

RESEARCH AND EDUCATION

Three-dimensional finite element analysis of endodontically treated teeth with weakened radicular walls restored with different protocols



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Endodontic treatment is commonly indicated for extensively damaged teeth with pulpal involvement.¹ Endodontically treated teeth exhibit a high risk for biomechanical failures as a consequence of tooth destruction² due to coronal/radicular caries, extensive restoration, or preparations for an intracanal post. The fracture strength depends on the amount of remaining dentin.^{3,4}

Metallic posts have been widely used as intracanal retainers in endodontically treated teeth regardless of the amount of remaining supporting tissue.⁵⁻⁸ Recently, restorative dentistry studies have indicated the use of prefabricated posts to restore endodontically treated teeth with severe coronal destruction. Fiber posts are fabricated with unidirectional fibers of glass or quartz embedded in a polymeric matrix of epoxy resin or its derivatives.⁹ These posts are less rigid and exhibit mechanical properties that are similar to those of dentin, which creates a homogenous assembly with the surrounding root.⁹ Additionally,

fiber posts exhibit appropriate bonding with resin cements and dentin and allow for more homogeneous stress distribution in weakened roots compared with metallic posts,⁸ resulting in better load distribution along the tooth.¹⁰ Moreover, in contrast to metallic posts, glass fiber posts (GFPs) also exhibit better esthetics, greater biocompatibility, and a lack of corrosion.¹⁰

ABSTRACT

Statement of problem. The restoration of weakened roots with glass fiber posts (GFPs) remains a challenge.

Purpose. The purpose of this study was to evaluate the stress distribution of endodontically treated teeth with weakened radicular walls restored with different protocols by 3-dimensional finite element analysis (3D-FEA).

Material and methods. The following 4 models of endodontically treated maxillary canines restored with metal ceramic crowns were simulated on the basis of computed microtomographic images to characterize the groups: GNW (control), a nonweakened root restored with a GFP; GW, a weakened root restored with a GFP; GDA, a weakened root restored with a direct anatomic GFP; and GIA, a weakened root restored with an indirect anatomic GFP. Loads of 180 N were applied to the lingual surface on the incisal third of the teeth at 45 degrees. The models were supported by a periodontal ligament and fixed in 3 axes ($x=y=z=0$). The von Mises stress (VMS) was calculated.

Results. All models exhibited VMS concentrations at the loading area and were distributed along the proximal surfaces of the root. The GFP exhibited a homogeneous stress distribution, and similar VMS distributions were observed in all of the reconstructive techniques.

Conclusions. Similar stress distributions were observed in the endodontically treated teeth, regardless of root weakness and the reconstructive technique for the radicular walls. (*J Prosthet Dent* 2015;114:383-389)

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Clinical Implications

Finite element analysis revealed that it is possible to preserve weakened teeth that have been endodontically treated and restored with posts when the restorative materials exhibit mechanical properties similar to tooth structure and when an appropriate bonding system is used.

Poor adaptation compromises the restoration of weakened or flared roots with GFPs.¹¹ Consequently, a thick layer of resin cement causes post debonding, particularly in the coronal region.¹¹ Thus, several materials and techniques have been suggested for reconstructing the radicular walls, including composite resin,^{8,12-15} glass ionomer,¹⁶ and accessory fiber posts.^{14,17-20} Additionally, the following techniques have been described: direct anatomic posts,¹¹ where the fiber post is customized with a layer of light-polymerized composite resin; light-transmitting posts,^{21,22} where weakened roots are restored with composite resin and light-transmitting plastic posts before cementation of the intracanal post; and accessory posts,²⁰ where a main post and an accessory post with a reduced diameter are cemented with resin cement.

In general, any technique for radicular reconstruction in endodontically treated teeth aims to improve post adaptation, reduce cement thickness, enhance retention, prevent adhesive failure, and increase mechanical resistance. Despite the advances in prefabricated posts and restorative materials, the best approach for the restoration of severely damaged teeth remains uncertain.²³

Many conclusions about the biomechanical performance of teeth restored with GFPs have been based on static experiments. Although these findings provide primary evidence, additional experiments should be conducted to simulate the clinical scenario, including dynamic loading⁴ and biomechanical stress distribution along the radicular dentin.²⁴⁻²⁷

The aim of this 3-dimensional (3D) finite element analysis (FEA) was to evaluate the stress distributions of endodontically treated teeth subjected to different reconstructive techniques to identify the weakened areas of the radicular wall. The null hypothesis was that no difference would be found between the techniques for the reconstruction of the radicular walls of weakened endodontically treated teeth or between teeth with and without weakened roots.

