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Effect of airborne-particle abrasion on 3-dimensional surface roughness and characteristic failure load of fiber-reinforced posts

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Abstract

Statement of problem

Debonding is the most common complication of fiber-reinforced posts (FRPs). Airborne-particle abrasion (APA) has been suggested to increase resin cement adhesion to the surface of FRPs. However, which abrasion protocol is the most favorable is unclear.

Purpose

The purpose of this in vitro study was to compare the surface roughness and characteristic failure load of three FRP systems following different APA protocols.

Material and methods

A total of 150 posts from 3 manufacturers (glass FRP, quartz FRP, and zirconia-enriched glass FRP) were randomly assigned to different surface treatments (NT: no treatment—control; E0: cleaned with 96% ethanol solution; E2: APA for 2 seconds/mm^2—ethanol cleaned, E5: APA for 5 seconds/mm^2—ethanol cleaned; and E10: APA for 10 seconds/mm^2—ethanol cleaned) forming 15 groups in total. APA was performed with 50-µm aluminum oxide. Each post was observed under a 3-dimensional (3D) laser microscope, and average 3D surface roughness (Sa) was measured. Failure was induced with a universal testing machine. Two specimens per group were evaluated under the same microscope to evaluate failure patterns. Surface roughness data were analyzed with the Welch ANOVA (α=.05), followed by the post hoc Games-Howell test. Failure load differences were determined by 2-parameter Weibull statistics and likelihood ratio contour plots (95% confidence bounds).

Results

Statistically significant differences were found in the mean surface roughness among the groups (Welch ANOVA, P<.001). APA resulted in a significant surface roughness increase in all tested post systems. No surface roughness difference was found between surface treatments E2, E5, and E10 in any tested post systems. Weibull statistics and likelihood contour plots revealed a significant decrease in the characteristic failure load for glass FRP after surface treatment E2 (88.7 N) compared with the control (95.3 N). Quartz FRP showed a significant decrease in the characteristic failure load after surface treatment E5 (103.6 N) compared with the control (108.9 N). Zirconia-enriched glass FRP showed no significant decrease in the characteristic failure load after any of the tested surface treatments. Qualitative morphological changes and failure pattern differences were observed among the tested post systems after the different surface treatments.

Conclusions

APA significantly increased surface roughness in all post systems. APA effects on characteristic failure load were dependent on the material used.

Clinical Implications

Selecting an appropriate airborne-particle abrasion protocol to improve the adhesion of fiber-reinforced posts could result in increased surface roughness without producing undesirable morphological changes and without affecting their characteristic failure load. However, any benefit from an airborne-particle abrasion protocol may be dependent on the material used.

Introduction

Fiber-reinforced posts (FRPs) are often used to support a composite resin foundation restoration when the loss of structure in an endodontically treated tooth is substantial. The popularity of FRPs has increased because their elastic modulus is closer to that of dentin,[1] they are metal free, and they facilitate removal if necessary.[2] Also, FRPs may lead to more favorable fracture patterns[3, 4] and may reduce the risk of root fracture.[5, 6, 7, 8]

FRPs are composed of fibers (carbon, glass, quartz, or polyethylene) embedded in a resin matrix.[9, 10, 11] Their long-term failure rate is 7% to 11%, and the most common type of failure is post debonding.[12, 13] Generally, FRPs are so highly cross-linked that it may be difficult to develop a successful bond to resin cements,[14] and this adhesion is significantly inferior to dental substrates.[15] Different surface-modifying techniques have been described aiming to increase the adhesion of resin cements to FRPs. These include the application of hydrofluoric acid,[16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28] phosphoric acid,[17, 23, 29] hydrogen peroxide,[21, 23, 24, 25, 29, 30, 31, 32] methylene chloride,[21, 28, 31] chloroform,[33] potassium permanganate,[21, 23] sodium ethoxide,[23] laser irradiation,[27] silane,[16, 18, 19, 20, 21, 22, 28, 29, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43] tribochemical coating systems,[16, 17, 23, 26, 27, 31, 40, 42, 43, 44, 45, 46] airborne-particle abrasion (APA),[16, 18, 19, 20, 23, 24, 25, 26, 27, 28, 30, 31, 32, 33, 36, 37, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53] and combinations of these techniques. These techniques have been used in various ways, and studies have been inconsistent, and, many times, confusing.[54]

