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RESEARCH AND EDUCATION

Influence of remaining tooth structure and restorative material type on stress distribution in endodontically treated maxillary premolars: A finite element analysis

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ABSTRACT

Statement of problem. How tooth preparation and material type affect the stress distribution of endodontically treated teeth restored with endocrowns remains unclear.

Purpose. The purpose of this finite element (FE) study was to determine the influence of the quantity of remaining dental tissues and material type on stress distribution in endodontically treated maxillary premolars using 3-dimensional FE analysis.

Material and methods. Five 3-dimensional FE models were constructed on the basis of the restorative methods used and the quantity of preserved tooth tissues: a sound maxillary premolar, an endodontically treated maxillary premolar restored with composite resin, and endodontically treated maxillary premolars restored with endocrowns with thicknesses of 1.0 mm, 2.0 mm, and 3.0 mm. The following endocrown materials were used: Paradigm MZ100, IPS Empress, IPS e.max CAD, and In-Ceram Zirconia. Stress distributions were analyzed under vertical and oblique loads.

Results. As the quantity of preserved dental tissues increased, the von Mises stress in dentin decreased, and the peak von Mises strain value of the cement layer increased. When the elastic modulus of the endocrown material increased, the von Mises stress in endocrown and dentin increased, and the peak von Mises strain value of the cement layer decreased.

Conclusions. Although the conservative preparation of teeth for endocrowns is likely to protect the residual tooth structure, it may cause future cohesive bonding failure. An increase in the elastic modulus of the material may benefit the durability of bonding between the endocrown and the abutment tooth; however, it may cause fracture of the residual tooth structure. (J Prosthet Dent 2017;117:646-655)

Clinical experience and evidence-based dentistry suggest that endodontically treated teeth should be restored with complete crowns, which rely on extracoronal retention to protect the residual tooth structure.[1,2] If the coronal portion of the tooth is severely damaged and a complete crown lacks retention, restorations that mainly rely on intraradicular retention, such as a post-and-core and crown, are recommended. Previous studies have shown that molars restored with complete crowns or post-and-cores and crowns have satisfactory long-term survival rates.[3,4] The smaller crowns and pulp chambers of premolars result in weaker retention of foundation restorations after tooth preparation for a complete crown.[5] Therefore, an endodontically treated premolar should usually be restored using a post-and-core and crown.[5] However, because of the oval root canals in premolars, more dentin is removed during preparation for a circular prefabricated post, and root perforation may occur.[6,7]

An endocrown is a restoration comprising a crown and a central retainer in the pulp chamber.[8] With the development of bonding techniques, improved restorative materials, and computer-aided design and computer-aided manufacturing (CAD-CAM), endocrowns can now provide sufficient stability and retention and can resist fracture under normal masticatory forces.[9]

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Clinical Implications

An endocrown is a feasible approach for restoring endodontically treated maxillary premolars when the shoulder finish line of the restoration is above the cementoenamel junction and conservative treatment is recommended in tooth preparation. Materials with an elastic modulus similar to that of enamel are suitable for fabricating endocrowns.

Clinical studies reported no significant difference in survival rates between the molars restored with endocrowns versus those restored with traditional techniques.[10] However, the clinical performance of endocrown-restored premolars is inferior to that of molars restored with endocrowns.[10,11] Cohesive failure of bonding is the main reason for failure in premolars restored with endocrowns.[10]

The clinical fracture of endocrown-restored teeth has also been reported.[12] In order to estimate the feasibility of restoring endodontically treated premolars with endocrowns, their stress distributions must be analyzed, particularly in terms of the pattern of strain distribution in the cement layer. Previous studies have suggested that the restorative methods used and the quantity of remaining tooth structure influence the fracture resistance of premolars restored with composite resin or complete crowns.[13-15] To date, little information is available on the influence of the height of the dentin wall around the pulp chamber on the stress distribution of endocrown-restored premolars. Additionally, a range of new materials, with elastic moduli ranging from 10 GPa to 250 GPa, is currently available. The restorative material type has been reported to affect the fatigue resistance and microleakage of restored premolars.[16-18] However, the influence of the elastic modulus of the material on stress distributions in endocrown-restored teeth remains unclear. As finite element (FE) analysis is widely used in dental biomechanical studies,[19,20] the purpose of the present study was to evaluate the influence of clinical and anatomic factors on stress distribution in maxillary premolars using FE analysis.

MATERIAL AND METHODS

Five individual FE models were created (Fig. 1A). Model S comprised a sound maxillary premolar and acted as the negative control. Model R comprised an endodontically treated maxillary premolar (ETP) restored with composite resin and acted as the positive control. Models E1, E2, and E3 comprised an ETP restored with endocrowns with thicknesses of 1.0 mm, 2.0 mm, and 3.0 mm.

An intact maxillary premolar extracted for orthodontic reasons was scanned using microcomputed tomography (eXplore Locus SP; GE Healthcare). The obtained data were converted to Digital Imaging and Communications in Medicine (DICOM) format and imported into an interactive medical image control system (Mimics 15.0; Materialise). Point clouds were divided into 3 portions (the enamel, dentin, and pulp) according to different pixel densities. The contour of each portion was generated using software (Geomagic Studio; Geomagic Inc). A 3-dimensional solid model was then reconstructed with computer-aided design software (CATIA V5R20; Dassault Systèmes). A 10×14×16 mm cuboid was generated to represent the alveolar bone and was connected to the model by a 0.2 mm thick periodontal ligament. The reconstructed model was imported into FE software (Ansys, v16.0; Swanson Analysis Inc) and was considered as model S, the negative control.

To simulate an ETP restored with composite resin, model R was created as follows. The pulp in model S was divided into 2 portions by a horizontal plane placed at the lowest point of the cementoenamel junction (CEJ). The pulp in the root canal was replaced by gutta percha and a 0.5 mm flowable resin; composite resin (Filtek P60; 3M ESPE) was used to fill the pulp chamber and the access cavity, which was covered with a 0.12 mm adhesive layer.

The influence of the quantity of remaining dental tissues on the stress distribution in ETPs that had been restored with endocrowns was investigated with 3 FE models with different endocrown thicknesses. The total height (H) of the endocrown was defined as the vertical distance between the highest point of the buccal cusp and the lowest point of the intaglio of the endocrown located in the horizontal plane at the lowest point of the CEJ on the buccal side; therefore, the total height of the endocrown was fixed at 9.0 mm. The thickness (T) of the endocrown was defined as the vertical distance between the lowest point of the occlusal grooves and the horizontal plane at the highest point of the central retainer. The vertical distance between the lowest point of the occlusal grooves and the horizontal plane at the highest point of the CEJ on the distal side was about 3.0 mm. Three FE models were created (Fig. 1B): model E1 with an endocrown thickness of 1.0 mm (T1) and height of 5.5 mm, model E2 with a thickness of 2.0 mm (T2) with more tooth structure removed, and model E3 with a thickness of 3.0 mm (T3) and the shoulder finish line at the CEJ.