MATERIAL AND METHODS

The 3D geometry of an unrestored maxillary canine and its characteristics were scanned via computed

microtomography (μ CT) (SkyScan 1174v2; Bruker microCT). A total of 994 transverse sections in 0.5 mm slices were obtained along the tooth. The study was approved by the research ethics committee of the University of Ribeirão Preto (CAAE 22249113.7.0000.5498). The μ CT data were imported into ScanIP software (Simpleware 4.1; Simpleware Ltd) for segmentation and fabrication of the masks based on the pixel density. Next, all structures (enamel, coronal and radicular dentin, pulp, and the periodontal ligament) were included in the 3D solid model. The periodontal ligament was obtained by Boolean operations and was 0.2 mm thick.²⁸

Based on this primary model, 4 models were fabricated according to the following groups: GNW (control), an endodontically treated root restored with a GFP; GW, a weakened endodontically treated root restored with a GFP without reconstruction of the internal radicular wall; GDA, a weakened endodontically treated root restored with a direct anatomic GFP; and GIA, a weakened endodontically treated root restored with an indirect anatomic GFP.

Software (Solidworks 2007; SolidWorks Corp) was used to fabricate computer-aided design structures to simulate the clinical scenarios of endodontic treatment, prosthetic rehabilitation, root enlargement, and reconstruction of the radicular walls. Next, all images were imported (ScanCAD v4.1; Simpleware Ltd) for mounting and fabricating the models using Boolean addition and subtraction operations.

The root canal was 15.0 mm in length and was considered endodontically treated in all models. The working length was established as 1.0 mm from the apical foramen. The model simulated instrumentation of the root canal up to file #50 and obturation with gutta-percha. Additionally, the restoration with a prefabricated GFP 1.5 mm in diameter and 14.0 mm in length was also simulated while maintaining 4.0 mm of gutta percha in the apical region. Root weakness was simulated in the GW, GDA, and GIA models based on a root enlargement of 10.0 mm in length and 1.8 mm in diameter in the apical region, 5.0 mm in the mesiodistal direction, and 3.0 mm in the buccolingual direction. The remaining radicular wall in the cervical region was 1.0 mm thick²⁰ (Fig. 1). Regardless of the reconstructive technique of the internal radicular wall, a 50- μ m thick cementation layer²⁹ was simulated in all models, with the exception of the GW model, in which the total thickness of the weakened area was simulated.

In all models, a composite resin core was simulated based on reductions of a sound tooth of 1.0 mm on the buccal and 2.0 mm on the incisal surfaces.²⁹ A metal ceramic crown was also designed and included a metallic coping 0.5 mm thick and a feldspathic veneering 0.5 mm thick on the buccal and lingual surfaces and 1.5 mm on the incisal surface.²⁹



Figure 1. Representation of weakened root.

In the GDA group, the composite resin was inserted by using the direct anatomic technique, and the indirect technique was used for the GIA group. In the direct anatomic technique, a layer of light-polymerizing composite resin was applied on the GFP surface to reproduce the root canal anatomy, and the GFP-composite resin assembly was cemented into the canal. In the indirect anatomic technique, the internal radicular wall was first reconstructed with composite resin so that the GFP was cemented into the restored canal (Fig. 2).

