Fracture resistance of permanent anterior incisors using fiber-reinforced composite posts

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This in vitro study investigated whether permanent anterior incisors that are endodontically treated with cemented fiber-reinforced composite (FRC) posts without additional canal preparation can potentially increase the resistance to fracture and thus reduce the rate of clinical failure in root canals. Extracted human permanent maxillary central incisors (n = 120) were randomly assigned to 2 experimental groups (n = 60): thermocycled (Group 1) and non-thermocycled (Group 2). These 2 groups were then further divided into 3 subgroups (n = 20). Subgroup 1.1 specimens had root canals prepared and obturated with FRC posts placed. Subgroup 1.2 specimens were prepared and obturated, but did not receive posts. Subgroup 1.3 specimens did not receive root canal preparation, and served as a control. The same processes were repeated for Subgroups 2.1, 2.2, and 2.3, respectively. Significant differences were found between the thermocycled and the non-thermocycled subgroups. Subgroup comparison within the thermocycled group (Group 1) showed significantly higher fracture resistance values for the teeth with post cementation ($P < .0001$).

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Following endodontic instrumentation of a root canal, an inherent loss of internal hard tissue (radicular dentin) with an associated decrease in fracture resistance occurs, especially when subjected to masticatory loading.[1,2] Teeth with gutta percha-filled roots have been shown to have a higher potential for fracture due to caries, inadequate access preparation, instrumentation of pulpal contents, lack of coronal or access seal, and dehydration from canal cleansers.[1-3] When additional shaping of the canal is needed—such as when more radicular dentin needs to be removed prior to post cementation—there is an increased risk of microfractures and flexural fatigue.[3]

Restorative root posts have traditionally provided strength, stability, and retention for the accompanying coronal coverage in endodontically treated teeth with extensive loss of tooth structure but have not been accepted as mechanisms for augmentation of root strength.[4-7] In recent decades, endodontic post systems have been introduced that provide alternatives to customized cast or prefabricated metal posts.[5] Prefabricated fiber posts have become a popular choice for dentists due to reduced cost, practicality, and the more conservative approach offered by these systems.[8,9] Fiber-reinforced composite (FRC) prefabricated posts provide several benefits as root restoratives, including enhanced esthetic qualities (white or translucent apearance), radiopacity for optimum radiographic viewing, biocompatibility, adhesive capability to dentin with an appropriate luting system, and retrievability (if needed).[2,4,5,8-17] These posts can be categorized as quartz, carbon, ceramic, and glass (silica), and are composed from various types of reinforcing fibers bound to a polymer or resin matrix.[2,4,5,9,12,18,19] The strength of this complex is incumbent upon the length, orientation, geometry, and concentration of the fibers as well as their bond to the matrix.[2,11,12,14,16,20] Several studies have shown that FRC posts display mechanical properties similar to dentin, such as their elastic moduli (stiffness), and increased flexural strengths, therein decreasing the incidence of tooth fracture.[2,4,7,11,12,18,21,22]

Flexural strength or resistance testing of post systems, using a universal testing machine or 3-point device, can reveal the strength of a material while under stress from application of either a single force or through cyclic loading.[2,3,7,8,10,12-16,18,19,21,23-28] Additional reports have used finite element analysis, testing the stress distribution of posts cemented into teeth.[11,22,29-31] This study presents an original experimental protocol, wherein a singular stress was applied to the tooth root (with/without post cementation), taking into consideration an innovative post system using synchronized posts, matched (color-coded) to nickel-titanium instrumentation files, and an external root taper formula, using a noncentric or asymmetric loading model of stress management.

The purpose of this in vitro study was to test the fracture resistance of endodontically treated permanent anterior teeth with subsequent FRC post cementation compared to specimens without inclusion of posts. The null hypothesis was that there was no statistically significant difference between groups of permanent anterior teeth prepared with/without cemented posts.