APA is thought to increase the retention of FRPs by increasing the available surface area and surface roughness and the subsequent interaction of the post material with resin-based materials through micromechanical interlocking and slide friction.[36, 48, 54, 55] APA is considered by many to be one of the most successful techniques and increases post retention[23, 45, 47] and bond strength,[16, 18, 25, 26, 30, 31, 33, 36, 49, 50, 52] whereas others disagree.[20, 28, 32, 48, 56] APA can be an aggressive procedure that could result in undesirable physical and mechanical property changes.[20, 30, 54, 57, 58] It should be understood that there is no established APA protocol for FRPs. The authors are unaware of studies that have investigated the effect of different APA protocols on the topographic and mechanical properties of different FRP systems. The purpose of this study was to evaluate and compare the surface roughness, topographic features, failure load, and failure patterns of 3 different FRP systems after different APA protocols. The null hypothesis was that no statistically significant differences would be found in the tested post systems among the different APA protocols.

Material and Methods

One hundred and fifty FRPs with continuous unidirectional fibers were tested. The posts belonged to 3 different systems (n=50 per system): (1) GC Fiber Post (GF; GC America Inc), (2) GT Fiber Post (QF; Dentsply Sirona), and (3) ICELight (ZF; Danville Materials Inc) (Fig. 1). The characteristics of the posts are presented in Table 1. The posts from each system were randomly assigned (Random Allocation Software 2.0) to 5 surface-treatment protocols (Table 1). The combination of post systems used and treatments performed resulted in 15 different groups, each consisting of 10 posts. APA was performed with 50-µm aluminum oxide particles emitted at a distance of 10 mm and 0.2 MPa pressure (MicroBlaster MB1002; Comco Inc). During this procedure, the posts were manually rotated so that the entire post surface was impacted by the particles. For treatments E0, E2, E5, and E10, the posts were ultrasonically cleaned in deionized water for 10 minutes, rinsed with 96% ethanol solution, and dried with an oil-free stream of air. All APA and related procedures were performed by the same operator (M.W.W.).

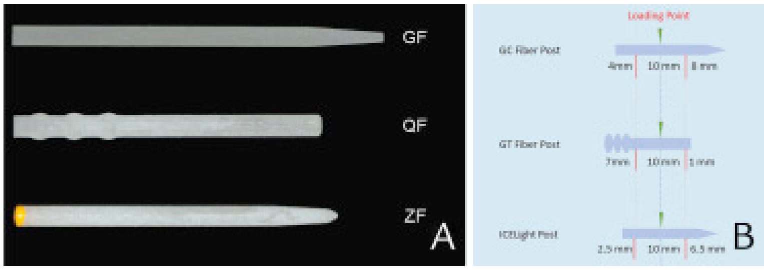

Figure 1. Fiber-reinforced post systems tested. A, GF: GC Fiber Post; QF: GT Fiber Post; ZF: ICELight Post. B, Schematic representation of specimen configuration during loading for each post system. *Red* lines represent location of supports. *Green* arrow shows location of loading point.

Table 1. Specifications and surface treatment of tested fiber-reinforced systems

Post System		Composition*	Size/Diameter	Geometry	Batch Number	Manufacturer
GF	GC Fiber Post	Glass fiber-reinforced composite resin	Red/1.2 mm	Parallel-tapered end	1507151	GC America Inc
QF	GT Fiber Post	60% quartz stretched fibers and 40% epoxy resin	Blue/1.25 mm	Parallel	0000100004	Dentsply Sirona
ZF	ICELight Post	70% fill of zirconia-enriched glass fibers	Yellow/1.2 mm	Parallel-tapered end	43 170	Danville Materials Inc
Surface Treatment						
NT	no treatment—as received (control)					
E0	96% ethanol solution					
E2	2 s/mm^2 APA—96% ethanol solution					
E5	5 s/mm^2 APA—96% ethanol solution					
E10	10 s/mm^2 APA—96% ethanol solution					

APA, airborne-particle abraded; GF, GC Fiber Post; QF, GT Fiber Post; ZF, ICELight Post. Airborne-particle abraded with 50-µm aluminum oxide particles at 0.2 MPa air pressure and 10-mm distance.
*According to manufacturer.