The mechanical properties of the materials (elasticity moduli [E] and the Poisson ratios [ν]) shown in Table 1 were inserted in the Simpleware software by using the ScanFE system according to data reported elsewhere.³⁰⁻³⁵ All materials were assumed to be homogeneous, isotropic, and linearly elastic, with the exception of the GFP, which was characterized as orthotropic, homogeneous, and linearly elastic.³⁶ The GFP was assumed to be orthotropic because the mechanical properties vary along the fiber direction (x) and the normal directions (y and z). Thus, the mechanical characteristics of the materials were represented by the elasticity moduli in the 3 directions (E_x , E_y , E_z) and the Poisson ratios (ν_{xz} , ν_{yz}) and shear moduli (G_{xz} , G_{yz}) in the orthogonal planes (xy, xz, and yz) (Table 2).³⁶ All structures of the models were considered to be perfectly joined.^{30,37}

The finite element mesh was fabricated using linear tetrahedral elements C3D4, and the models presented specific nodes and elements numbers of 234 824 nodes and 1 243 290 elements for the GNW, 212 861 nodes and 1 111 373 elements for the GW, 392 069 nodes and 2 157 784 elements for the GDA, and 273 597 nodes and

1 449 942 elements for the GIA models. A study of the convergence of the finite element models was conducted to assess the mesh quality. The convergence analysis confirmed accuracies of 95% regarding the densities of the finite element meshes in all models. Mesh refining was based on a convergence analysis of 6%.³⁸

The finite element mesh of each model was imported with a finite element software (Abaqus 6.10-EF1; Dassault Systèmes Simulus Co) to simulate a static occlusal loading of 180 N on the lingual surface of the incisal third of the tooth at 45 degrees in all models.²⁹ For the boundary condition, the nodes of the periodontal ligament were fixed in the 3 axes in the Cartesian plane (x, y, and z) assuming values of $x=y=z=0$ (Fig. 3).

The qualitative results are presented as stress maps (the hot color represents the highest stress values, and the cold colors represent the lowest stress values), while the quantitative results are presented as von Mises stress (VMS) values.

RESULTS

The analyses of the stress distributions were conducted according to von Mises criteria. Considering the whole model, including all structures (ceramic, metallic coping, composite resin core, GFP, resin cement, radicular dentin, periodontal ligament, and composite resin structures) in each model, the highest stress value and concentration were observed at the loading point in ceramic veneer. Although additional stress concentrations were found along the proximal surface of the radicular dentin and in the apical thirds of the roots in all models, these stresses were lower than those observed in ceramic veneer (Table 3, Fig. 4).

In all models, homogeneous stress distributions and VMS values were observed along the GFP, periodontal ligament, radicular dentin, core, and composite resin. Additionally, stress concentrations were also present in the buccodistal regions of the apical areas of the cement in all models regardless of the cement thickness and configuration (Fig. 4). The GDA and GIA groups with the composite resin exhibited similar VMS stress distributions (Fig. 4).

DISCUSSION

The reconstruction of weakened endodontically treated teeth remains a challenge for restorative dentistry because the crown is typically extensively damaged. The results of the present study confirmed the null hypothesis because no differences in the radicular stress distributions were found between the reconstructive techniques for the radicular walls of weakened endodontically treated teeth. Additionally, no differences in stress magnitudes or VMSs was observed, and these parameters influence