Materials and methods

Previously extracted human permanent maxillary central incisors (n = 120) were stored in a 1% Chloramine-T solution (Thermo Fisher Scientific, Inc.) consisting of 12% active chlorine diluted in tap water at room temperature. This study protocol, involving human research specimens (teeth), was submitted to the University of Tennessee Health Sciences Center Institutional Review Board for an "Exempt" status review. All teeth, with similar dimensions, were examined using 40X microscopy to rule out the presence of immature apices, carious lesions, abrasive/erosive cavities, fractures or fissures, and restorations.

The teeth were subsequently divided into 2 major experimental groups (n = 60), thermocycled (Group 1) and non-thermocycled (Group 2). These groups were further divided into 3 subgroups (n = 20) (Table 1).

Specimen preparation

In Subgroups 1.1, 1.2, 2.1, and 2.2, access openings were prepared on the lingual surface of the crowns, and the canal working length was obtained by measuring the length of the initial instrument (size 10 file) at the root apical foramen (minus 1 mm). Canal instrumentation was accomplished using stainless steel hand files (Henry Schein Dental) and EndoSequence (Brasseler USA) 0.04 and 0.06 mm tapered nickel-titanium files in a rotary driven 4:1 reduction handpiece powered by an EndoTouch torque-limited electric motor (SybronEndo). The canals were enlarged until a size 40 master apical file (MAF) with 0.06 mm taper was achieved. Following each successive file, the root canals were irrigated with 2 ml of 6% sodium chloride using a plastic syringe with a 30 gauge closed-end needle. The canals were then irrigated with 2 ml of 17% ethylenediaminetetraacetic acid solution for 1 minute to remove the smear layer, followed by a final rinse using sterile water and drying with sterile paper points. Root obturations were completed with AH Plus (DENTSPLY Maillefer) root canal sealer and gutta percha (Henry Schein Dental) using a lateral condensation technique. In subgroups 1.1 and 2.1, gutta percha was removed to within 5 mm of the working length using a Touch and Heat device (Kerr Corporation). The canal post space was rinsed with tap water and dried with sterile paper points. A small (tip size 50 with a 0.06 mm taper) EndoSequence fiber post (Brasseler USA) was placed into the canal and evaluated for passive fit. No additional canal post preparation for these teeth was required prior to cementation. The canals were then conditioned using OneStep total-etch phosphoric acid etchant (Bisco, Inc.), followed by rinsing with tap water and drying with an air/water syringe. OneStep adhesive agent (Bisco, Inc.) was applied to each canal space and light cured for 20 seconds. The posts were cemented using Dual Link composite dual cure luting cement (Bisco, Inc.). Any excess post length was removed with a high-speed handpiece and diamond bur. Access openings were conditioned using the OneStep acid etchant, followed by application of the OneStep adhesive agent. In order to seal the canal space coronally, Filtek Z100 composite resin restorative (3M ESPE) was inserted into all access openings and light polymerized with a quartz-tungsten halogen light (Henry Schein Dental) for 40 seconds. The light was monitored with a radiometer and provided adequate intensity (≥800 mW/cm^2) (Fig. 1). All specimens were then stored in tap water at room temperature. All Group 1 subgroup specimens were thermocycled for 1,000 cycles in separate water baths of 5°C and 55°C ± 2°C, with a dwell time of 60 seconds in each bath and transfer time of 3 seconds. Following the thermocycling regimen, the specimens were stored in tap water at room temperature prior to 3-point testing. Specimens in the Group 2 subgroups were stored in tap water at room temperature until further testing (approximately 7 days). All materials were used following manufacturers' instructions.

The specimens from each group were tested using a universal testing machine (Instron 5567, Instron Corp.) using Bluehill PC software (version 4.0, Instron Corp.). This device digitally displays flexure in newtons (N) vs flexure extension (mm) and stops automatically when the specimen fractures.

Table 1. Division of each subgroup per treatment (n = 20).