Each post was examined under a 3-dimensional (3D) measuring laser confocal microscope (LEXT OLS4000; Olympus Corp) with a ×20 magnification dry objective lens (MPLAPON20xLEXT; Olympus Corp). The dedicated objective lens had a 0.60 numerical aperture and a high-performance working distance (1.0 mm). Captured images were analyzed with computer software (OLS50-BSW; Olympus Corp) and 3D surface roughness (Sa) was recorded. Sa represents the height difference of each surface point to the arithmetic mean of the surface. To determine a representative roughness value for each post, Sa values were measured in 3 different areas for each post, and then an average value was calculated. Each measured area was 650×650 µm. All pretesting microscope measurements were performed by 1 operator (E.J.S.). The surface of each post was also evaluated qualitatively after treatment for surface alterations as a result of the different treatment protocols.

A universal testing machine (model 5500; Instron Corp) was used to load the posts until failure. Testing was similar to a 3-point bending procedure (Fig. 1). The span length between the supports was 10 mm and was centered within the straight cylindrical portion of the posts. The capacity of the load cell was 500 N. A stainless-steel load piston was used with a crosshead speed of 1 mm/min. Failure was defined as the load in which the specimen showed a sudden drop in the force-time graph and/or when a crack was seen. The mechanical testing was conducted in room temperature by a single operator (M.M.W.).

Two specimens per group were randomly selected (Random Allocation Software 2.0) to be evaluated under the same 3D laser confocal microscope by the same operator (C.P.E.). A ×10 magnification dedicated dry objective lens with a 0.30 numerical aperture, and a 10.4-mm working distance was used (MPLFLN10xLEXT; Olympus Corp) to observe and qualitatively evaluate the area of failure for each of the 30 representative specimens.

A power analysis was conducted to determine the sample size, to have 80% power to detect differences at $P<.05$ and an effect size of f=0.325 (G*Power 3.1.9.2; Erdfelder, Faul & Buchner). Sa values were measured in micrometers (µm). The normality of distribution for each group was tested with the Shapiro-Wilk test ($P>.05$). However, the Levene test detected nonhomogenous variances among the groups ($P<.05$). Thus, the Welch ANOVA was used to detect differences among the groups with "surface roughness" as the dependent variable ($\alpha=.05$), followed by post hoc tests (Games-Howell) to locate differences. The statistical analysis was conducted with computer software (IBM SPSS Statistics, v19.0; IBM Corp).

Brittle materials fail because crack propagation originates from flaws on a surface or within the material. FRPs are brittle materials, and as such, the variability of load until failure can be better described by determining their Weibull distribution.[59], [60], [61] Small data sets can be best fitted by using a 2-parameter Weibull distribution with a maximum likelihood curve fitting.[62] For this data set, the Weibull shape parameter (β) described the slope of the distribution (Weibull modulus). The Weibull scale parameter (η) described the load at which a specimen has a 63.2% failure probability (characteristic failure load).[60] A likelihood contour method was used to determine whether the Weibull distributions were statistically different (SuperSMITH Weibull 5.08-32 and Super SMITH Visual 5.08-32; Fulton Findings LLC). When there was no overlap between the likelihood contour plots (95% confidence bounds), the differences were considered significant.[62], [63]

Results

The mean ±standard deviation (SD) Sa values for each of the 15 groups is presented in Table 2. The Welch ANOVA showed statistically significant differences among the groups ($F[14,50.717]=48.704$, $P<.001$). Multiple comparisons with the Games-Howell correction showed that 2-seconds/mm^2 APA resulted in a statistically significant increase of surface roughness values in all tested post systems compared with their corresponding controls, that is, no treatment (NT) groups (groups GFNT, QFNT, and ZFNT) ($P<.05$). In addition, surface roughness after 5- and 10-seconds/mm^2 APA was not statistically significant in all post systems compared with that after 2-seconds/mm^2 APA ($P>.05$). Cleaning the post surface with 96% ethanol solution did not produce any significant change in surface roughness for QF and ZF compared with their corresponding controls (*P*>.05) but produced a statistically significant increase in surface roughness for GF (*P*<.05) (Table 2).

Table 2. Mean ±SD surface roughness in 3D (Sa) recorded in micrometers (μm) after different surface treatments

Surface Treatment	Post System		
	GF	QF	ZF
NT	2.25 ±0.14^{A}	2.21 ±0.23^{A}	2.52 ±0.18^{A}
E0	2.71 ±0.07^{B}	2.51 ±0.29^{A,B}	2.81 ±0.19^{A,B}
E2	3.32 ±0.31^{C}	3.47 ±0.51^{C}	3.73 ±0.25^{C}
E5	4.24 ±0.82^{C}	3.92 ±0.51^{C}	3.60 ±0.25^{C}
E10	3.68 ±0.29^{C}	4.10 ±0.63^{C}	3.66 ±0.41^{C}

NT, no treatment—as received (control); E0, 96% ethanol solution; E2, 2 s/mm^2 APA—96% ethanol solution; E5, 5 s/mm^2 APA—96% ethanol solution; E10, 10 s/mm^2 APA—96% ethanol solution; GF, GC Fiber Post; QF, GT Fiber Post; ZF, ICELight Post; SD, standard deviation. Different uppercase letters indicate statistically significant difference in same column (*P*<.05).

