams. (a) Region of coronal dentin where the specimens were obtained. Tubules were aligned perpendicular to the beam length and parallel to the plane of maximum normal stress in flexure. (b) Application of bur and air-jet treatments. The bur treatments were conducted with a handpiece operated at maximum speed and with water spray. The air-jet treatments were conducted with 1.1-mm nozzle diameter, air pressure of 300 kPa, abrasive flow rate of 6.4 grams/min, and traverse speed of 400 mm/min. At a stand-off distance of 10 mm, the coverage diameter at contact was approximately 2.5 mm, which exceeded the specimen width. The treatments were conducted with spherical glass particles (50- μ m particle size). (c) Nominal specimen geometry and flexure loading configuration for both monotonic and fatigue loading. All dimensions in millimeters. The beams were loaded with the treated surfaces subjected to tension.

Eden Prairie, MN, USA) and routine methods as described elsewhere (Arola and Reprogel, 2006; Ryou *et al.*, 2011). Quasi-static flexure was performed under displacement control loading at a rate of 0.06 mm/min [Fig. 1(c)]. Fifteen beams were evaluated from each of the 3 groups. The instantaneous load and load-line displacement were monitored at a frequency of 2 Hz to failure, with the average test requiring slightly less than 5 min. The strength was determined according to conventional beam theory (Popov, 1978) in terms of the maximum measured load (P) and beam geometry [b , h ; Fig. 1(c)] according to $3Pl/bh^2$, where l is the loading span ($l = 2$ mm). The flexural strength of each group was evaluated by a 2-parameter Weibull distribution (Weibull, 1951). In addition, the flexure strengths were compared by one-way ANOVA, and the critical value (α) was set at 0.05.

Cyclic loading experiments were conducted with the loading arrangement for quasi-static evaluation [Fig. 1(c)] with a stress ratio ($R = \text{min load/max load}$) of 0.1 and 5-Hz frequency. These conditions are consistent with previous studies (Arola and Reprogel, 2005, 2006). Each beam was subjected to cyclic loading until failure at a cyclic stress that resulted in failures of 1,000 cycles or greater. Cyclic loading was discontinued for those beams that endured more than 1,200 kcycles, since that is near the apparent endurance limit (Nalla *et al.*, 2003; Arola and

Figure 2. Surface textures and SEM micrographs of prepared dentin beams. (a) Surface profiles obtained from each method of preparation; micrographs of specimens of the (b) control, (c) carbide bur treatment, and (d) air-jet treatment. Note the large peak-to-valley height and overall roughness of the specimen treated with the air jet in (a). Also note the parallel lines on the surfaces of the control and bur-treated specimens that result from direction of movement of the diamond abrasive particles on the slicing wheel and the bur rotation, respectively. All 3 specimens showed some degree of a smear layer, which obscures details of the microstructure beneath. However, the surfaces of the specimens treated with the air jet (d) showed distinct craters that resulted from the abrasive impact and repeated bombardment. These features are very different from those exhibited by the control and bur-treated surfaces.

Reprogel, 2005). The fatigue life distribution of the specimens that underwent fatigue failure in each group was modeled according to the Basquin-type model (Stephens *et al.*, 2001),

$$\sigma = A(N)^B$$

where A and B are the fatigue-life coefficient and exponent, respectively, and were obtained from a regression of the fatigue responses plotted on a log-normal scale. The apparent endurance limit was estimated from the models for a fatigue limit defined at 1×10^7 cycles. The strength distributions were compared over the defined range of cycles to failure by a Wilcoxon Rank Sum test with the critical value (α) set at 0.05.

Surfaces obtained by bur and abrasive air-jet preparations were analyzed by scanning electron microscopy (SEM: JEOL Model JSM 5600, Peabody, MA, USA) in secondary electron imaging mode. Fracture surfaces were examined by SEM and optical microscopy to identify flaws or the origin of failure.

RESULTS

Surface profiles representative of each group are shown in Fig. 2(a). The mean values for the average (R_a) and peak-to-valley roughness (R_v) for the control group were $0.36 \pm 0.11 \mu\text{m}$ and $2.36 \pm 0.60 \mu\text{m}$, respectively. Those values (R_a ; R_v) for the beams

treated with burs and the air jet were $0.59 \pm 0.13 \mu\text{m}$; $3.06 \pm 0.73 \mu\text{m}$ and $1.53 \pm 0.35 \mu\text{m}$; $8.32 \pm 1.29 \mu\text{m}$, respectively. There was no significant difference in the surface roughness values between the control and bur-treated groups ($p > 0.05$). The surface roughness of the air-jet-treated beams was significantly greater ($p \leq 0.001$) than that of the control and bur treatment groups. Micrographs of the specimen surfaces are shown in Fig. 2, including the control [Fig. 2(b)] and examples of bur treatment [Fig. 2(c)] and the air jet [Fig. 2(d)]. All three groups showed evidence of a smear layer that partially concealed the underlying microstructure. While the air-jet-treated surfaces exhibited greater roughness in comparison with the other groups, the smear layer was not removed completely.