Group 1 (Thermocycled; n = 60)
Subgroup 1.1. Endodontically treated, instrumented to size 40 with final 0.06 mm taper, obturated with gutta percha, post placement
Subgroup 1.2. Endodontically treated, instrumented to size 40 with final 0.06 mm taper, obturated with gutta percha, no post placement
Subgroup 1.3. Control group, no treatment
Group 2 (Non-thermocycled; n = 60)
Subgroup 2.1. Same as Subgroup 1.1
Subgroup 2.2. Same as Subgroup 1.2
Subgroup 2.3. Same as Subgroup 1.3

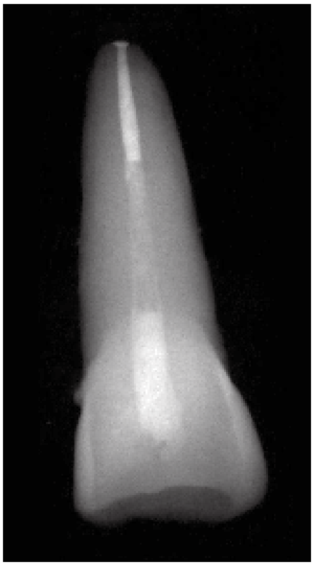

Fig. 1. A radiograph of a maxillary central incisor showing a cemented post in a canal space with accompanying insertion of composite resin restorative.

Flexural test method

A single point bending method of loading consisting of 2 bottom supports and an upper central support (anvil), with a loading angle of 90 degrees, load cell of 5000 N, and crosshead speed of 2 mm/min was used for all transverse flexural strength measurements. This method was designed for rectangular bars or cylindrical specimens, and thus the stress readings under 3-point bending were designated by the equation: $\sigma = PL/\pi R3$, where P = applied load; L = support span; π = 3.14; R = radius (Fig. 2). As the specimens in this study were not true cylinders, but tapered cylinders with the diameter of the apical portion smaller than the diameter of the coronal part. Consequently, the tensile stress in the apical end would be much higher than in the coronal portion. In such cases, root fractures would not be uncommon. To avoid this problem, noncentric, asymmetric loading was applied to the specimens, resulting in lower tensile stresses occuring in the apical end of the tooth (Fig. 3 and 4). With this configuration, all fractures occurred at the point of the applied load. The offset of the load

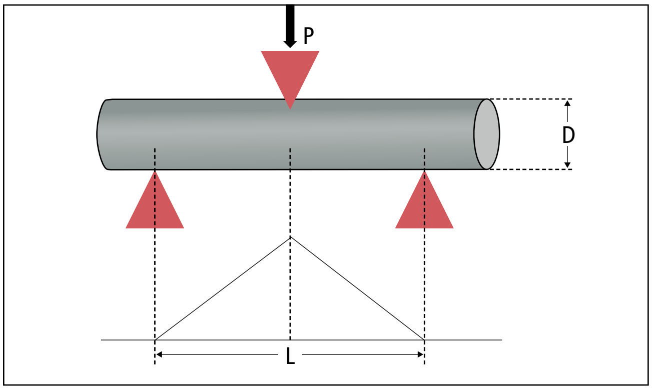

Fig. 2. Stress diagram illustrating the initial 3-point bending apparatus for a cylinder: L = support span; P = applied load; D = cylinder diameter.

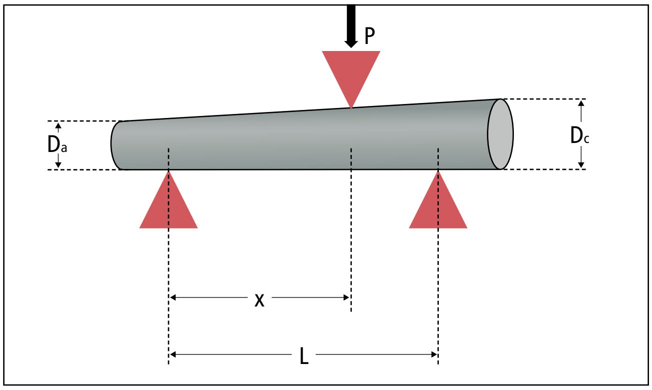

Fig. 3. Diagram of a tapered cylinder (tooth) in noncentric loading position: L = support span; P = applied load; X = applied load point coordinate; Da = diameter at apical end of the beam at the supporting member; Dc = diameter at coronal end of the beam at the supporting member.