Qualitative evaluation of the confocal laser microscopy images led the following observations: Cleaning with 96% ethanol solution did not cause any obvious post surface alterations in all tested post systems. In GF, APA resulted in gradual fracture of the superficial glass fibers and composite resin matrix (Fig. 2). In QF, APA resulted in gradual fracture of the superficial quartz fibers and epoxy resin, without exposure of deeper fibers as APA time increased (Fig. 3). In ZF, APA resulted in almost complete removal of the superficial glass fibers without deeper fiber exposure as APA time increased (Fig. 4).

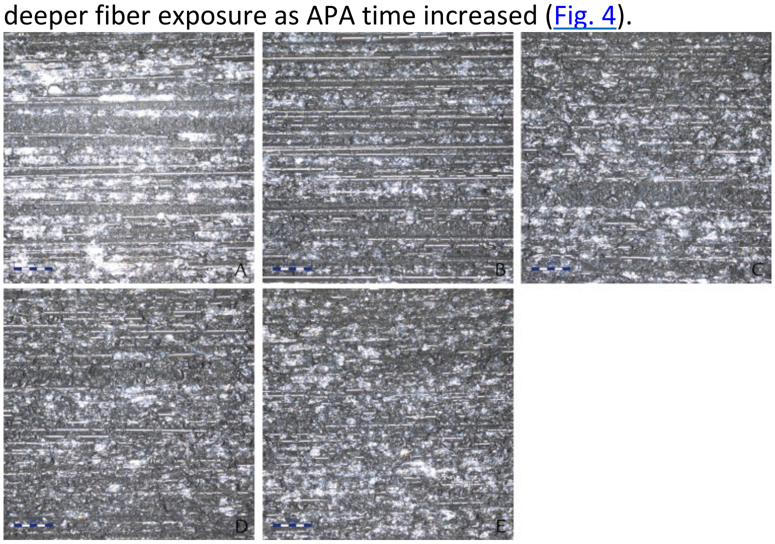

Figure 2. Confocal laser microscope images of post system GF (GC Fiber Post) after different surface treatments. A, GFNT. B, GFE0. C, GFE2. D, GFE5. E, GFE10. Airborne-particle abrasion resulted in fracture/removal of superficial glass fibers and external layer of composite resin matrix leading to further exposure of deeper glass fibers (original magnification ×427) (NT: No treatment–control; E0: 96% ethanol solution; E2: APA for 2 s/mm^2—96% ethanol solution; E5: APA for 5 s/mm^2—96% ethanol solution; E10: APA for 10 s/mm^2—96% ethanol solution).

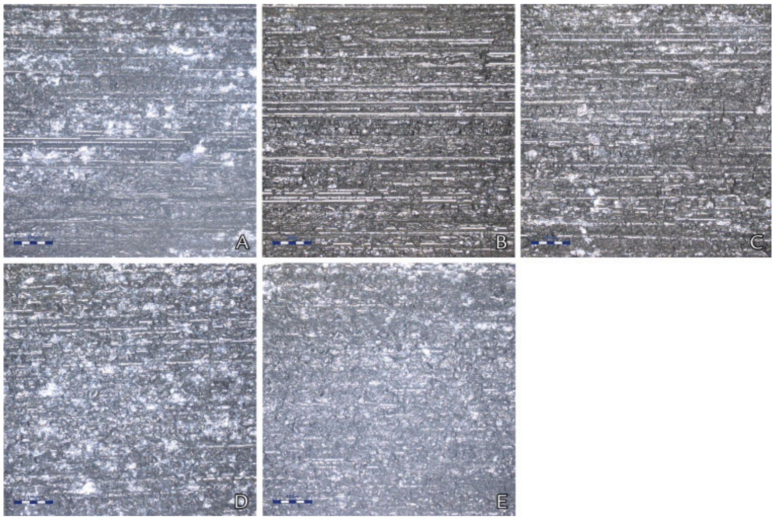

Figure 3. Confocal laser microscope images of post system QF (GT Fiber Post) after different surface treatments. A, QFNT. B, QFE0. C, QFE2. D, QFE5. E, QFE10. Airborne-particle abrasion resulted in fracture/removal of superficial quartz fibers and external layer of epoxy resin matrix (original magnification ×427) (NT: No treatment–control; E0: 96% ethanol solution; E2: APA for 2 s/mm^2—96% ethanol solution; E5: APA for 5 s/mm^2—96% ethanol solution; E10: APA for 10 s/mm^2—96% ethanol solution).