A typical stress-strain diagram obtained for flexural loading of a beam that received bur treatment is shown in Fig. 3(a). The average strength and strain-to-fracture obtained from each method of preparation are also presented in this Fig. There was no significant difference ($p > 0.05$) in the flexure strength among the 3 groups; the overall average flexure strength was 150 MPa. The flexure strength distributions of the specimens for each method of preparation are shown in Fig. 3(b), along with the Weibull parameters. There was no substantial difference in the strength distributions for the control beams and those receiving treatments.

A fatigue life diagram for the control dentin specimens is shown in Fig. 4(a). Equivalent diagrams for the dentin receiving bur and air-jet treatments are shown in Figs. 4(b) and 4(c), respectively, with a 95% confidence interval for the control. Equations describing the mean fatigue response are presented in each diagram. Overall, the dentin specimens receiving surface treatments exhibited significantly lower fatigue strength than the control. The strength distributions of the bur ($Z = -5.6$; $p \leq 0.0001$) and air-jet ($Z = -4.43$; $p \leq 0.0001$) treatments over the defined range of cycles to failure were significantly different as well. The apparent endurance limit for the control specimens at 1×10^7 cycles is approximately 44 MPa. Similarly, for the bur and air-jet treatments, the apparent endurance limit is 28 and 35 MPa, respectively. Both surface treatments resulted in a mean fatigue life less than one-tenth that achieved by the control specimens for the same level of cyclic stress.

DISCUSSION

When specimens were evaluated under *quasi*-static loading to failure, there was no significant difference in the apparent strength of coronal dentin between the treated and control

groups. There was also no substantial difference in the Weibull distributions, thereby indicating that the *quasi*-static behavior was controlled by the same predominant flaw size and flaw-size distributions. However, both the bur and abrasive air-jet treatments caused a significant reduction in fatigue strength with respect to the control. Therefore, the null hypothesis must be rejected.

In comparison of the surface roughness of the control beams and those undergoing treatment with carbide burs, there was no significant difference. The largest surface roughness resulted from the air-jet process, due to the random nature of particle impingement and the development of craters on the prepared surface. Nevertheless, the reduction in fatigue strength of the air-jet-treated beams was lower than that from bur treatment (Fig. 4), indicating that the surface profiles primarily represent characteristics of the smear layer (Bester *et al.*, 1995) and do not characterize the underlying subsurface damage. Optical microscopy and SEM evaluation of the fracture surfaces did not reveal flaws serving as the origin of failure. However, it is possible to estimate the apparent flaw length of each treatment by the Kitagawa-Takahashi diagram (1976), which is shown in Fig. 4(d) for the 3 groups. In this approach, the “intrinsic” flaw size is estimated by equating the stress-life and fatigue crack growth responses for dentin. A value of $0.83 \text{ MPa} \cdot \text{m}^{0.5}$ is used for the stress intensity threshold (Bajaj *et al.*, 2006; Ivancik *et al.*, 2012) and a value of unity for the geometry factor. The reduction in apparent endurance limit of dentin [Fig. 4(d)] is interpreted to reflect the introduction of defects from the method of treatment that exceeds the intrinsic flaw size of the control (28 μm). Note that this value is smaller than the first estimate for the intrinsic flaw size reported for dentin by Kruzic and Ritchie (2006); differences are related to previous estimates for the endurance limit and stress intensity threshold. (Additional discussion is given in the Appendix.) The apparent subsurface flaw lengths resulting from the bur and abrasive air-jet treatments in this approach are 70 μm and 45 μm , respectively. While smaller than the values documented for laser preparation of dentin (Staninec *et al.*, 2009), they caused a significant reduction in the fatigue resistance. Thus, small flaws introduced during the cutting of dentin are detrimental to its durability.