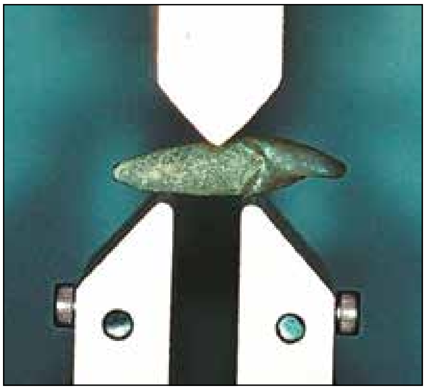

Fig. 4. Photograph of a maxillary central incisor placed in the 3-point bending apparatus. Note the asymmetric loading.

Table 2. Mean stress (MPa ± SD) of each subgroup (n = 20).

Subgroup	Mean MPa (SD)
1.1	365.245 (97.0904)
1.2	239.550 (51.5961)
1.3	310.435 (84.2653)
2.1	240.015 (52.7740)
2.2	245.480 (44.5512)
2.3	424.485 (59.2710)

Table 3. Mean stress (MPa) comparisons for subgroup pairs ($P < 0.05$).

Subgroup	Mean MPa
2.3[a]	424.485
1.1[a,b]	365.245
1.3[b]	310.435
2.2[c]	245.480
2.1[c]	240.015
1.2[c]	239.550

Subgroups not connected by the same letter are significantly different.

toward the coronal portion of the tooth was determined by the ratio of the diameters such that $x/(L-x)=D_c/D_a$, where D_c = diameter of the coronal portion of tooth/D_a = diameter of the apical end of the tooth, thus compensating for the geometry of the tapered cylinder. With this equation, the distance "x" was calculated and the 3-point bending device was set accordingly. The equation for the stress in a tapered beam at a distance "x" from the left supporting member is $\sigma= 4x(L-x)P/\pi LR^3$. In this formula, the stress in the specimen was calculated in megapascals (MPa) based upon the radius (R) of each specimen. For testing purposes, the span (L) was 12 mm (distance between the supporting members). These equations were derived using methods described in separate texts.[32,33]

Results

Statistical analysis of the data was performed using JMP9 (SAS Institute, Inc.). One-way analysis of variance (ANOVA) and post hoc Tukey tests were carried out ($P < 0.05$). Table 2 presents the mean fracture resistance values (MPa) and standard deviations of all specimen subgroups. Significant differences were revealed comparing the thermocycled and non-thermocycled subgroups. Regarding subgroup comparisons within the thermocycled group, significant ($P < .0001$) differences were exhibited between Subgroups 1.1 and 1.2 (teeth restored with FRC posts vs teeth obturated without FRC posts). Also, significant differences were shown between Subgroups 1.1 and 1.3 (teeth restored with FRC posts vs control teeth), and Subgroups 1.2 and 1.3 (teeth obturated without FRC posts vs control teeth) (Table 3).

Discussion

Among the important parameters for long-term restorative success of endodontically treated teeth include preservation of tooth structure, incorporation of contemporary adhesion science (luting of post to internal canal tooth substrate), and inclusion of biomechanical properties (resistance to fracture, elasticity, uniform stress distribution) into post composition and shape.[4-6,9] Traditionally, the primary purpose of an endodontic post was to retain the coronal restoration.[4-7] However, studies have demonstrated that because root-filled (gutta percha) teeth are more prone to fracture, the bonding of filling materials into canal spaces can serve to reinforce roots, thus increasing the fracture resistance.[5,34-37] *Fracture resistance,* as it pertains to dental materials, has been defined as the "highest load a sample can withstand."[7] Specifically referring to a synthetic post, *resistance* is the capacity of the post to withstand lateral and rotational forces, and is influenced by both the post size and rigidity and by the amount of tooth structure available.[5,9,38] Consequently, it seems that the overall contributing factors for the post-treatment success of a restored endodontically treated tooth should be attributed to the amount of remaining radicular dentin and coronal tooth structure, with the concurrent use of fiber-reinforced posts that include conservative design characteristics and biomechanical properties similar to dentin.[4-6,9]

The restoration of endodontically treated posterior teeth has focused primarily on the restorability of coronal function through the placement of a canal post, a "core build-up" procedure, followed by an indirect final restoration. However, following instrumentation of an intact anterior tooth (that is displaying significant pre-treatment coronal tooth structure), post placement and complete coverage with an indirect restoration or crown may be unnecessary, since the forces of occlusion involved with the anterior dentition are usually singular, traumatic events.[5] With advances in endodontic post technology—such as new design concepts and materials that are biomimetically similar to tooth structure—perhaps post cementation following endodontic treatment of an anterior tooth can more closely substitute for the excavated pulp and instrumented dentin tissues, thus serving as a reinforcement surrogate for the root, and not just as a pillar for restoration retention.