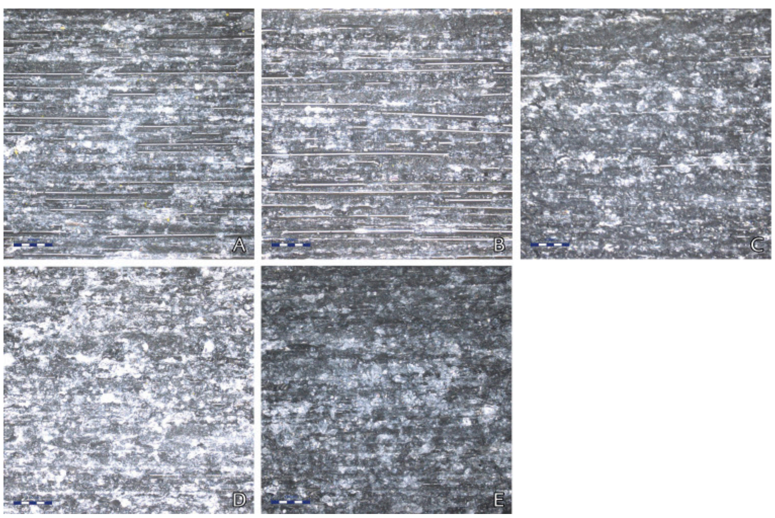

Figure 4. Confocal laser microscope images of post system ZF (ICELight Post) after different surface treatments. A, ZFNT. B, ZFE0. C, ZFE2. D, ZFE5. E, ZFE10. Almost complete removal of superficial zirconia-enriched glass fibers observed with airborne-particle abrasion (original magnification ×427) (NT: No treatment–control; E0: 96% ethanol solution; E2: APA for 2 s/mm^2—96% ethanol solution; E5: APA for 5 s/mm^2—96% ethanol solution; E10: APA for 10 s/mm^2—96% ethanol solution).

The results of the 2-parameter Weibull analysis are presented in Table 3. For GF, the likelihood ratio contour plot showed a statistically significant decrease in characteristic failure load after 2-seconds/mm^2 APA compared with the control. For QF and ZF, the likelihood ratio contour plot showed no significant difference of the characteristic failure load after 2-seconds/mm^2 APA. QF showed a statistically significant decrease in characteristic failure load compared with the control after 5-seconds/mm^2 APA. For ZF, the characteristic failure load was not significantly different among the various surface-treatment protocols and the control. Cleaning with 96% ethanol solution did not affect the characteristic failure load of any of the tested FRP systems (Fig. 5).

Table 3. Characteristic failure load measured in newtons (N) after different surface treatments

Surface Treatment	Post System		
	GF	QF	ZF
NT	95.3[A]	108.9[A]	87.1[A,B]
E0	93.9[A,B]	107.4[A,B]	87.8[A]
E2	88.7[B,C]	106.0[A,B]	85.9[A,B]
E5	82.5[C,D]	103.6[B]	85.8[A,B]
E10	81.7[D]	96.9[C]	84.7[B]

E0, 96% ethanol solution; E2, 2 s/mm^2 APA—96% ethanol solution; E5, 5 s/mm^2 APA—96% ethanol solution; E10, 10 s/mm^2 APA—96% ethanol solution; GF, GC Fiber Post; NT, no treatment—as received (control); QF, GT Fiber Post; ZF, ICELight Post; SD, standard deviation. Different uppercase letters indicate statistically significant difference in same column (P<.05).