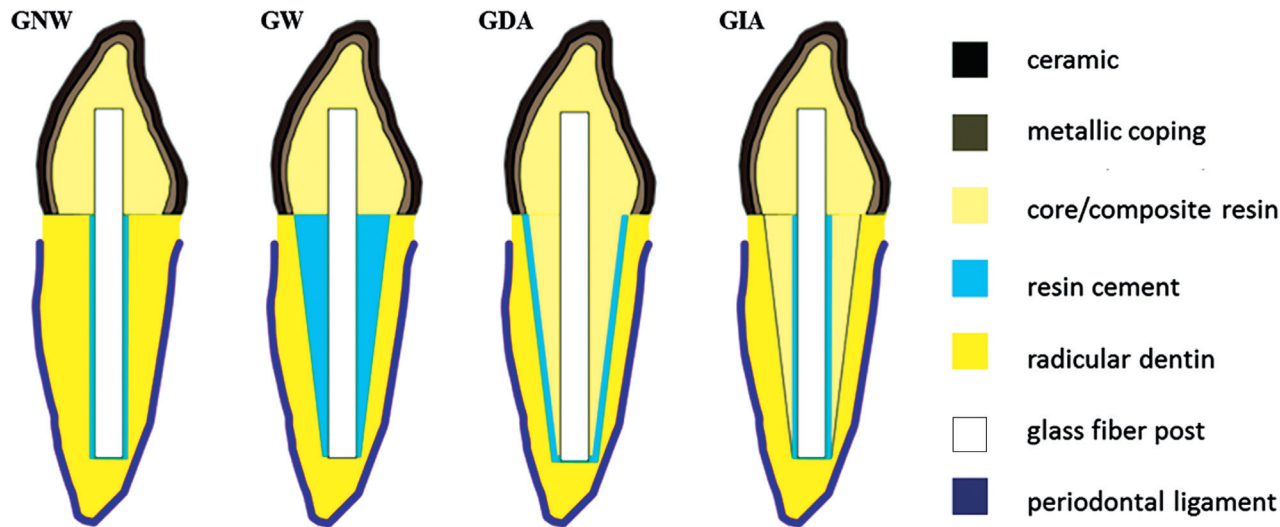


Figure 2. Different groups with different reconstructive techniques and intracanal posts.

Table 1. Mechanical properties of materials simulated

Material	E (GPa)	ν	Reference
Resin cement	18.6	0.28	30
Ceramic	69	0.30	31
Metallic coping	200	0.33	31
Composite resin	12	0.30	33
Dentin	18.6	0.31	34
Periodontal ligament	6.89×10^{-5}	0.45	34
Gutta percha	1.4×10^{-1}	0.45	35

the fracture strengths of teeth with and without weakened roots.

The highest VMS concentrations were found in the loading areas of the ceramic veneers in all models, likely as a result of the higher elasticity modulus of the ceramic compared to the other materials. Thus, the ceramic was able to absorb the stress and transfer it at lower intensity to the adjacent structures and to the proximal and apical regions. In this sense, correct occlusal adjustment is important for equilibrating occlusion.³⁹

Stress concentration in the proximal surface is relevant because the majority of the fractures occur in this area.²⁵ Additionally, stress that is generated in the post in the buccolingual direction causes vertical fractures of the roots.²⁶

The stress concentration in the apical third of the radicular dentin probably occurred as a result of yield stress concentration in the radicular region opposite to the loading point. This characteristic of stress concentration significantly increases when angled load is applied as a result of material rigidity and tooth bending. Furthermore, the root taper and post characteristics also lead to increased stress in the apical third.⁴ Prefabricated posts used for the restoration of endodontically treated teeth with severe crown destruction can be classified

Table 2. Orthotropic mechanical properties of glass fiber post

E (GPa)	ν	Shear modulus (GPa)	Reference
X=37	Xy=0.27	Gxy=3.1	36
Y=9.5	Xz=0.34	Gxz=3.5	
Z=9.5	Yz=0.27	Gyz=3.1	

according to their configuration,^{5,6} surface,^{5,6} and material.⁷ The post system should be carefully selected to reduce the risk to fracture and preserve the root structure in case of failure.² Thus, in the present study, the selections of post material and configuration were based on scientific evidence due to better stress distribution,⁴⁰ a lower risk to root fracture,²⁴ and a greater possibility (30%) of restoration when root fracture occurs.¹⁹ Furthermore, some studies have demonstrated that the parallel walls the GFPs reduce stress in radicular dentin.³⁷

The VMS values in the apical third were lower than those in the ceramic veneer. Although this maximum stress was below the flexural strength of radicular dentin, the risk for failure should be considered because repetitive loading might cause fatigue and stress accumulation.²⁷ Long-term high-stress concentrations might cause microgaps at the material/dentin interface and result in bacterial contamination and periapical lesions.⁴¹

The restoration with GFPs provided homogeneous stress distributions, as previously shown by Coelho et al⁴⁰ and Veríssimo et al.²⁵ The low elasticity modulus of the GFP allows for a mechanical performance of the restored tooth that is similar to that of a natural tooth. When a natural tooth is subjected to eccentric loading, the stress is higher at the external surface and decreases to zero toward the transverse section.⁴ Thus, the risk of failure is reduced at the post/cement interface as a consequence of



Figure 3. Three-dimensional virtual image representing boundary conditions, loading, and finite element mesh. Yellow arrow indicates loading area, and periodontal ligament shows boundary conditions of model.

the low stress values and the risk fracture of the core is elevated.⁴²

Regardless of the reconstructive technique of the radicular wall, the VMS distributions and magnitudes observed in the radicular dentins of the experimental models (GW and GIA) were similar to those observed in the nonweakened model (GNW), which indicates that the reconstructive techniques provided appropriate stress distributions along the materials and roots. Zogheib et al¹⁸ evaluated the compressive strengths of nonvital human teeth subjected to 3 reconstructive protocols of the radicular dentin (indirect anatomic GFPs, accessory posts, and direct anatomic GFPs) and found that no technique improved root strength.