The null hypothesis was rejected in the present study. Cementation of FRC posts in prepared teeth roots (vs obturated roots only) did impart a significant influence regarding the fracture resistance of those roots. Thermocycling seemed to exhibit a positive influence on the specimens with FRC posts cemented (Subgroup 1.1), compared to the Subgroup 2.1 specimens that had post inclusion, but were not thermocycled. This occurrence could not be explained within the parameters of this study. However, results displayed within the thermocycled Subgroups (1.1-1.3) revealed that FRC post cementation showed increased fracture resistance values compared to specimens tested without inclusion of posts. A 2004 retrospective study by Schwartz & Robbins surmised that inclusion of posts into anterior teeth, with minimal loss of tooth structure, "is of little or no benefit" and can even increase the probability of restorable failure.[5] However, the authors perhaps did not consider the conservative technique of post placement, whereby no additional radicular dentin is removed following endodontic instrumentation, as exhibited in the EndoSequence technique in this study. Additional summations by the same authors seem to support the fact that cementation of flexible posts (with similar modulus of elasticity as dentin) following endodontic instrumentation resulted in increased stress resistance and fewer occurrences of fracture.[5] Also, a more conservative post-treatment restorative procedure on a tooth with a complete structure (crown + root) should allow for less movement of the post/restoration complex and, in turn, less coronal microleakage.[5] Given these views combined with results from the present study, it could be surmised that FRC post placement may be a beneficial feature for anterior tooth restoration following endodontic instrumentation and obturation.

The EndoSequence endodontic system uses a rotary tapered nickel-titanium instrument file (0.04 or 0.06) with corresponding prefabricated, tapered posts. The post composition consists of 68% glass fibers (zirconia 18%) and 32% epoxy resin.[17] This system matches (through color-coding) the size and shape of the instrumented root canal space, creating a fully tapered preparation from orifice to apex, resulting in removal of less radicular dentin, thus increasing the retentiveness of the cemented (bonded) post and ultimately, the structural integrity of the entire tooth-post-restoration complex.[17] A study conducted by Versluis et al concluded that the use of nickel-titanium files reduce the fracture susceptibility of the root as a result of the creation of smooth and round canal space tapers.[30] In the present study, with knowledge of the MAF size (tip size and taper) and the length of the gutta percha remaining in the canal, the canal size at the coronal aspect of the remaining gutta percha was calculated. With this information, the appropriate post size for each tooth root (canal) was chosen. A 0.06 mm tapered canal preparation has several benefits for the clinician as well as for the patient. Primarily, this taper effectively removes tooth structure in the coronal portion of the canal, resulting in increased proprioceptiveness for the operator and consequently a more precise fit for the filling material (gutta percha and post). The increased 0.6 mm taper provides increased cleansibility of the irrigation agents and thus decreased post-treatment sensitivity for the patient.[39,40] The present study also used a total-etch or etch-and-rinse adhesive system, in combination with a dual cure cement. Contemporary evidence has shown that this type of adhesive system still provides the best surface conditioning prior to FRC post cementation.[4,6]

According to Huysmans & Van der Varst, tooth/post restorations are complex systems in which the stress distribution within the structure is multiaxial, non-uniform, and depends on the magnitude and direction of the applied external loads.[41] Laboratory or in vitro testing of posts has included: static fracture tests (3-point bending) measuring the single loading of a post (post-tooth complex), thereby simulating forces found during trauma; fatigue tests measuring repeated loading, including dynamic, functional, or parafunctional stresses of posts or teeth/post complexes; and finite element analysis studies involving 3-dimensional computer models simulating the physical limitations of post design and material qualities.[2,7,11-14,16,18,19,21-23,26-31] Although the information from these studies was sometimes conflicting, most conclusions indicated that FRC posts demonstrated positive results due to uniform stress distribution (fracture loading/resistance) and similar elastic moduli (stiffness)—properties important for the prevention of root fractures.[2,7,11-14,16,18,19,21-23,26-31]