The luting material was a resin-based cement (Multilink Automix; Ivoclar Vivadent AG), and its thickness was 0.12 mm. As the bond strength between the luting material and enamel differs from that between the luting material and dentin, the risk of cementing failure between cement–enamel and cement–dentin may be different. Thus, the cement layer was subdivided into 2 portions: the portion between the endocrown and the enamel and the portion between the endocrown and

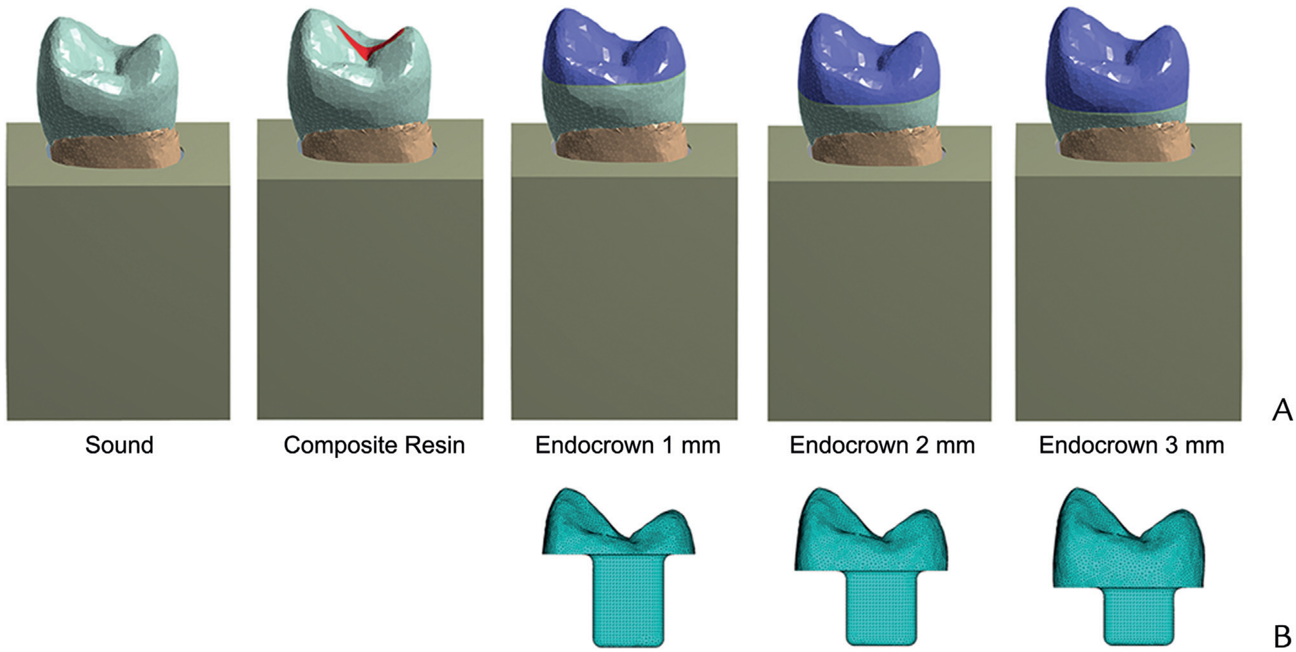

Figure 1. A, Finite element models of models S, R, E1, E2, and E3. B, Endocrown thicknesses for models E1, E2, and E3.

dentin. Flowable resin (2 mm thick) was then placed between the cement layer and the gutta percha. A lithium disilicate–reinforced glass-ceramic (IPS e.max CAD; Ivoclar Vivadent AG) was chosen as the endocrown material.

To study the influence of the material used for the endocrown on stress distribution, models E1, E2, and E3 were further analyzed using composite resin (Paradigm MZ100; 3M ESPE), high-leucite content ceramic (IPS Empress; Ivoclar Vivadent AG), and zirconia ceramic (In-Ceram Zirconia; Vita Zahnfabrik). The elastic moduli of these materials range from 16 GPa to 240 GPa (Table 1). All models were assumed to have perfect bonding. The tissues and materials in this study were considered homogeneous, isotropic, and with linear elasticity (Table 1).

Because the load direction could influence the stress/strain distribution of teeth,[31,32] 2 conditions were considered. In the first, a vertical load of 200 N[33,34] was applied to the premolar with an 8 mm diameter stainless steel ball. The force was decomposed into 2 component forces and separately applied to the buccal and palatal cusp incline surfaces; the resultant force was 200 N and parallel to the long axis of tooth. Second, an oblique load of 200 N, at 30 degrees to the long axis of the tooth, was applied to the palatal cusp incline surface. The mesial, distal, and bottom surfaces of the bone block were fixed in all directions.

All models were meshed using software (HyperMesh; Altair Engineering). To control the mesh quality, the indexes, Tetra Collapse and Jacobian, were assessed, and the unqualified elements were modified. The data were reimported into the software (Ansys; Swanson Analysis Inc). The von Mises stress (VMS) distribution in dental tissues and restorations and the von Mises strain distribution of the cement layer were analyzed, and the peak values of the maximum tensile/shear stress in the different portions of the cement layer were calculated.

Table 1. Material properties[a]

Material	Elastic Modulus (GPa)	Poisson Ratio
Enamel[21]	84.10	0.33
Dentin[21]	18.60	0.31
Pulp[22]	0.0068	0.45
Periodontal ligament[23]	0.07	0.45
Alveolar bone[23]	1.37	0.30
Glass ionomer cement[24]	22.00	0.35
Filtek P60[25]	19.70	0.32
Multilink Automix[26]	5.00	0.29
Flowable resin[27]	5.30	0.28
Gutta percha[22]	0.07	0.40
Paradigm MZ100[21]	16.00	0.24
IPS Empress[21]	65.00	0.19
IPS e.max CAD[28,29]	100.00	0.20
In-Ceram Zirconia[30]	242.00	0.26

[a]Filtek P60 restorative system and Paradigm MZ100 mill bloc manufactured by 3M ESPE. IPS Empress and IPS e.max CAD restorative systems and Multilink Automix luting system manufactured by Ivoclar Vivadent AG. In-Ceram Zirconia restorative system manufactured by Vita Zahnfabrik.