The GW technique is clinically simple because it only requires the cementation of the GFP with resin cement without previous reconstruction of the radicular walls. However, failures in cementation might occur due to misfits and poor adhesion of the post as a consequence of a thick cement layer, the formation of air bubbles, and salivary contamination.⁴³ Furthermore, the insertion of a thick layer of cement causes high levels of stress at the adhesive interface due to polymerization shrinkage¹⁹ and poor polymerization in the apical region.^{19,22}

Among the techniques for the reconstruction of the radicular walls, the direct anatomic post (GDA) is a simple approach that allows for the adaptation of the GFP to the root canal²⁰ with a thinner cementation layer compared with the GW model. In contrast, although the

Table 3. Maximum von Mises stress (σ_{VM}) for each structure in each model (MPa)

Structure	Group			
	GNW	GW	GDA	GIA
Ceramic	2.5500	3.3000	4.3000	2.8000
Cement	0.0710	0.0780	0.0940	0.2000
Metallic coping	0.0900	0.0930	0.2200	0.0490
Gutta percha	0.0010	0.0010	0.0010	0.0010
Periodontal ligament	0.0040	0.0040	0.0040	0.0044
Core	0.0130	0.0230	0.0230	0.0190
Glass fiber post	0.0001	0.0001	0.0003	0.0003
Radicular dentin	0.1400	0.1300	0.1300	0.1800
Composite resin	-	-	0.0760	0.0440

GFP, glass fiber post; GNW (control), nonweakened root restored with GFP; GW, weakened root restored with GFP; GDA, weakened root restored with direct anatomic GFP; GIA, weakened root restored with indirect anatomic GFP.

indirect anatomic post technique (GIA) exhibited results similar to those of the GDA, this method is clinically dependent on light transmission. Although the light-transmitting post provides transmission of up to 10 mm in length, some studies have shown that transmission is lower than 40% of the light incidence,¹⁵ which results in reduced hardness of the composite resin in the apical region compared with the middle and cervical thirds.²²

FEA is based on a numerical method that evaluates a complex mechanical problem and identifies the regions of stress concentration that are prone to failure.³⁴ However, this method does not predict the fracture pattern or its progression along the materials.³⁶ For problem solving, the mechanical characteristics of the materials (the elasticity modulus and the Poisson ratio) must be added to the software system so that the software can identify the different materials. In this sense, the slight differences in VMS magnitudes and values between the teeth with and without weakened roots and the reconstructive techniques applied to the radicular wall might have resulted from methodologic limitations.

Radicular dentin and resin cement exhibit similar elasticity moduli (18.6 GPa) that are close to the modulus of the composite resin (12 GPa) that is used to fabricate the core and reconstruct the radicular walls.^{30,34} Thus, the finite element software assumed that the structures were similar, which resulted in similar performances of the nonweakened and weakened models (GNW and GW) relative to the experimental (GDA and GIA) and control (GNW) groups. Although the incompatibility of the elasticity modulus might lead to interface displacement,⁴⁴ the thickness of the radicular wall is important for avoiding tooth fracture.³ In vitro studies have shown that some reconstructive techniques for weakened roots improve the fracture strength.^{14,15}

Another limitation of this study was the assumption that the materials were isotropic, homogeneous, and linearly elastic, with the exception of the GFP, which was represented as orthotropic. Thus, the virtual simulation