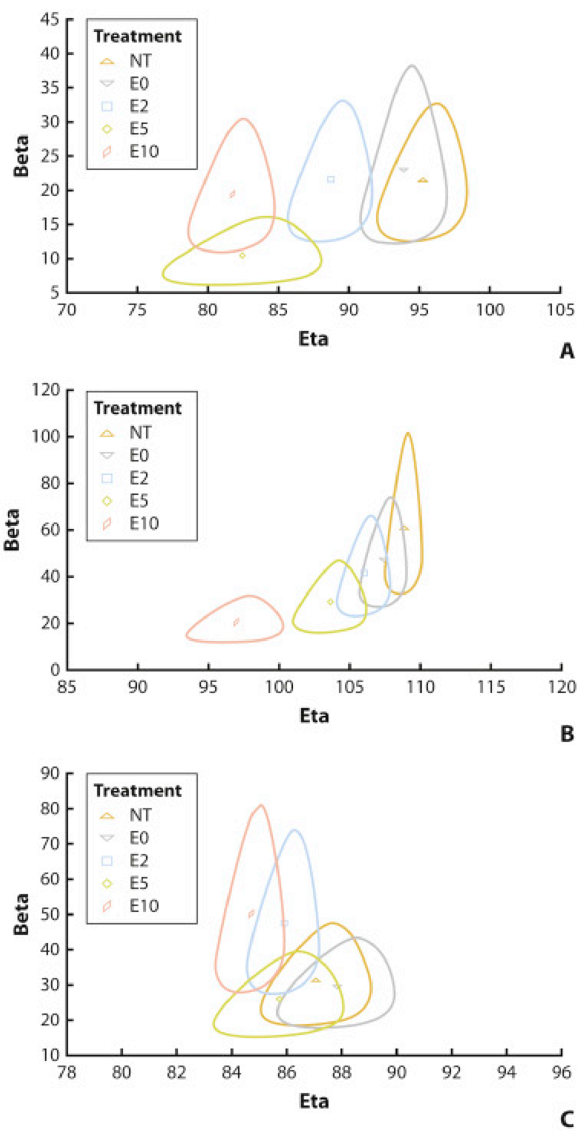

Figure 5. Likelihood ratio contour plots (95% confidence bounds). A, Post system GF (GC Fiber Post). B, Post system QF (GT Fiber Post). C, Post system ZF (ICELight Post). Beta (β): Weibull scale parameter, Eta (η): Weibull shape parameter (characteristic failure load) (NT: No treatment–control; E0: 96% ethanol solution; E2: APA for 2 s/mm^2—96% ethanol solution; E5: APA for 5 s/mm^2—96% ethanol solution; E10: APA for 10 s/mm^2—96% ethanol solution). APA, airborne-particle abrasion.

Evaluation of the confocal laser microscopy images of the representative specimens after failure led to the following observations. GF showed fracture lines in the resin matrix when the posts were subjected to 2-seconds/mm^2 APA (GFE2). These fracture line patterns tended to be longitudinal to the fiber orientation and mostly around the fibers and were no different from the GFNT or the GFE0 groups. When APA time increased to 5 or 10 seconds/mm^2, delamination or debonding of fibers was also noted. QF showed fracture lines in the resin matrix as well as some bending/rupture of fibers in the control group (QFNT). These failure patterns were similar to those in the QFE0 and QFE2 groups. When APA time increased to 5 or 10 seconds/mm^2, fracture and debonding of fibers were also noted. ZF showed fracture lines in the resin matrix that were perpendicular to the fiber orientation, as well as bending/rupture of fibers irrespective of surface treatment (Fig. 6).

