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Biomechanical Assessment of Restored Mandibular Molar by Endocrown in Comparison to a Glass Fiber Post-Retained Conventional Crown: 3D Finite Element Analysis

Mohammed Abu Helal, MDS & Zhigang Wang, DDS, PhD

Prosthodontic Department, Henan Provincial People's Hospital, People's Hospital of Zhengzhou University, Zhengzhou, China

Keywords
3D FE analysis; biomechanical behavior; endocrown; glass fiber post; mvM stress.

Correspondence
Zhigang Wang, Prosthodontic Department, Henan Provincial People's Hospital; People's Hospital of Zhengzhou University, No. 7, Weiwu Road, Zhengzhou, P.R. China, 450003.
E-mail: zhgwang27@163.com

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Abstract

Purpose: To compare equivalent and contact stresses in a mandibular molar restored by all-ceramic crowns through two methods: ceramic endocrowns and ceramic crowns supported by fiber-reinforced composite (FRC) posts and core, by using 3D finite element analysis during normal masticatory load.
Materials and Methods: Three 3D models of a mandibular first molar were made and labeled as such: intact molar with no restoration (A); ceramic endocrown-restored molar (B); ceramic crown supported by FRC posts and core restored molar (C). By using 3D FE analysis with contact components, normal masticatory load was simulated. The mvM stresses in all models were calculated. Maximal mvM stresses in the ceramic of restorations, dentin, and luting cement were contrasted among models and to values of materials' strength. Contact shear and tensile stresses in the restoration/tooth interface around restorations were also calculated.
Results: The highest mvM stress levels in the enamel and dentin for the tooth restored by ceramic endocrown were lower in the crown ceramic than in tooth restored with FRC posts and all-ceramic crowns; however, in the resin adhesive cement interface it was lower for ceramic crown supported by FRC posts than the in ceramic endocrown restoration. The maximum contact shear and tensile stress values along the restoration/tooth interface of ceramic endocrowns were lower than those with ceramic crowns supported by FRC posts.
Conclusions: Ceramic endocrown restorations presented a lower mvM stress level in dentin than the conventional ceramic crowns supported by FRC posts and core. Ceramic endocrown restorations in molars are less susceptible to damage than those with conventional ceramic crowns retained by FRC posts. Ceramic endocrowns properly cemented in molars must not be fractured or loosen during normal masticatory load. Therefore, ceramic endocrowns are advised as practicable, minimally invasive, and esthetic restorations for root canal treated mandibular molars.

The restoration of extremely damaged nonvital teeth is a challenging procedure in conservative dentistry. Clinical data concerning the restorative procedure of pulpless teeth are still questionable and frequently rely on uncertain empirical literature. The loss of dental tissues associated with caries, extensive cavity preparation, and trauma along with physical changes or dehydration in the dentin is an essential reason for both stiffness and fracture strength reduction of endodontically treated teeth (ETT).[1-3] Previously, the rehabilitation of root canal treated teeth with extended dental tissue loss was accomplished by creating full crowns retained by cast metal cores.[4]

The rehabilitation of ETT became noticeably easier, more practical, and biocompatible with the presence of intracanal posts made of glass fiber and adhesive systems.[5] However, the requirement for using fiber posts and core has become less obvious, particularly in posterior teeth, with the new era of adhesive dentistry aligned with the introduction all-ceramic crowns with high mechanical properties.[6] Therefore, it has become practical to reconstruct posterior teeth with extreme coronal damage with ceramic onlay, overlay, and endocrown restorations, which acquire retention and stability by means of adhesive bonding, allied with the surface accessible inside the pulp chamber.[7,8] Generally speaking, the long-term success of an ETT to a great extent relies upon the choice of an appropriate restorative material, which could save the remaining tooth structure.[8]

Nevertheless, because of the absence of information about biomechanical behavior of endocrowns and the expectation that

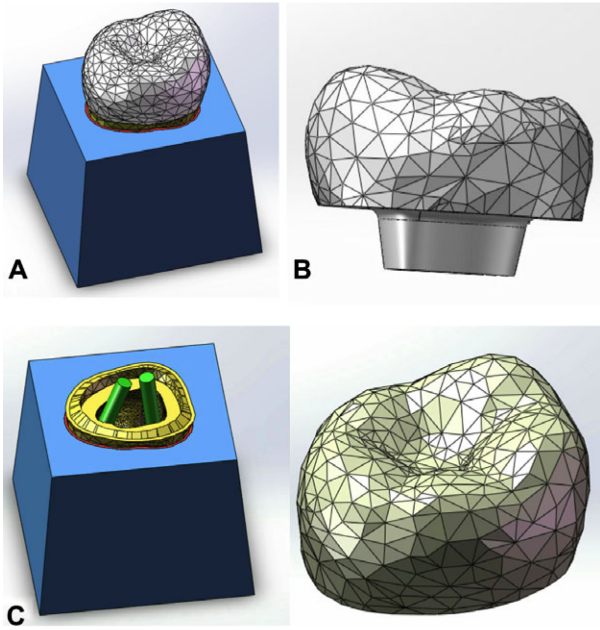

Figure 1 Models of: (A) first mandibular molar tooth with roots and periodontium (model A); (B) ceramic endocrown (model B); (C) ceramic crown supported by glass fiber post and composite core. (model C).