The thermocycling procedure can be an important testing parameter which attempts to reproduce, in vitro, the manner in which the oral cavity is subjected to thermal irritation from hot/cold foods and beverages. Endodontically restored teeth can potentially contain several different types of materials (adhesive agent, cement, post, build-up material, and crown) which can be susceptible to variations in temperature. However, somewhat contradictory information has been presented in various in vitro studies demonstrating the effects of a thermocycling regimen on FRC post cementation.[13,26,42-45] Therefore, taking all the information into consideration, long-term exposure of cemented posts (in this case, posts cemented into extracted human teeth) to water or thermal barriers is still not fully understood. In the present study, significant differences were exhibited between the thermocycled Subgroups (1.1 & 1.2 and 1.1 & 1.3), perhaps reflecting a more realistic situation that occurs in the oral cavity.

This study protocol was different from most in vitro studies that measured either stress fracture of FRC posts only, or single or repeated load testing (3-point device) of FRC posts cemented in a tooth, or compressive loading of FRC posts cemented in teeth at angles other than 90 degrees.[2,3,7,8,10,12-16,18,19,21,23-28] In the present study, the post system included passive fit posts (0.06 mm taper) that had the same taper as the original (size 40) MAF files. Consequently, additional canal preparation was unnecessary, allowing for a custom fit between the canal space and post, which in turn, increased the amount of usable root dentin, thereby strengthening the root. A previous study conducted by D'Arcangelo et al seemed to somewhat corroborate these results, suggesting that fiber-reinforced posts restored the mechanical properties in maxillary incisors following endodontic treatment (with the inclusion of veneer preparations).[46] Also, an individualized offset stress fracture model of noncentric or asymmetric loading was applied to each specimen, resulting in a lower likelihood of continuous, predictable apical-end fractures and thus less problematic, more accurate stress fracture values.

Although the results from the present study showed promising data regarding the EndoSequence canal preparation and post cementation system for permanent anterior teeth treatment, limitations included a small sample size. In addition, the complexities and relationships involved with the human dentition (occlusal and stomatognathic relationships), although somewhat accounted for in the offset fracture model, could not be fully addressed in a laboratory study of this magnitude. Clinical, long-term studies would be necessary to corroborate the data attained in this in vitro study.

Conclusion

In this in vitro study, using an objective means of testing (single 3-point test) of a FRC post/tooth complex, insight to the interactions of these materials in a clinical environment was explored. Subgroup comparison (within the thermocycled group), showed significantly ($P < 0.0001$) higher fracture resistance values for the teeth with post cementation vs obturated teeth only. These results suggest that structural support of an endodontically treated tooth (root) can be supplemented with the addition of an FRC post. Use of the EndoSequence file and post system allowed for a significant reduction in the amount of radicular dentin removed (with no additional canal preparation following instrumentation), resulting in a more passive fit and patent seal for post cementation. Therefore, it seems that the relatively minimal cost incurred in the cementation of an FRC post in an intact anterior tooth (root) following endodontic treatment is warranted.