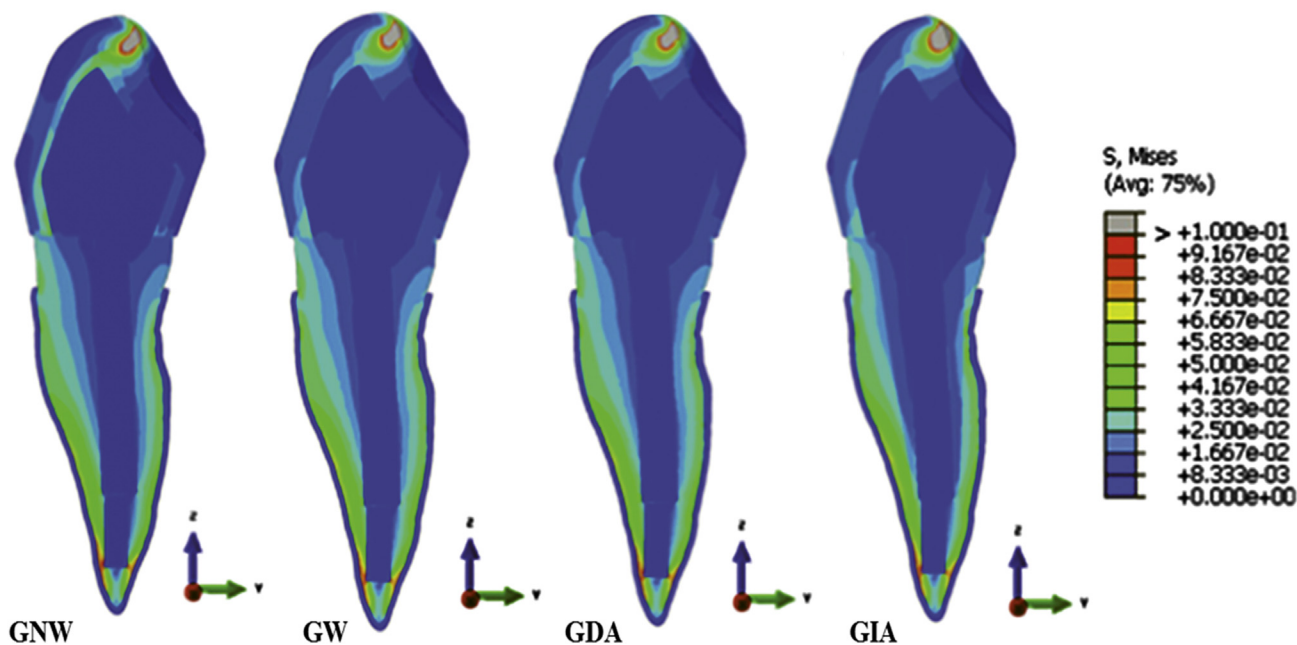


Figure 4. General von Mises stress (VMH) distribution of each model. Colors indicate levels of stress from low (dark blue) to high (red).

did not reproduce the heterogeneity of the actual scenario because the biologic tissues (enamel, dentin, periodontal ligament, and bone tissue) are anisotropic and heterogeneous.

The method of stress evaluation also influenced the results. In the present study, the VMS was selected for analysis of the results. According to Eraslan et al,²⁸ the VMS represents tensile, compressive, and shear stress and a combination of different stress types. The VMS is widely used as an indicator of damage predictability. Considering that the compressive strength of dentin is higher than its tensile strength, the VMS can be compared with the tensile strength of dentin in evaluations of the risk of fracture.³⁷

Within the limitations of a computational simulation using FEA, in vitro studies of the fracture areas are required for the appropriate selection of reconstructive techniques for the internal radicular walls. Extension of the present findings to clinical scenarios suggests that the use of restorative materials with mechanical properties similar to those of natural teeth and the selection of appropriate bonding systems is a successful approach for reproducing dental structures in weakened endodontically treated teeth.

CONCLUSIONS

In the present study, similar VMS values and distributions were observed in the nonweakened and weakened roots after the use of different reconstructive protocols for the radicular walls of endodontically treated teeth. Considering the limitations of FEA, additional in vitro studies are

required to evaluate the fracture areas in order to predict the best reconstructive technique for radicular walls.