RESULTS

The VMS in model S under a vertical load was concentrated in the enamel and dentin (Fig. 2). The VMS in the

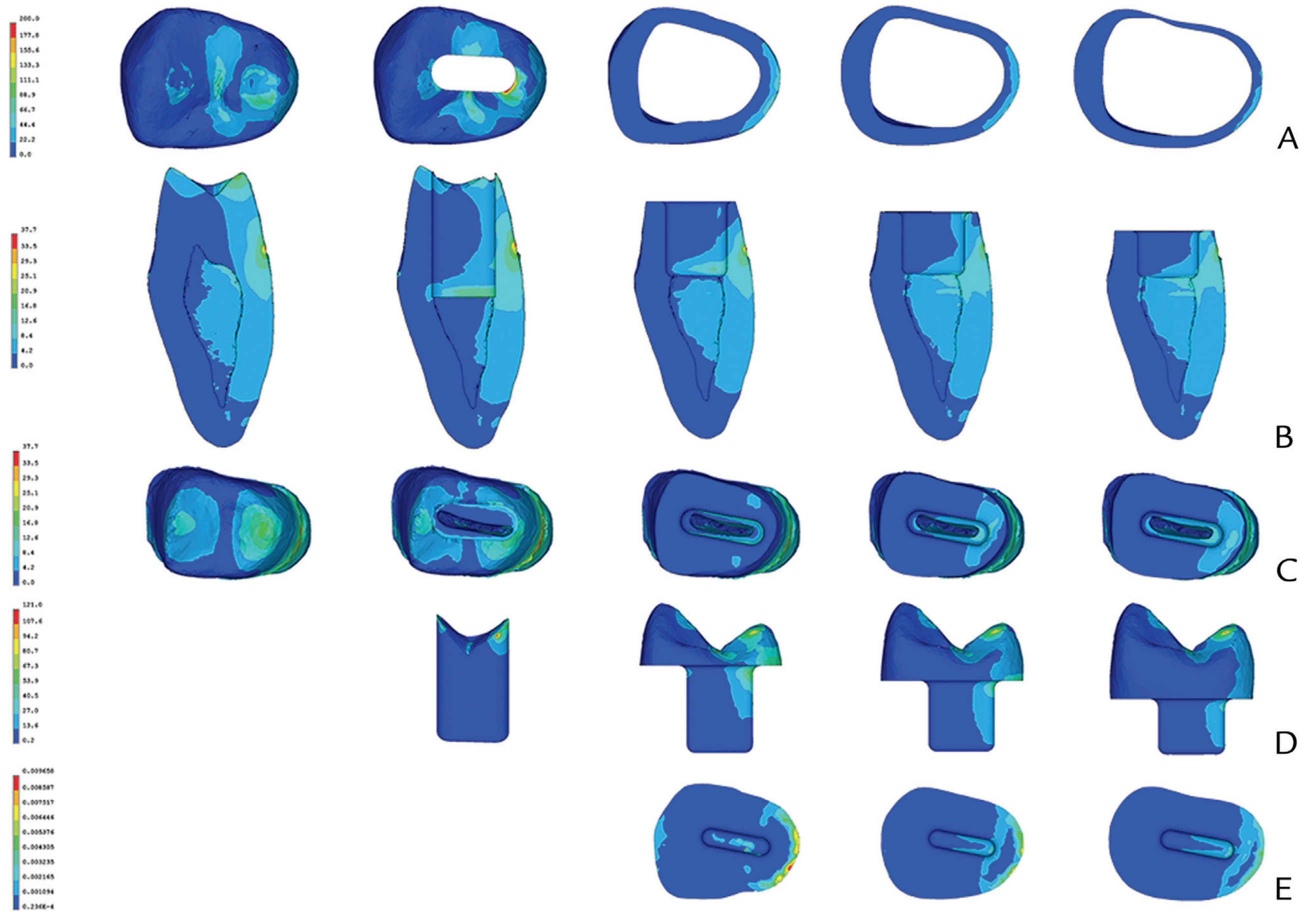

Figure 2. Von Mises stress distributions (MPa) in natural tooth and teeth restored with composite resin and endocrowns. A, Enamel. B, C, Dentin. D, Restoration, and von Mises strain distributions of models E1, E2, and E3. E, Cement layer under vertical load of 200 N.

Table 2. Peak von Mises stress values in enamel, dentin, restoration, and total under vertical and oblique loads (MPa)

	Enamel		Dentin		Restoration		Total*	
Model	Vertical	Oblique	Vertical	Oblique	Vertical	Oblique	Vertical	Oblique
S	98.4	152.0	32.3	76.9			98.4	152.0
R	200.0	226.0	37.7	81.5	82.8	115.0	200.0	226.0
E1	56.4	148.0	33.7	70.1	121.0	156.0	121.0	156.0
E2	54.2	140.0	31.1	65.3	113.0	156.0	113.0	156.0
E3	53.1	143.0	30.4	63.4	121.0	167.0	121.0	167.0

*Including all dental tissues and restoration.

enamel was concentrated in the loading area, occlusal fissure, and palatal side of the palatal cusp, while that in the dentin was concentrated in the region below the cusps and in the tooth cervix. In model R, the regions where VMS concentrated in the enamel around the composite resin were similar to those in model S. However, the VMS in the dentin was increased in the cervical area of the tooth. In an ETP restored with an endocrown (model E1), the VMS was concentrated in the endocrown and dentin. The VMS in the endocrown was concentrated in the loading area, the occlusal fissure, and the central retainer on the palatal side. The regions of VMS concentration in the dentin were similar to those in model S. The von Mises strain in the cement layer was concentrated at the palatal margin, coronally. With increasing endocrown thickness (models E2 and E3), the VMS was increased in the coronal dentin on the palatal side, and the peak von Mises strain value in the cement layer decreased from 0.0097 to 0.0046.

Under oblique loads, the peak VMS values increased in all models (Table 2). Although the regions where VMS concentrated in the enamel in model S were similar to