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Disclaimer

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References

1. Schafer E, Zandbiglari T, Schafer J. Influence of resin-based adhesive root canal fillings on the resistance to fracture of endodontically treated roots: an in vitro preliminary study. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2007;103(2):274-279.
2. Novais VR, Quagliatto PS, Bona AD, Correr-Sobrinho L, Soares CJ. Flexural modulus, flexural strength, and stiffness of fiber-reinforced posts. *Indian J Dent Res.* 2009;20(3):277-281.
3. Santana ER, Castro CG, Simamoto-Junior PC, Soares PV, Quagliatto PS. Influence of post system and remaining coronal tooth tissue on biomechanical behaviour of root filled molar teeth. *Int Endod J.* 2011;44(5):386-394.
4. Goracci C, Ferrari M. Current perspectives on post systems: a literature review. *Aust Dent J.* 2011;56(Suppl 1):77-83.
5. Schwartz RS, Robbins JW. Post placement and restoration of endodontically treated teeth: a literature review. *J Endod.* 2004;30(5):289-301.
6. Dietschi D, Duc O, Krejci I, Sadan A. Biomechanical considerations for the restoration of endodontically treated teeth: a systematic review of the literature, part II (evaluation of fatigue behavior, interfaces, and in vitro studies). *Quintessence Int.* 2008;39(2):117-129.
7. Plotino G, Grande NM, Bedini R, Pameijer CH, Somma F. Flexural properties of endodontic posts and human root dentin. *Dent Mater.* 2007;23(9):1129-1135.
8. Newman MP, Yaman P, Dennison J, Rafter M, Billy E. Fracture resistance of endodontically treated teeth restored with composite posts. *J Prosthet Dent.* 2003;89(4):360-367.
9. Perdiagao J, Manteira P, Gomes G, Santos V. Restoring teeth with prefabricated fiber-reinforced resin posts. *Pract Proced Aesthet Dent.* 2007;19(6):359-364; quiz 365.
10. Al-Wahadni AM, Hamdan S, Al-Omiri M, Hammad MM, Hatamleh MM. Fracture resistance of teeth restored with different post systems: in vitro study. *Oral Surg Oral Med Oral Pathol Oral Radio Endod.* 2008;106(2):e77-e83.
11. Lanza A, Aversa R, Rengo S, Apicella D, Apicella A. 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor. *Dent Mater.* 2005;21(8):709-715.
12. Lassila LVJ, Tanner J, Le Bell AM, Narva K, Vallittu PK. Flexural properties of fiber reinforced root canal posts. *Dent Mater.* 2004;20(1):29-36.
13. Grandini S, Chieffi N, Cagidiaco MC, Goracci C, Ferrari M. Fatigue resistance and structural integrity of different types of fiber posts. *Dent Mater.* 2008;27(5):687-694.
14. Grandini S, Goracci C, Monticelli F, Tay FR, Ferrari M. Fatigue resistance and structural characteristics of fiber posts: three-point bending test and SEM evaluation. *Dent Mater.* 2005;21(2):75-82.
15. Akkayan B, Gulmez T. Resistance to fracture of endodntically treated teeth restored with different post systems. *J Prosthet Dent.* 2002;87(4):431-437.
16. Cheleux N, Sharrock PJ. Mechanical properties of glass fiber-reinforced endodontic posts. *Acta Biomater.* 2009;5(8):3224-3230.
17. Inside Dental Products. *Brasseler USA Dental EndoSequence Fiber Post System* [press release]. Available at: https://www.dentalaegis.com/products/brasseler-usa/endosequence-fiber-post-system. Accessed December 4, 2013.
18. Seefeld F, Wenz HJ, Ludwig K, Kern M. Resistance to fracture and structural characteristics of different fiber reinforced post systems. *Dent Mater.* 2007;23(3):265-271.