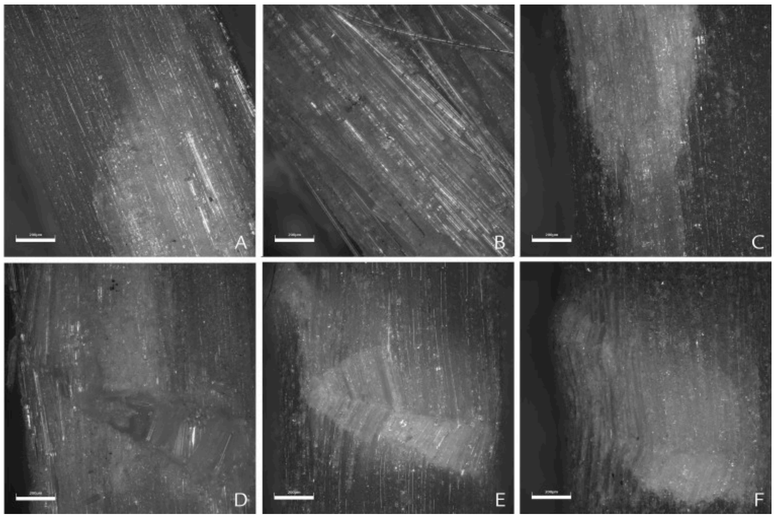

Figure 6. Representative post failure confocal laser microscope images of tested post systems after airborne-particle abrasion for 2 and 10 s/mm^2. A, GFE2. B, GFE10. C, QFE2. D, QFE10. E, ZFE2. F, ZFE10. Lighter areas in resin matrix indicate presence of cracks (original magnification ×216) (NT: No treatment–control; E0: 96% ethanol solution; E2: APA for 2 s/mm^2—96% ethanol solution; E5: APA for 5 s/mm^2—96% ethanol solution; E10: APA for 10 s/mm^2—96% ethanol solution).

Discussion

This study showed that 3D surface roughness was significantly increased after APA in all post systems. Characteristic failure load was significantly decreased in posts GF and QF after different APA times. Also, surface topographical features and failure patterns were different among the groups. Thus, the results support the rejection of the null hypotheses.

Previous studies testing the effect of APA on the surface characteristics, mechanical properties, and bonding capabilities of FRPs have yielded various results.17, 18, 19, 20, 23, 24, 25, 26, 27, 28, 30, 31, 33, 40, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52 This study is in agreement with previous studies showing that APA resulted in increased surface roughness.24, 26, 27, 31, 53 In addition, APA increases bond strength16, 17, 25, 26, 27, 30, 31, 36, 49, 50, 52 and retention of FRPs in endodontically treated teeth.18, 23, 33, 45, 47 However, others found that APA has little effect on bond strength20, 32, 42, 48, 56 or that the bond strength is actually reduced.28 Most studies showed that flexural properties of posts were not affected by APA,19, 20, 28, 44, 51 whereas 1 study reported that APA increased the tested posts' elastic modulus.30 The present study found that characteristic failure load may or may not be significantly affected depending on the APA protocol or the post system. Comparing the results of previous studies is difficult as there is variability in the types of particles, particle size, air pressure, abrasion distance, and abrasion time. Previously, 50-µm aluminum oxide,16, 18, 19, 20, 23, 24, 25, 28, 30, 31, 33, 36, 37, 43, 45, 47, 51, 52, 56 110-µm aluminum oxide,26, 27, 32, 48, 49, 50, 53 and 30-µm silica-modified aluminum oxide have been used.16, 17, 26, 27, 31, 42, 43, 44, 45, 46 Particles were emitted with 0.2,[18, 19, 20, 26, 27, 28, 30] 0.25,[23, 24, 25, 31, 47, 56] 0.28,[17, 32, 36, 44, 45, 46, 48, 49, 50, 52, 53] or 0.4 MPa[16, 33, 37, 43, 51] of air pressure, from a distance of 10,[17, 24, 26, 27, 30, 31, 32, 36, 44, 46, 48, 49, 50, 51, 52, 53] 15,[28] 20,[16, 33, 43] 30,[24, 25, 47, 56] or 50 mm,[18, 19, 37] and for 2,[37] 3,[30] 5,[23, 24, 25, 32, 36, 47, 48, 49, 50, 52, 53, 56] 10,[16, 18, 19, 20, 26, 27, 28, 31, 33, 45, 51] 15,[43, 44, 46] or 20 seconds.[17] None of these studies compared different APA protocols.

This study used 50-µm aluminum oxide particles. The lowest air pressure reported (0.2 MPa) was used, and the particles were emitted from a distance of 10 mm, the distance most commonly used in previous studies. The only variant changed was abrasion time. Sa values were calculated as they may be more representative of each specimen's roughness than the roughness values obtained with profile analysis (Ra).[26, 27, 31] Flexural properties were not calculated as these depend on the specimen's diameter, which may be affected in a nonuniform way as a result of APA.[30] Also, valid measurements of flexural properties for endodontic post materials require appropriate specimen length/diameter ratio, which should be at least 16:1 for the support length during bending tests.[61] Commercially available posts are considerably shorter and may not be appropriate for calculation of flexural strength and flexural modulus. Also, most endodontic posts are not right cylinders, do not have a constant cross section, and are not symmetrical about their axes, all of which are necessary assumptions for the use of flexure mathematical formulas.[64] Instead, Weibull distribution characteristics were calculated based on the failure load of the specimens.