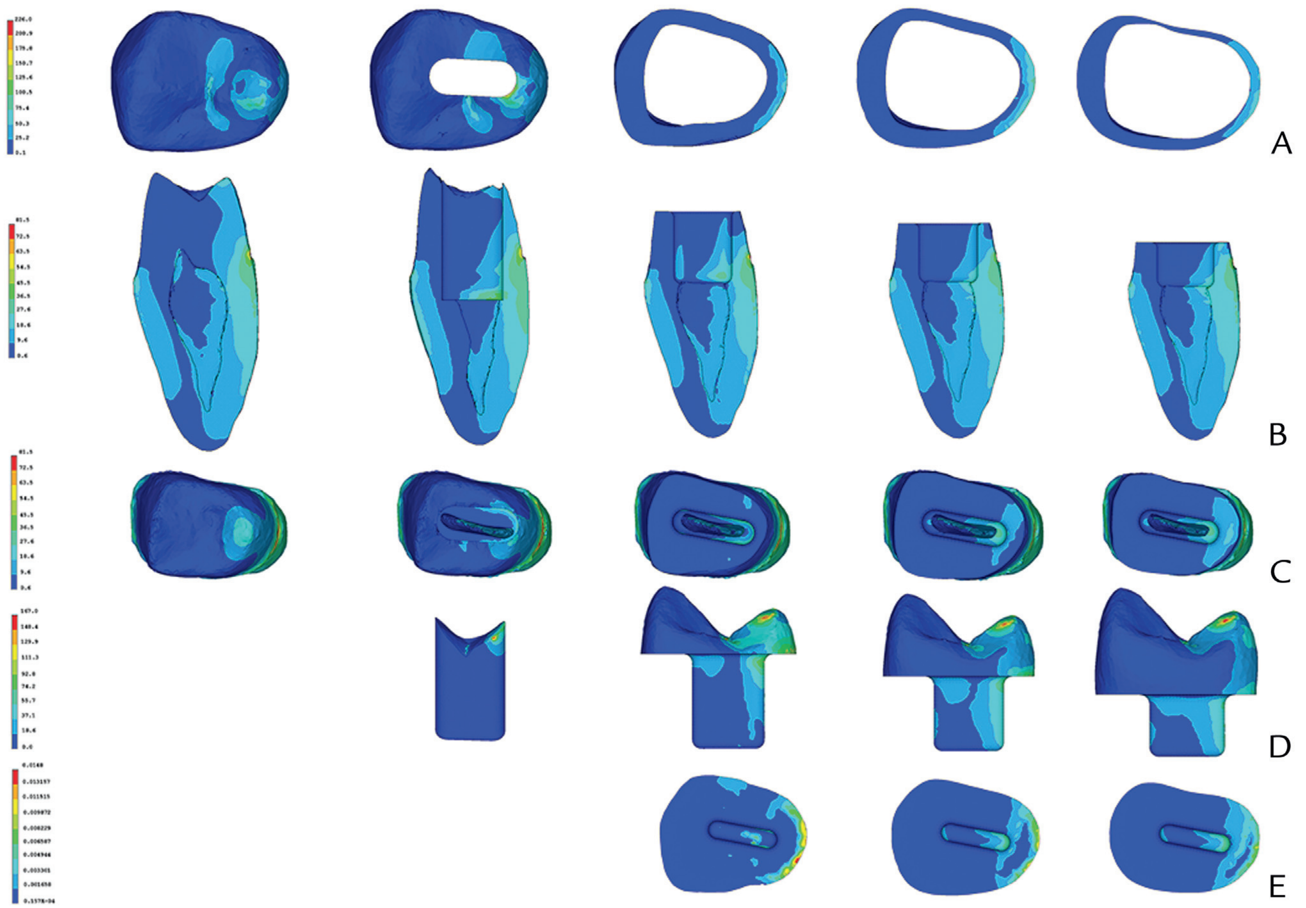

Figure 3. Von Mises stress distributions (MPa) in natural tooth and teeth restored with composite resin and endocrowns. A, Enamel. B, C, Dentin. D, Restoration and von Mises strain distributions of models E1, E2, and E3. E, Cement layer under oblique load of 200 N.

Table 3. Peak values of maximum tensile stress, maximum shear stress, ultimate tensile strength, and ultimate shear strength at cement-enamel interface, cement-dentin interface, and cement–endocrown interface under vertical and oblique loads (MPa)

	Cement-Enamel				Cement-Dentin				Cement-Endocrown			
	Vertical		Oblique		Vertical		Oblique		Vertical		Oblique	
Model	MTS	MSS	MTS	MSS	MTS	MSS	MTS	MSS	MTS	MSS	MTS	MSS
E1	8.12	6.71	16.80	10.02	4.43	3.92	8.35	9.64	8.08	6.58	21.42	17.69
E2	7.22	6.66	14.58	9.62	4.43	2.69	10.16	6.90	11.58	11.90	18.37	11.31
E3	5.77	3.96	13.54	6.56	3.05	2.72	10.42	7.18	3.96	8.22	13.93	10.41
US	40.00[a]	37.00[b]	40.00	37.00	39.20[35]	29.10[b]	39.20	29.10	22.40[36]	27.70[37]	22.40	27.70

MTS, maximum tensile stress; MSS, maximum shear stress; US, ultimate strength. [a]Information from "Micro-tensile bond strength of four luting resins to human enamel and dentin" (2011). [b]Information provided by manufacturer.

those under a vertical load, the VMS in the dentin was concentrated in the cervical third and middle third of the root, rather than in the cervical region (Fig. 3). In model R, the same trend of stress transfer was also observed. The VMS distribution pattern in model E1 was similar to those in model S and model R, and the von Mises strain in the cement layer concentrated at the palatal margin, coronally. With increasing endocrown thickness (models E2 and E3), the VMS increased in the coronal dentin on the palatal side. Peak von Mises strain values in the cement layer (0.0148 in model E1, 0.0141 in model E2, and 0.0088 in model E3) decreased gradually. The maximum tensile stress and maximum shear stress of all interfaces were below the ultimate tensile strength and ultimate shear strength of the corresponding interfaces under vertical and oblique loads (Table 3).

When lithium disilicate was used as endocrown material, the VMS in model E1 was concentrated in the enamel, dentin, and endocrown under an oblique load (Fig. 4). When using composite resin or leucite ceramic, which have