Machining damage is most detrimental to brittle materials, due to their low fracture toughness and inability to undergo inelastic deformation (Quinn *et al.*, 2005). Dentin exhibits spatial variations in apparent brittleness, *i.e.*, it increases with proximity of the pulp, due to an increasing mineral-to-collagen ratio and microstructure (Ryou *et al.*, 2011). There is also a reduction

Figure 3. Results from *quasi*-static loading of the coronal dentin beams to fracture. **(a)** Representative flexural response to failure for a control specimen and the mechanical properties, and **(b)** strength distributions and Weibull parameters. The Weibull modulus (m ; a measure of scatter regarded as measure of consistency or goodness) and characteristic strength value (C ; a measure of strength) were estimated by a least-squares error estimation.

in the resistance to fatigue crack growth with depth (Ivancik *et al.*, 2011). That raises the potential for degradation in the fatigue strength of coronal dentin *via* cavity preparations when deep preparations are cut, where dentin is most brittle.

With age, dentin undergoes a reduction in both fatigue strength and fatigue crack growth resistance (Kinney *et al.*, 2005; Arola, 2007), as well as a reduction in fracture toughness (Koester *et al.*, 2008; Nazari *et al.*, 2009). This transition increases the likelihood that flaws will be introduced into the tooth during cavity preparation, along with the potential for fatigue to facilitate tooth fracture. Therefore, the influence of bur treatments on the fatigue properties of old dentin could be far more detrimental than identified here.

There are some important limitations to this evaluation. The fatigue testing was conducted with a frequency of 5 Hz, which is higher than that of mastication. The fatigue response of dentin is dependent on frequency (Nalla *et al.*, 2003; Kruzic *et al.*, 2005). [Additional comments on this topic are presented in the Appendix.] Also important, the control method of preparation may have introduced small flaws that degrade the fatigue strength of dentin with respect to an uncut tooth surface. The high-speed bur treatments involved a single bur type with a very moderate feed rate and narrow range of cutting conditions. Thus, the estimated reduction in fatigue strength resulting from

Figure 4. Fatigue life diagrams for the dentin beams and critical cyclic stress range to failure. Each datapoint corresponds to the failure of a single dentin beam, and datapoints with arrows identify beams that did not fail, and the test was discontinued. The R^2 accompanying each empirical equation represents the goodness of fit. (a) Control. (b) Carbide bur treatment. (c) Air-jet treatment. (d) Kitagawa-Takahashi diagram describing the critical cyclic stress range for fatigue failure of dentin. A geometry factor of unity was assumed in estimating the flaw sizes. The 95% confidence interval for the fatigue strength distribution of the control specimens has been added for comparison in (b) and (c). Note the identification of the intrinsic flaw size in (d) for each condition of specimen preparation. Beams receiving bur treatment exhibited the largest value (70 μm) in comparison with the control.

the bur treatments could be very conservative. Further work is under way to identify the extent of degradation that results from cutting cavity preparations and the methods that can be used to follow the preparation and maximize the durability of dentin.

In summary: An experimental evaluation was conducted to distinguish the influence of cutting dentin by bur and air-jet preparations on the durability of this tissue under both *quasi*-static and fatigue loading. Results showed that there was no influence of the method of cutting on the strength when estimated by *quasi*-static loading. However, both methods of cutting caused a significant reduction ($p \leq 0.0001$) in fatigue strength. Results of this investigation are the first to show that the methods presently used for cutting of dentin introduce flaws that reduce the durability of dentin. This is a critical issue, since weakened tooth structure under cyclic loading has less capability of providing a sound foundation for supporting restorative materials.