REFERENCES

- Joshi S, Mukherjee A, Kheur M, Mehta A. Mechanical performance of endodontically treated teeth. *Finite Elem Anal Des* 2001;37:587-601.
- Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. *J Endod* 1989;15:512-6.
- Assif D, Gorfil C. Biomechanical considerations in restoring endodontically treated teeth. *J Prosthet Dent* 1994;71:565-7.
- Kishen A. Mechanisms and risk factors for fracture predilection in endodontically treated teeth. *Endod Top* 2006;13:57-83.
- Caputo AA, Standlee JP. Pins and posts-why, when and how. *Dent Clin North Am* 1976;20:299-311.
- Sivers JE, Johnson WT. Restoration of endodontically treated teeth. *Dent Clin North Am* 1992;36:631-50.
- Huysmans MC, Peters M, Plasschaert AJ. The restoration of endodontically treated teeth. A literature study of the mechanical behavior of post-core restorations. *Ned Tijdschr Tandheelk* 1993;100:308-11.
- Saupe WA, Gluskin AH, Radeke RA Jr. A comparative study of fracture resistance between morphologic dowel and cores and a resin-reinforced dowel system in the intraradicular restoration of structurally compromised roots. *Quintessence Int* 1996;27:483-91.
- Barjau-Escribano A, Sancho-Bru JL, Forner-Navarro L, Rodríguez-Cervantes PJ, Pérez-González A. Influence of prefabricated post material on restored teeth: fracture strength and stress distribution. *Oper Dent* 2006;31:47-54.
- Ferrari M, Vichi A, Garcia-Godoy F. Clinical evaluation of fiber-reinforced epoxy resin posts and cast post and cores. *Am J Dent* 2000;13:15B-8B.
- Grandini S, Goracci C, Monticelli F, Borracchini A, Ferrari M. SEM evaluation of the cement layer thickness after luting two different posts. *J Adhes Dent* 2005;7:235-40.
- Lui JL. Composite resin reinforcement of flared canals using light transmitting plastic posts. *Quintessence Int* 1994;25:313-9.
- Marchi GM, Paulillo LA, Pimenta LA, De Lima FA. Effect of different filling materials in combination with intraradicular posts on the resistance to fracture of weakened roots. *J Oral Rehabil* 2003;30:623-9.
- Silva GR, Santos-Filho PC, Simamoto-Júnior PC, Martins LR, Mota AS, Soares CJ. Effect of post type and restorative techniques on the strain and fracture resistance of flared incisors roots. *Braz Dent J* 2011;22:230-7.
- Zogheib LV, Pereira JR, do Valle AL, de Oliveira JA, Pegoraro LF. Fracture resistance of weakened roots restored with composite resin and glass fiber post. *Braz Dent J* 2008;19:329-33.