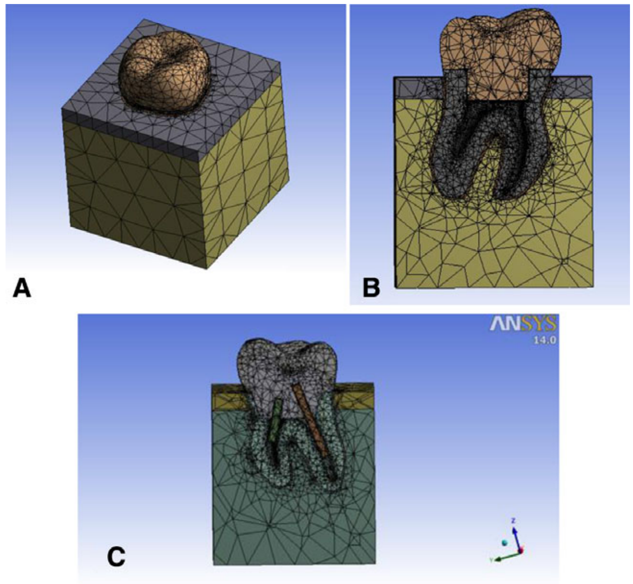

Figure 2 Meshed models of: (A) intact molar; (B) tooth restored by ceramic endocrown; (C) tooth restored with ceramic crown supported by FRC posts and composite core.

this type of restoration would behave similarly or superiorly to conventional crowns (because of the potential to be retained in the pulp chamber by micromechanical retention given by the adhesive system and resin cement), the present study has attempted to assess which restoration (ceramic endocrown or ceramic crown with fiber-reinforced composite [FRC] post) will provide minimal stress in mandibular molars, and the possibility to use endocrowns rather than conventional crowns supported by FRC posts for ETT molars considering the mechanical response of the restored tooth to masticatory load. The null hypothesis in this study was that the endocrown is not superior to post-and-core crowns in terms of biomechanical response to normal masticatory load.

Materials and methods

Generation of FE models

To generate accurate 3D computer models of intact molar teeth, a freshly extracted intact mandibular first molar tooth was inserted into a resin block for scanning 9000C 3D (Kodak, Rochester, NY) computed tomography (CT) with a tube voltage of 60 Kv, voxel dimension of 100 μm, and exposure time of 10.8 seconds. To identify the dental hard tissues and to recognize them with finite element analysis (FEA) software (Workbench v.14.0; ANSYS, Canonsburg, PA), all CT image profile records were manipulated by Kodak CS 3D-Imaging program. Three 3D FEA models were fabricated through a precise calculation in the program, and by deducting the pulp

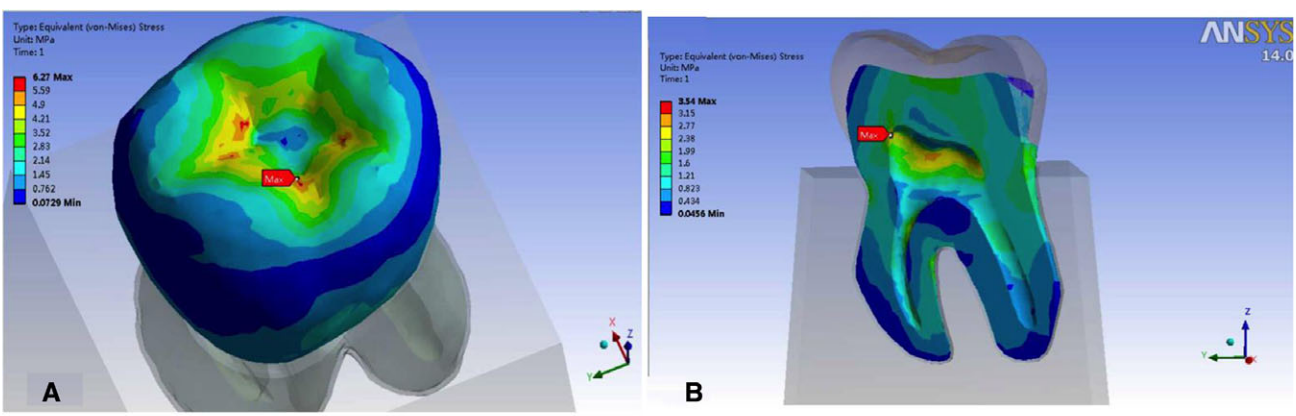

Figure 3 Distribution of the mvM stresses and contact stresses in intact molar model A during the masticatory load (MPa). (A) The mvM stresses in enamel; (B) the mvM stresses in dentin.