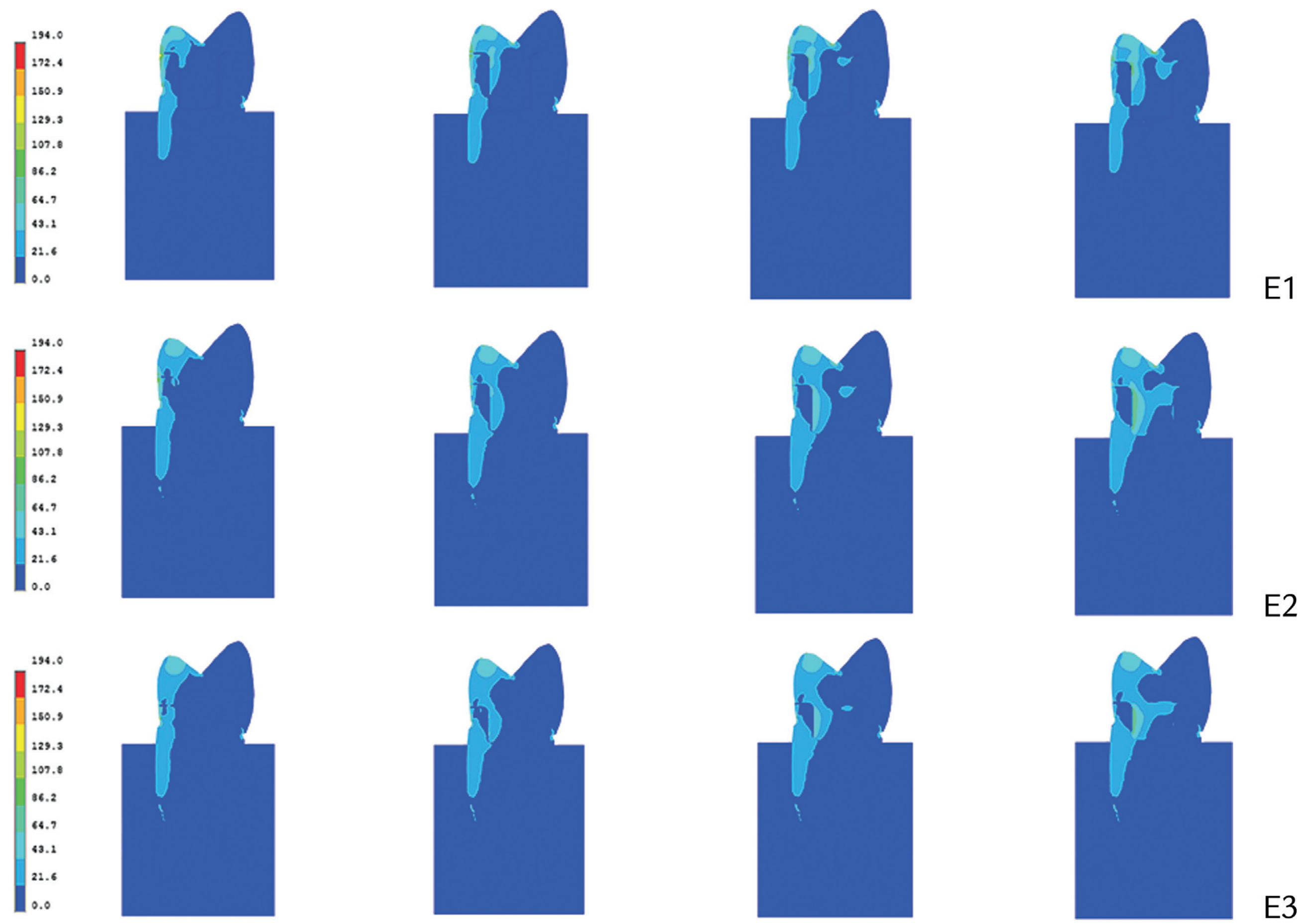

Figure 4. Von Mises stress distributions (MPa) in models E1, E2, and E3 in total under oblique load of 200 N.

a lower elastic modulus, the VMS remained concentrated in these parts but increased in the enamel (Fig. 5) and decreased both in the central retainer (Fig. 6) and in the dentin near the end of the central retainer on the palatal side (Fig. 7). Furthermore, the peak von Mises strain value in the cement layer increased from 0.0148 to 0.0268. The same variation could be observed in models E2 and E3.

When the zirconia ceramic, which has a much higher elastic modulus (242 GPa), was used as the endocrown material instead of lithium disilicate, the regions of VMS concentration did not change (Fig. 4). However, the VMS in the enamel decreased (Fig. 5), and the VMS in the central retainer (Fig. 6) and in the dentin near the end of the central retainer on the palatal side (Fig. 7) increased. With an increase in the endocrown material's elastic modulus, the peak von Mises strain value in the cement layer decreased from 0.0148 to 0.0134. The same variation could be observed in models E2 and E3.

DISCUSSION

According to the present study, the VMS distribution in the maxillary premolar restored with composite resin was more uneven than that in the natural premolar, which was in accordance with an earlier study.[13] If the ETP was restored with an endocrown, the pattern of VMS distribution was similar to that found in a natural maxillary premolar. A previous study showed that failure of cohesive bonding was the main reason for failure in endocrown-restored teeth.[10] The present study demonstrated that, when the ETP was restored with an endocrown made of lithium disilicate-reinforced glass ceramic, the maximum tensile stress and maximum shear stress of all interfaces were below the ultimate tensile strength and ultimate shear strength of the corresponding interfaces. Consequently, such an endocrown allowed reliable restoration of ETP from a biomechanical perspective. When the load direction changed from vertical to oblique, the VMS in the natural tooth and restored teeth increased markedly, which implies that premolars subjected to an oblique load were more at risk of fracture. This finding was confirmed by a previous study.[32]

In this study, 3 different endocrown thicknesses were used to study the influence of the quantity of preserved dental tissues on the stress distributions in