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REFERENCES

- Arola D (2007). Fracture and aging in dentin. In: Dental biomaterials: imaging, testing and modeling. Curtis R, Watson T, editors. Cambridge, UK: Woodhead Publishing, pp. 314-342.
- Arola D, Replogel RK (2005). Effects of aging on the mechanical behavior of human dentin. *Biomaterials* 26:4051-4061.
- Arola D, Replogel RK (2006). Tubule orientation and the fatigue strength of human dentin. *Biomaterials* 27:2131-2140.
- Arola D, Huang MP, Sultan MB (1999). The failure of amalgam restorations due to cyclic fatigue crack growth. *J Mater Sci Mater Med* 10:319-327.
- Arola D, Bajaj D, Ivancik J, Majd H, Zhang D (2010). Fatigue of biomaterials: hard tissues. *Int J Fatigue* 32:1400-1412.
- Bajaj D, Nazari A, Sundaram N, Arola D (2006). Aging, dehydration and fatigue crack growth in human dentin. *Biomaterials* 27:2507-2517.
- Banerjee A, Kidd EA, Watson TF (2000). Scanning electron microscope observations of human dentine after mechanical caries excavation. *J Dent* 28:179-186.
- Bester SP, de Wet FA, Nel JC, Driessen CH (1995). The effect of airborne particle abrasion on the dentin smear layer and dentin: an in vitro investigation. *Int J Prosthodont* 8:46-50.
- Charbeneau GT, Peyton FA, Anthony DH (1957). Profile characteristics of cut tooth surfaces developed by rotating instruments. *J Dent Res* 36:957-966.
- Ivancik J, Neerchal NK, Romberg E, Arola D (2011). On the reduction in fatigue crack growth resistance of dentin with depth. *J Dent Res* 90:1031-1036.
- Ivancik J, Majd H, Bajaj D, Romberg E, Arola D (2012). Contributions of aging to the fatigue crack growth resistance of human dentin. *Acta Biomater* 8:2737-2746.
- Kinney JH, Marshall SJ, Marshall GW (2003). The mechanical properties of human dentin: a critical review and re-evaluation of the dental literature. *Crit Rev Oral Biol Med* 14:13-29.
- Kinney JH, Nalla RK, Pople JA, Breunig TM, Ritchie RO (2005). Age-related transparent root dentin: mineral concentration, crystallite size, and mechanical properties. *Biomaterials* 26:3363-3376.
- Kitagawa H, Takahashi S (1976). Applicability of fracture mechanics to very small cracks or the cracks in the early stages. In: Proceedings of the Second International Conference on Mechanical Behavior of Materials. Metals Park, OH: ASM, pp. 627-631.
- Koester KJ, Ager JW 3rd, Ritchie RO (2008). The effect of aging on crack-growth resistance and toughening mechanisms in human dentin. *Biomaterials* 29:1318-1328.
- Kruzic JJ, Ritchie RO (2006). Kitagawa-Takahashi diagrams define the limiting conditions for cyclic fatigue failure in human dentin. *J Biomed Mater Res A* 79:747-751.
- Kruzic JJ, Nalla RK, Kinney JH, Ritchie RO (2005). Mechanistic aspects of in vitro fatigue-crack growth in dentin. *Biomaterials* 26:1195-1204.
- Leidal TI, Tronstad L (1975). Scanning electron microscopy of cavity margins finished with ultra high speed instruments. *J Dent Res* 54:152-159.

- Nalla RK, Imbeni V, Kinney JH, Staninec M, Marshall SJ, Ritchie RO (2003). In vitro fatigue behavior of human dentin with implications for life prediction. *J Biomed Mater Res* 66:10-20.
- Nazari A, Bajaj D, Zhang D, Romberg E, Arola D (2009). On the reduction in fracture toughness of human dentin with age. *J Mech Behav Biomed Mater* 2:550-559.
- Popov EP (1978). Mechanics of materials. 2nd ed. Englewood Cliffs, NJ: Prentice-Hall Inc.
- Quinn GD, Ives LK, Jahanmir S (2005). On the nature of machining cracks in ground ceramics. Part I: SRBSN strengths and fractographic analysis. *Mach Sci Tech* 9:169-210.
- Ryou H, Amin N, Ross A, Wang DH, Eidelman N, Romberg E, *et al.* (2011). Contributions of microstructure and chemical composition to the mechanical properties of dentin. *J Mater Sci Mater Med* 22:1127-1135.
- Sehy C, Drummond JL (2004). Micro-cracking of tooth structure. *Am J Dent* 17:378-380.
- Staninec M, Meshkin N, Manesh SK, Ritchie RO, Fried D (2009). Weakening of dentin from cracks resulting from laser irradiation. *Dent Mater* 25:520-525.
- Stephens RI, Fatemi A, Stephens RR, Fuchs HO (2001). Metal fatigue in engineering. 2nd ed. New York, NY: John Wiley and Sons, Inc.
- Watson TF, Cook RJ (1995). The influence of bur blade concentricity on high-speed tooth-cutting interactions: a video-rate confocal microscopic study. *J Dent Res* 74:1749-1755.
- Weibull W (1951). A statistical distribution function of wide applicability. *J Appl Mech* 18:293-297.
- Xu HH, Kelly JR, Jahanmir S, Thompson VP, Rekow ED (1997). Enamel subsurface damage due to tooth preparation with diamonds. *J Dent Res* 76:1698-1706.
- Yan J, Taskonak B, Mecholsky JJ (2009). Fractography and fracture toughness of human dentin. *J Mech Behav Biomed Mater* 2:478-484.