Table 1 Mechanical characteristics of the materials

Material	Modulus of elasticity (GPa)	Poisson's ratio	Tensile strength (MPa)	Compressive strength (MPa)
Enamel[15,22]	84.1	0.33	11.5	384
Dentin[16,23]	18.6	0.31	105.5	297
Periodontium[17]	0.05	0.45		
Cortical bone[8]	13.7	0.3		
Trabecular bone[8]	1.37	0.3		
Glass fiber post[21,24]	Ex = 37	Vx = 0.34	Rmx = 1200	Rcx = 1000
	Ey = 9.5	Vy = 0.27	Rmy = 73	Rcy = 160
	Ez = 9.5	Vz = 0.27	Rmz = 73	Rcz = 160
Composite core[20,25]	14.1	0.24	41	293
Ceramic crown[18,26]	65.0	0.19	48.8	162.9
Resin cement[19,27]	8.3	0.35	45.1	178

and dentin volumes from dentin and enamel volumes. Three 3D solid models of enamel, dentin, and pulp were generated. These models were completely adaptable with the FEA computer-aided mechanical software (ANSYS, Workbench v.14.0) used in this study. The periodontal ligament (PDL) and trabecular and cortical bone were simulated around the models. PDL thickness was considered to be 0.2 mm, while the cortical bone and lamina dura were considered to be 2 and 0.3 mm, respectively.[9]

The coordinate axis system for all the models was arranged as follows: The X axis demonstrated the molar lingual surface, while the Y axis was directed upwards, and the Z axis indicated the molar mesial surface as shown in this article's figures.

Model A: Intact molar with no restoration

The crown length was 6.7 mm in the occluso-cervical dimension and 10.5 mm in the buccolingual dimension. Mesial and distal root length were 11 and 12 mm, respectively[10] (Fig 1A).

Model B: Ceramic endocrown-restored molar

This model fabrication process was as follows: at 6.7 mm distance from the cusp tips, model B with endocrown was divided into sections vertically with the long axis of the tooth. Then within the prepared pulp chamber surface a cube with dimensions $3.6 \times 5.2 \times 2.2$ mm^3 in conjunction with smooth margins was formed and joined with the divided portion of the crown. Then a layer of resin cement (0.1-mm thick) was created between the prepared tooth surface and the inner surface of the crown (Fig 1B). Model B with ceramic endocrown was made in this manner (the restored molar was the same one used for model A).

Model C: Ceramic crown supported by FRC posts and core restored molar

This model creation process was as follows: the tooth was prepared for a conventional ceramic crown, with a 2 mm occlusal clearance, 1 mm heavy chamfer margin, and with 6° inclination for axial wall preparation.[11] At 6.7 mm from the cusp tips, model C with ceramic crown supported by FRC posts was divided into sections vertically with the long axis of the tooth, at that point, in an attempt to simulate glass fiber posts, two cylinders were created with dimensions of 9.0×1.0 mm and 9.5×1.0 mm, respectively. The simulated FRC posts were inserted at depths of 5.7 and 6.3 mm into the roots of the tooth model and then joined to the core (Fig 1C). A layer of resin cement (0.1-mm thick) was created between the simulated fiber posts and the prepared canals, in addition to the inner surface of the ceramic crown. Model C with ceramic crown and fiber posts was made in this way (the restored molar was the same used for model A).

Mesh generation

This process, an essential step of the FEA to obtain predictions on complex geometries, divides the system domain into a set of many finite elements whose quantities rely upon the meshed structure geometry. Thus, the meshing process provides a precise representation of the actual model's geometries.

All models were obtained from the same mesh design in order to avoid variations in stress levels among the models. Using 8-node parametric elements containing 3 degrees of freedom per node, the models in the new condition were meshed and redefined. A convergence test verified models' accuracy. The study models had a sum of 79,803 elements and 138,018 nodes in model A (Fig 2A); 77,109 elements and 135,545 nodes in model B (Fig 2B); and 91,549 elements and 163,036 nodes in model C (Fig 2C).