19. Mannocci F, Sherriff M, Watson TF. Three-point bending test of fiber posts. *J Endod.* 2001;27(12):758-761.
20. Callister WD Jr. Composites. In: *Materials Science and Engineering; An Introduction.* 3rd ed. Hoboken, NY: Wiley; 1997:513-541.
21. Galhano GA, Valandro LF, de Melo RM, Scotti R, Bottino MA. Evaluation of the flexural strength of carbon fiber-, quartz fiber-, and glass fiber-based posts. *J Endod.* 2005;31(3):209-211.
22. Santos AF, Meira JB, Tanaka CB, et al. Can fiber posts increase root stresses and reduce fracture? *J Dent Res.* 2010;89(6):587-591.
23. Stewardson DA, Shortall AC, Marquis PM. The effect of the elastic modulus of endodontic posts on static load failure. *Int Endod J.* 2011;44(5):458-468.
24. Abo El-Ela OA, Atta OA, El-Mowafy O. Fracture resistance of anterior teeth restored with a novel nonmetallic post. *J Can Dent Assoc.* 2008;74(5):441.
25. Castro CG, Santana FR, Roscoe MG, Simamoto PC Jr, Santos-Filho PC, Soares CJ. Fracture resistance and mode of failure of various types of root filled teeth. *Int Endod J.* 2012:45(9)840-847.
26. Drummond JL, Bapna MS. Static and cyclic loading of fiber-reinforced dental resin. *Dent Mater.* 2003;19(3): 226-231.
27. Stewardson DA, Shortall AC, Marquis PM, Lumley PJ. The flexural properties of endodontic post materials. *Dent Mater.* 2010;26(8):730-736.
28. Silva GR, Silva NR, Soares PV, Costa AR, Fernandes-Neto AJ, Soares CJ. Influence of different load application devices on fracture resistance of restored premolars. *Braz Dent J.* 2012;23(5):484-489.
29. Meira JB, Esposito CO, Quitero MF, et al. Elastic modulus of posts and the risk of root fracture. *Dent Traumatol.* 2009;25(4):394-398.
30. Versluis A, Messer HH, Pintado MR. Changes in compaction stress distributions in roots resulting from canal preparation. *Int Endod J.* 2006;39(12):931-939.
31. Silva NR, Castro CG, Santos-Filho PC, et al. Influence of different post design and composition on stress distribution in maxillary central incisor: finite element analysis. *Indian J Dent Res.* 2009;20(2):153-158.
32. Huddleston JV. *Introduction to Engineering Mechanics.* London: Addison-Wesley Publishing Co.;1961:178-192, 324-339.
33. Nash WA. *Strength of Materials.* 4th ed. Columbus, OH: McGraw-Hill; 1998:177-185.
34. Sagsen B, Er O, Kahraman Y, Akdogan G. Resistance to fracture of roots filled with three different techniques. *Int Endod J.* 2006;40(1):31-35.
35. Teixeira FB, Teixeira EC, Thompson JY, Trope M. Fracture resistance of roots endodontically treated with a new resin filling material. *J Am Dent Assoc.* 2004; 135(5):646-652.
36. Schmage P, Nergiz I, Markopoulou S, Pfeiffer P. Resistance against pull-out force of prefabricated coated FRC posts. *J Adhes Dent.* 2012;14(2):175-182.
37. Moosavi H, Maleknejad F, Kimyai S. Fracture resistance of endodontically-treated teeth restored using three root-reinforcement methods. *J Contemp Dent Pract.* 2008;9(1):30-37.
38. Trabert KC, Caput AA, Abou-Rass M. Tooth fracture – a comparison of endodontic and restorative treatments. *J Endod.* 1978;4(11):341-345.
39. Koch K, Brave D. Endosequence: a new post preparation technique. *Endod Practice.* 2010;3(2):22-26.
40. Koch KA, Brave DG. Real world endo sequence file. *Dent Clin North Am.* 2004;48(1):159-182.
41. Huysmans MC, Van der Varst PG. Finite element analysis of quasistatic and fatigue of post and cores. *J Dent.* 1993;21(1):57-64.
42. Genovese K, Lamberti L, Pappalettere C. Structural behaviour of endodontically treated teeth under thermomechanical loading. *Proc Inst Mech Eng H.* 2006; 220(8):909-928.
43. Mazzitelli C, Monticelli C, Toledano M, Ferrari M, Osorio R. Effect of thermocycling on the bond strength of self-adhesive cements to fiber posts. *Clin Oral Investig.* 2012;16(3):909-915.
44. Stewardson DA, Shortall AC, Marquis PM. The effect of clinically relevant thermocycling on the flexural properties of endodontic post materials. *J Dent.* 2010;38(5):437-442.
45. Vichi A, Vano M, Ferrari M. The effect of different storage conditions and duration on the fracture strength of three types of translucent fiber posts. *Dent Mater.* 2008;24(6):832-838.
46. D'Arcangelo C, De Angelis F, Vadini M, Zazzeroni S, Ciampoli C, D'Amario M. In vitro resistance and deflection of pulpless teeth restored with fiber posts and prepared for veneers. *J Endod.* 2008;34(7):838-841.

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