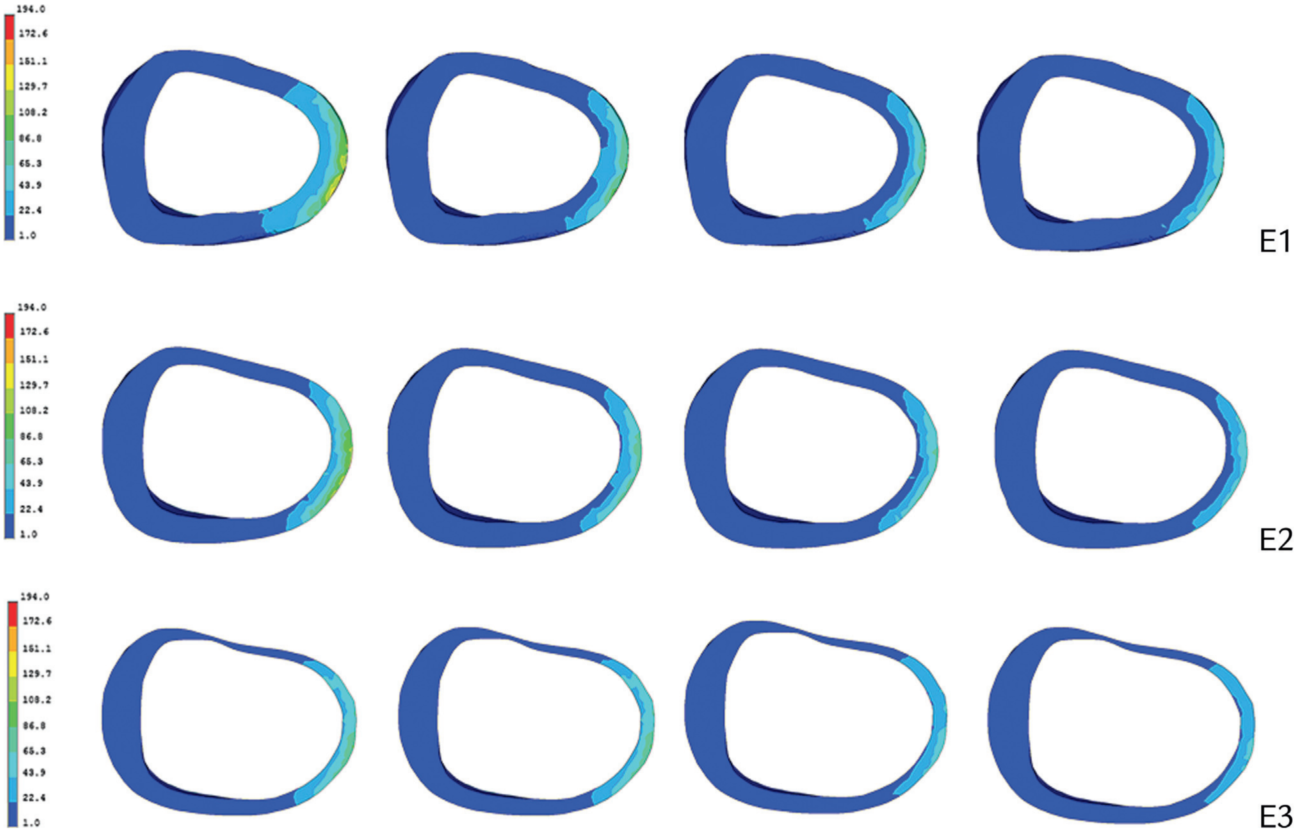

Figure 5. Von Mises stress distributions (MPa) in models E1, E2, and E3 in enamel under oblique load of 200 N.

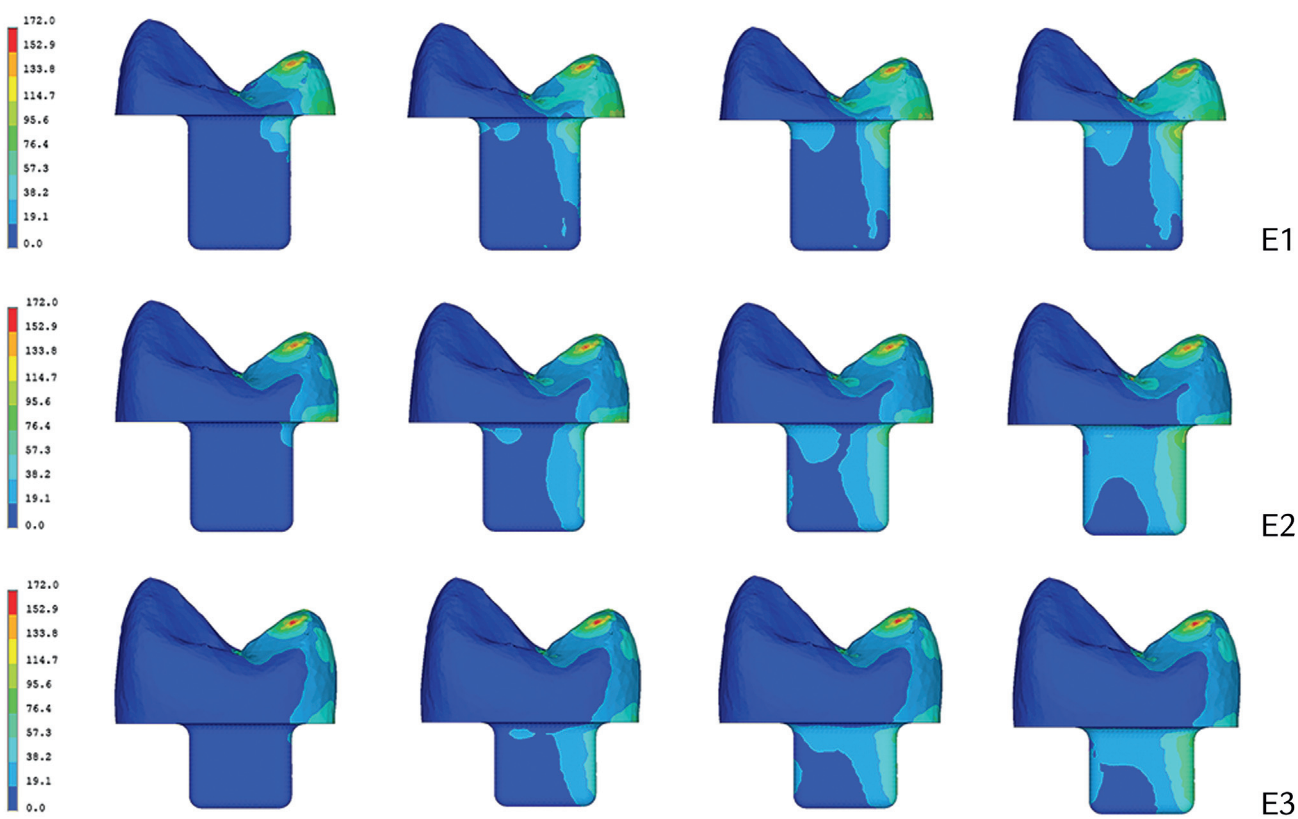

Figure 6. Von Mises stress distributions (MPa) in models E1, E2, and E3 in endocrown under oblique load of 200 N.