APA resulted in increased surface roughness in all tested post systems. As shown by the laser confocal microscopy images qualitative analysis, APA caused the partial removal of the post resin matrix, partial fracture of fibers, and/or exposure of deeper post fibers. The increase in surface roughness could be explained by an increase in the available contact area because of these procedures.[48] Although the extent of resin matrix removal and fiber fracture was dependent on abrasion time, it was also different among the post systems used. GF was a glass FRP system, QF was a quartz FRP system, and ZF was a zirconia-enriched FRP system. The resin matrix composition was also different among the systems. These differences may have resulted in a different resistance to APA. The measured surface roughness was not statistically different after 2, 5, and 10-seconds/mm^2 APA; however, in systems GF and ZF, there was a tendency for reduced surface roughness when more than 2 seconds/mm^2 of APA was applied. Although not statistically significant, excessive APA times may result in partial smoothing of the surface, partially negating any initially gained advantage in terms of surface roughness. Also, the post surface was cleaned with 96% ethanol solution after APA to obtain a more reliable roughness measurement. However, cleaning the post surface with ethanol alone resulted in slightly increased surface roughness for all systems, and for GF, this increase was statistically significant. Immersion of resin-based materials in alcohol may result in softening of the material.[65] The resin matrix may have been partially dissolved by the ethanol solution. However, the extent of this phenomenon may be dependent on the susceptibility to dissolution of the resin matrix.

For the post system GF, 2-seconds/mm^2 APA resulted in a significant decrease in the characteristic failure load. QF showed a significant characteristic failure load decrease only after 5 seconds/mm^2 of APA. In contrast, ZF did not show any significant decrease in characteristic failure load, irrespective of the APA protocol used. These differences could be explained by the resistance to abrasion each post system may have. The presence of zirconia within the composition of ZF posts may have resulted in a harder material that could resist APA better and which prevented significant changes in this system's mechanical performance. The tested post systems had different geometric characteristics, so direct comparisons among the systems were not attempted. QF generally exhibited higher characteristic failure load values, and ZF generally showed lower characteristic failure load values. This could be explained by the fact that QF was 0.05 mm thicker than the other 2 tested systems. Alternatively, these differences may be explained by any differences in the modulus of elasticity. Quartz FRPs have been reported to have a lower modulus of elasticity than most glass FRPs and, as a result, may fracture at higher load values.[10, 11, 61] In contrast, zirconia-enriched posts may exhibit a higher modulus of elasticity, and a brittle fracture can happen at lower load values.61 A similar behavior has been previously observed in FRPs that are generally stiffer, such as carbon FRPs.10

Even though general assumptions can be made for other post systems, the results may be directly related to the materials or the methodology used, and this can be a limitation of this study. In addition to the types of fibers and the composition of the resin matrix, other factors such as fiber orientation, fiber density, diameter of fibers, interfacial adhesion between fibers and resin matrix, and the polymerization process during post manufacturing can also play an important role.11 Another limitation could be that the posts were subjected to static loading under room temperature conditions. Whether the results would be different if the posts were thermally or mechanically fatigued to simulate a clinical situation is unknown. Thermocycling and aqueous storage can affect the flexural properties of post materials, but the magnitude of change may not be sufficient to affect clinical performance.9, 51 GF and QF showed a 7% and 5% characteristic load reduction after 2 and 5 seconds/mm^2 of APA, respectively. This was statistically significant, but it is yet to be determined if it is clinically meaningful. When APA was 5 seconds/mm^2 or more, a fracture or delamination of fibers from the resin matrix was noted in GF and QF. This was indicative of significant alteration of the posts' structural integrity. Finally, whether the tested surface treatments could have a significant impact on post adhesion to resin cements and to radicular dentin or on the clinical performance of restored endodontically treated teeth is unknown. Future research could be directed toward comparing the effect of different APA protocols on adhesion to radicular dentin and/or fatigue resistance of endodontically treated teeth. In addition, clinical studies should be performed to validate these results.

Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Surface roughness was significantly increased in all post systems after 2 seconds/mm^2 of APA.
2. More than 2 seconds/mm^2 of APA produced no additional benefit in terms of surface roughness.
3. Glass fiber-reinforced posts exhibited a significant decrease in the characteristic failure load after 2 seconds/mm^2 of APA.
4. Quartz fiber-reinforced posts exhibited a significant decrease in the characteristic failure load after 5 seconds/mm^2 of APA.
5. The characteristic failure load of zirconia-enriched glass fiber-reinforced posts was not significantly affected by APA time.

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