16. Lui JL. Cement reinforcement of a weakened endodontically treated root: a case report. *Quintessence Int* 1992;23:533-8.
17. Naumann M, Preuss A, Frankenberger R. Load capability of excessively flared teeth restored with fiber-reinforced composite posts and all-ceramic crowns. *Oper Dent* 2006;31:699-704.
18. Zogheib LV, Saavedra Gde S, Cardoso PE, Valera MC, Araújo MA. Resistance to compression of weakened roots subjected to different root reconstruction protocols. *J Appl Oral Sci* 2011;19:648-54.
19. Bonfante G, Kaizer OB, Pegoraro LF, do Valle AL. Fracture strength of teeth with flared root canals restored with glass fibre posts. *Int Dent J* 2007;57:153-60.
20. Clavijo VG, Reis JM, Kabbach W, Silva AL, Oliveira Junior OB, Andrade MF. Fracture strength of flared bovine roots restored with different intraradicular posts. *J Appl Oral Sci* 2009;17:574-8.
21. Solomon CS, Osman YI. Aesthetic restoration of the compromised root: a case report. *SADJ* 2003;58:370, 373-6, 381.
22. Teixeira CS, Silva-Sousa YT, Sousa-Neto MD. Effects of light exposure time on composite resin hardness after root reinforcement using translucent fibre post. *J Dent* 2008;36:520-8.
23. Marchi GM, Mitsui FH, Cavalcanti AN. Effect of remaining dentin structure and thermal-mechanical aging on the fracture resistance of bovine roots with different post and core systems. *Int Endod J* 2008;41:969-76.
24. Romeed SA, Dunne SM. Stress analysis of different post-luting systems: a three-dimensional finite element analysis. *Aust Dent J* 2013;58:82-8.
25. Veríssimo C, Simamoto Júnior PC, Soares CJ, Noritomi PY, Santos-Filho PC. Effect of the crown, post, and remaining coronal dentin on the biomechanical behavior of endodontically treated maxillary central incisors. *J Prosthet Dent* 2014;111:234-46.
26. Lertchirakarn V, Palamara JE, Messer HH. Patterns of vertical root fracture: factors affecting stress distribution in the root canal. *J Endod* 2003;29:523-8.
27. Nalla RK, Kinney JH, Marshall SJ, Ritchie RO. On the in vitro fatigue behavior of human dentin: effect of mean stress. *J Dent Res* 2004;83:211-5.
28. Eraslan O, Aykent F, Yücel MT, Akman S. The finite element analysis of the effect ferrule height on stress distribution at post-and-core-restored all-ceramic anterior crowns. *Clin Oral Invest* 2009;13:223-7.
29. Watanabe MU, Anchieta RB, Rocha EP, Kina S, Almeida EO, Freitas AC Jr, et al. Influence of crown ferrule heights and dowel material selection on the mechanical behavior of root-filled teeth: a finite element analysis. *J Prosthodont* 2012;21:304-11.
30. Sorrentino R, Aversa R, Ferro V, Auriemma T, Zarone F, Ferrari M, et al. Three-dimensional finite element analysis of strain and stress distributions in endodontically treated maxillary central incisors restored with different post, core and crown materials. *Dent Mater* 2007;23:983-93.
31. Dejak B, Mlotkowski A. The influence of ferrule effect and length of cast and FRG posts on the stresses in anterior teeth. *Dent Mater* 2013;29:e227-37.
32. Pierrisnard L, Bohin F, Renault P, Barquins M. Corono-radicular reconstruction of pulpless teeth: a mechanical study using finite element analysis. *J Prosthet Dent* 2002;88:442-8.
33. Ausiello P, Apicella A, Davidson CL. Effect of adhesive layer properties on stress distribution in composite restorations-a 3D finite element analysis. *Dent Mater* 2002;18:295-303.
34. Reinhardt RA, Krejci RF, Pao YC, Stannard JG. Dentin stresses in post reconstructed teeth with diminishing bone support. *J Dent Res* 1983;62:1002-8.
35. Friedman CM, Sandrik JL, Heuer MA, Rapp GW. Composition and mechanical properties of gutta-percha endodontic points. *J Dent Res* 1975;54:921-5.
36. 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;21:709-15.
37. Asmussen E, Peutzfeldt A, Sahafi A. Finite element analysis of stresses in endodontically treated, dowel-restored teeth. *J Prosthet Dent* 2005;94:321-9.
38. Pessoa RS, Muraru L, Júnior EM, Vaz LG, Sloten JV, Duyck J, Jaecques SV. Influence of implant connection type on the biomechanical environment of immediately placed implants-CT-based nonlinear, three-dimensional finite element analysis. *Clin Implant Dent Relat Res* 2010;12:219-34.
39. Gomes ÉA, Barão VA, Rocha EP, de Almeida ÉO, Assunção WG. Effect of metal-ceramic or all-ceramic superstructure materials on stress distribution in a single implant-supported prosthesis: three-dimensional finite element analysis. *Int J Oral Maxillofac Implants* 2011;26:1202-9.
40. Coelho CS, Biffi JC, Silva GR, Abrahão A, Campos RE, Soares CJ. Finite element analysis of weakened roots restored with composite resin and posts. *Dent Mater J* 2009;28:671-8.
41. Sterzenbach G, Franke A, Naumann M. Rigid versus flexible dentin-like endodontic posts: clinical testing of a biomechanical concept seven-year results of a randomized controlled clinical pilot trial on endodontically treated abutment teeth with severe hard tissue loss. *J Endod* 2012;38:1557-63.
42. Santos AF, Meira JB, Tanaka CB, Xavier TA, Ballester RY, Lima RG, et al. Can fiber posts increase root stresses and reduce fracture? *J Dent Res* 2010;89:587-91.
43. Grandini S, Sapio S, Simonetti M. Use of anatomic post and core for reconstructing an endodontically treated tooth: a case report. *J Adhes Dent* 2003;5:243-7.
44. Ona M, Wakabayashi N, Yamazaki T, Takaichi A, Igarashi Y. The influence of elastic modulus mismatch between tooth and post and core restorations on root fracture. *Int Endod J* 2013;46:47-52.

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