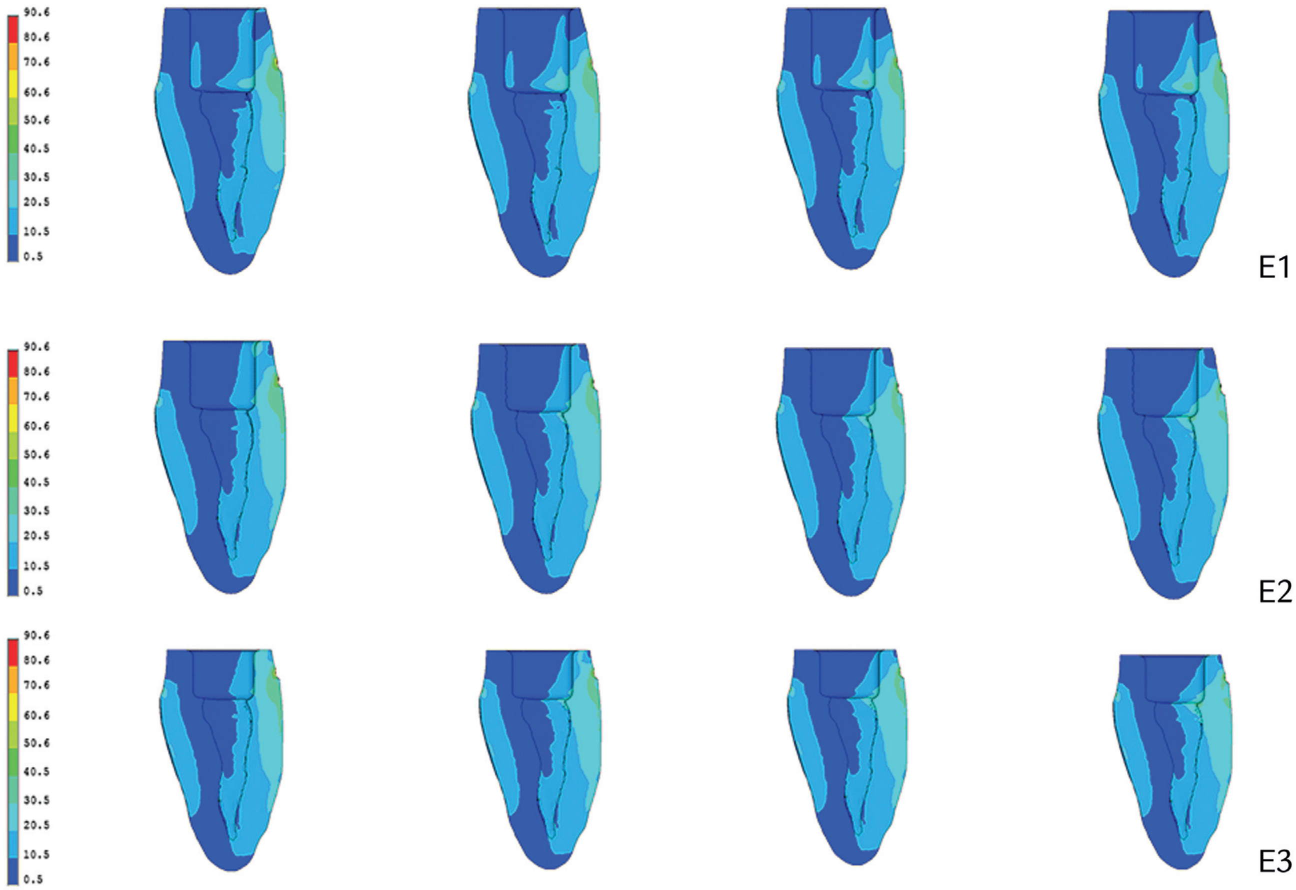

Figure 7. Von Mises stress distributions (MPa) in models E1, E2, and E3 in dentin under oblique load of 200 N.

endocrown-restored maxillary premolars. When more dental tissues were preserved during tooth preparation for an endocrown, the thickness of the endocrown decreased, and the peak von Mises strain value in the cement layer increased. Consequently, the endocrown may be more easily dislodged at a future stage. However, with the decrease in the endocrown thickness, the VMS in the coronal dentin on the palatal side decreased, which would reduce the risk of future tooth fracture. Compared with failure of cohesive bonding, tooth fracture is more catastrophic. On the basis of these results, conservative treatment in tooth preparation for an endocrown is recommended. Importantly, if too much dental tissue is removed and the shoulder finish line of the endocrown is completely below the CEJ after tooth preparation, the use of an endocrown may not be suitable because of the increased risk of tooth fracture and the decreased retention of the endocrown. In such a situation, restoring the ETP with a post-and-core and crown would be more suitable.

In this study, the influence of material type on the stress distributions of endocrown-restored maxillary premolars was also investigated. Lithium disilicate-reinforced glass ceramic, which has a slightly higher elastic modulus than enamel (100 GPa versus 84 GPa), is commonly used for indirect restorations such as inlays, complete crowns, and endocrowns. According to the results, when the endocrown was made of zirconia-based ceramic, with an elastic modulus (about 240 GPa) much higher than that of enamel, the deformation under the same load condition was markedly smaller compared with that of an endocrown made of lithium disilicate-reinforced glass ceramic. Thus, the peak von Mises strain value in the cement layer decreased, implying that the use of a high elastic modulus material benefits bonding. However, with the increase in the elastic modulus of the material, the VMS tended to be transferred to the residual tooth structure, perhaps increasing the risk of future tooth fracture.

High-leucite content ceramic is also frequently used in dentistry. As its elastic modulus is notably lower than that of lithium disilicate-reinforced glass ceramic (65 GPa versus 100 GPa), endocrowns made of high-leucite content ceramic could dissipate more energy through deformation under the same load condition. Consequently, the area in which VMS is concentrated in the dentin near the end of the central retainer on the palatal side decreases, thereby reducing the risk of tooth fracture. Compared with high leucite content ceramic, the composite resin block has an even lower elastic modulus (16 GPa versus 65 GPa) and may lead to a higher long-term survival rate of endocrown-restored maxillary premolars. Previous studies also reported that teeth restored with overlay-type restorations made of composite resin demonstrated better fatigue resistance compared with those made of porcelain.[16,17]

Although the VMS is less concentrated in the dentin, the peak value of maximum tensile stress at the cement–endocrown interface would exceed the ultimate tensile strength under an oblique load, indicating that interface fracture would occur between the cement layer and the endocrown. One in vitro study also concluded that more microleakage may be expected if the endocrown is made of resin nanoceramic material.[18] Taken together, these findings indicate that choosing an endocrown material with an elastic modulus similar to that of enamel may not only help to keep the remaining tooth intact but may also benefit the bonding effect.

This study simulated a 200 N force applied to a premolar with a stainless steel ball of 8 mm in diameter in different directions, as this simulated mastication. Additionally, high-quality elements were obtained using HyperMesh software. The present study only analyzed the stress distribution under a static load. However, teeth are subjected to fatigue load in an oral environment. Because the fatigue strength of the cement layer is significantly lower than its ultimate strength, the restoration is more easily dislodged under a fatigue load. Therefore, further studies under fatigue analysis are indicated.

CONCLUSIONS

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

1. Although using conservative treatment when preparing a tooth for an endocrown may protect the residual tooth structure, it may cause future cohesive bonding failure.
2. An increase in the elastic modulus of the material may benefit the durability of bonding between the endocrown and the abutting tooth; however, it may cause fracture of the residual tooth structure.

REFERENCES

1. Hargreaves KM, Berman LH. Cohen's pathways of the pulp expert consult. 11th ed. St Louis: C. V. Mosby; 2015. p. 821-8.
2. Aquilino SA, Caplan DJ. Relationship between crown placement and the survival of endodontically treated teeth. J Prosthet Dent 2002;87:256-63.
3. De Backer H, Van Maele G, De Moor N, Van den Berghe L, De Boever J. An 18-year retrospective survival study of full crowns with or without posts. Int J Prosthodont 2006;19:136-42.
4. Balkenhol M, Wostmann B, Rein C, Ferger P. Survival time of cast post and cores: a 10-year retrospective study. J Dent 2007;35:50-8.
5. Cheung W. A review of the management of endodontically treated teeth. Post, core and the final restoration. J Am Dent Assoc 2005;136:611-9.
6. Tsesis I, Rosenberg E, Faivishevsky V, Kfir A, Katz M, Rosen E. Prevalence and associated periodontal status of teeth with root perforation: a retrospective study of 2,002 patients' medical records. J Endod 2010;36:797-800.
7. Tamse A, Katz A, Pilo R. Furcation groove of buccal root of maxillary first premolars-a morphometric study. J Endod 2000;26:359-63.
8. Bindl A, Mörmann WH. Clinical evaluation of adhesively placed Cerec endocrowns after 2 years-preliminary results. J Adhes Dent 1999;1:255-65.
9. Sevimli G, Cengiz S, Oruç S. Endocrowns: review. J Istanbul Univ Faculty Dent 2015;49:57-63.
10. Bindl A, Richter B, Mörmann WH. Survival of ceramic computer-aided design/manufacturing crowns bonded to preparations with reduced macroretention geometry. Int J Prosthodont 2005;18:219-24.
11. Biacchi GR, Mello B, Basting RT. The endocrown: an alternative approach for restoring extensively damaged molars. J Esthet Restor Dent 2013;25:383-90.
12. Bernhart J, Brauning A, Altenburger MJ, Wrbas KT. Cerec3D endocrowns-two-year clinical examination of CAD/CAM crowns for restoring endodontically treated molars. Int J Comput Dent 2010;13:141-54.
13. Soares PV, Santos-Filho PC, Gomide HA, Araujo CA, Martins LR, Soares CJ. Influence of restorative technique on the biomechanical behavior of endodontically treated maxillary premolars. Part II: strain measurement and stress distribution. J Prosthet Dent 2008;99:114-22.
14. Serin KT, Yildirim T, Ulker M. Effects of different cusp coverage restorations on the fracture resistance of endodontically treated maxillary premolars. J Prosthet Dent 2016;116:404-10.
15. Ibrahim AM, Richards LC, Berekally TL. Effect of remaining tooth structure on the fracture resistance of endodontically-treated maxillary premolars: an in vitro study. J Prosthet Dent 2016;115:290-5.
16. Magne P, Knezevic A. Simulated fatigue resistance of composite resin versus porcelain CAD/CAM overlay restorations on endodontically treated molars. Quintessence Int 2009;40:125-33.
17. Magne P, Knezevic A. Influence of overlay restorative materials and load cusps on the fatigue resistance of endodontically treated molars. Quintessence Int 2009;40:729-37.
18. El-Damanhoury HM, Haj-Ali RN, Platt JA. Fracture resistance and microleakage of endocrowns utilizing three CAD-CAM blocks. Oper Dent 2015;40:201-10.
19. Singh SV, Bhat M, Gupta S, Sharma D, Satija H, Sharma S. Stress distribution of endodontically treated teeth with titanium alloy post and carbon fiber post with different alveolar bone height: a three-dimensional finite element analysis. Eur J Dent 2015;9:428-32.
20. Diana HH, Oliveira JS, Ferro MC, Silva-Sousa YT, Gomes EA. Stress distribution in roots restored with fiber posts and an experimental dentin post: 3D-FEA. Braz Dent J 2016;27:223-7.
21. Dejak B, Mlotkowski A, Langot C. Three-dimensional finite element analysis of molars with thin-walled prosthetic crowns made of various materials. Dent Mater 2012;28:433-41.
22. Vukicevic AM, Zelic K, Jovicic G, Djuric M, Filipovic N. Influence of dental restorations and mastication loadings on dentine fatigue behaviour: image-based modelling approach. J Dent 2015;43:556-67.
23. Holmes DC, Diaz-Arnold AM, Leary JM. Influence of post dimension on stress distribution in dentin. J Prosthet Dent 1996;75:140-7.
24. Xu B, Wang Y, Li Q. Modeling of damage driven fracture failure of fiber post-restored teeth. J Mech Behav Biomed Mater 2015;49:277-89.
25. Papadogiannis DY, Lakes RS, Papadogiannis Y, Palaghias G, Helvatjoglu-Antoniades M. The effect of temperature on the viscoelastic properties of nano-hybrid composites. Dent Mater 2008;24:257-66.
26. Firidinoglu K, Toksavul S, Toman M, Sarikanat M, Nergiz I. Fracture resistance and analysis of stress distribution of implant-supported single zirconium ceramic coping combination with abutments made of different materials. J Appl Biomech 2012;28:394-9.
27. Yaman SD, Sahin M, Aydin C. Finite element analysis of strength characteristics of various resin based restorative materials in class V cavities. J Oral Rehabil 2003;30:630-41.
28. Ritzberger C, Apel E, Höland W, Peschke A, Rheinberger VM. Properties and clinical application of three types of dental glass-ceramics and ceramics for CAD-CAM technologies. Materials 2010;3:3700-13.
29. Coldea A, Fischer J, Swain MV, Thiel N. Damage tolerance of indirect restorative materials (including PICN) after simulated bur adjustments. Dent Mater 2015;31:684-94.
30. Guazzato M, Albakry M, Swain MV, Ironside J. Mechanical properties of In-Ceram Alumina and In-Ceram Zirconia. Int J Prosthodont 2002;15:339-46.
31. Holmgren EP, Seckinger RJ, Kilgren LM, Mante F. Evaluating parameters of osseointegrated dental implants using finite element analysis-a two-dimensional comparative study examining the effects of implant diameter, implant shape, and load direction. J Oral Implantol 1998;24:80-8.
32. Palamara D, Palamara JEA, Tyas MJ, Messer HH. Strain patterns in cervical enamel of teeth subjected to occlusal loading. Dent Mater 2000;16:412-9.
33. Toparli M. Stress analysis in a post-restored tooth utilizing the finite element method. J Oral Rehabil 2003;30:470-6.

34. Lin CL, Chang YH, Liu PR. Multi-factorial analysis of a cusp-replacing adhesive premolar restoration: a finite element study. J Dent 2008;36:194-203.
35. Kawano S, Fu J, Saikaew P, Chowdhury AA, Fukuzawa N, Kadowaki Y, et al. Microtensile bond strength of a newly developed resin cement to dentin. Dent Mater J 2015;34:61-9.
36. Passia N, Lehmann F, Freitag-Wolf S, Kern M. Tensile bond strength of different universal adhesive systems to lithium disilicate ceramic. J Am Dent Assoc 2015;146:729-34.
37. Lise DP, Perdigao J, Van Ende A, Zidan O, Lopes GC. Microshear bond strength of resin cements to lithium disilicate substrates as a function of surface preparation. Oper Dent 2015;40:524-32.

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