Boundary condition and load application

Boundary condition is an important factor in FEA, reflecting the manner of movements occurring at the nodes and their relationships. The following were considered for all models: (1) the materials used in all models were considered to be isotropic, homogenous, and linearly elastic; (2) FEA models were considered to be securely placed in the alveolar bone, without any movement in any direction; (3) In all directions, the nodes were strained on the roots' outer surface; and (4) There was no flaw in any of the components.[12,13]

In an attempt to imitate the normal occlusal load, the vertical (axial) load was directed toward five diverse contact points toward the models' occlusal surfaces: three were on the buccal cusps' outer aspects, while the other two were on the lingual

Table 2 Maximum values of mvM stresses in FE models of mandibular molars with various restorations (MPa)

Models of mandibular molars		Maximal stresses mvM (MPa)			
		Enamel/Ceramic of restoration	Posts	Dentin	Resin composite luting cement
A	Intact tooth	6.27	–	3.54	–
B	Tooth with endocrown	8.85	–	10.8	3.36
C	Tooth with FRC posts and ceramic crown	9.96	6.6	12.2	3.1

cusps' inner aspects. The applied force was 300 N in magnitude, which simulates average occlusal load.[14]

Materials' mechanical properties

Leucite-reinforced ceramic was the material of choice for the fabrication of ceramic endocrown and ceramic crowns supported by FRC posts. It was cemented to the prepared tooth in the different restorations by the commercially accessible composite luting material (Variolink II; Ivoclar Vivadent, Schaan, Liechtenstein). The posts and core materials in model C were created from fiberglass and composite resin, respectively. We entered the qualities for modulus of elasticity, Poisson's ratio, and compressive and tensile strength for various materials including: enamel, dentin, PDL, ceramics, composite luting cement, and composite core (Table 1). The materials used in the study models differed in tensile and compressive strength; however, they were considered to be isotropic, homogenous, and linearly elastic.

Analysis method (linear static FEA)

Computer-aided mechanical software (ANSYS Workbench v.14.0) was used in this study.[28] To calculate the stress patterns for different models, a linear static FEA was done. To assess the materials' strength under complex stress conditions, the standard mvM stress, which constantly has a positive value, was used. Dental tissues, ceramic material, FRC post, and composite core differ in terms of compressive and tensile strength.[29] Furthermore, mvM stress relies on the stress state of the entire field, and is generally accepted as an index for the normal stress values in various structures restored by different materials.[30] The proportion between the compressive and tensile strength was considered for all materials.

The highest stress levels for each model were calculated and contrasted to each other as well as to the material's tensile strength. In addition, contact stresses along the restoration/tooth interface of each restoration were calculated.

Table 3 Maximum values of contact tensile and shear stresses along the restoration/tooth interface under various restorations in molars (MPa)

Models of mandibular molars		Contact stresses (MPa)	
		Tensile	Shear
B	Tooth with endocrown	4.72	5.09
C	Tooth with FRC posts and ceramic crown	5.32	5.75

Results

The main concentration of this study was on the mvM stress values at the restoration/tooth interface of restoration, posts, dentin, and at the resin composite luting cement (Figs 3 to 7). The mvM stress and contact stress values in different surfaces were visualized using shade images to demonstrate stress distributions. The red zone indicates the highest stress levels, while the dark blue zone indicates the lowest stress levels. The mvM stress levels in dental tissues (enamel, dentin) and around resin luting cement among different restorations were calculated (Table 2). Likewise, we calculated the contact tensile and shear stress levels around the restoration/tooth interface (Table 3).

Model A

For the intact molar with no restoration, the highest mvM stress value in enamel (6.27 MPa) was concentrated around the central groove (Fig 3A), whereas the highest mvM stress value in the dentin was located at the mesial part of the pulp chamber, reaching 3.54 MPa (Fig 3B, Table 2).

Model B

In the ceramic endocrown model, the highest mvM stress level was recorded in the central groove of the ceramic endocrown, and it was 8.85 MPa (Fig 4A), while the highest mvM stress level in the dentin was found in the pulp chamber region, and it was 10.8 MPa (Fig 4B). The maximum mvM value in the resin cement was located in the prepared pulp chamber of the endocrown, reaching 3.36 MPa (Fig 4C, Table 2). Contact tensile and shear stress levels are presented in Figure 5 and Table 3.

Model C

In the ceramic crown retained by FRC posts and core model, the highest mvM stress level in the ceramic of the crown was situated around the mesial groove of the crown surface, and it was 9.96 MPa (Fig 6A). While in dentin, the highest mvM stress level was found at the mesial part of the pulp chamber, and it was 12.2 MPa (Fig 6B). The highest mvM stress level in the resin/cement interface was located on the inner surface of the crown, and it was 3.1 MPa (Fig 6C).

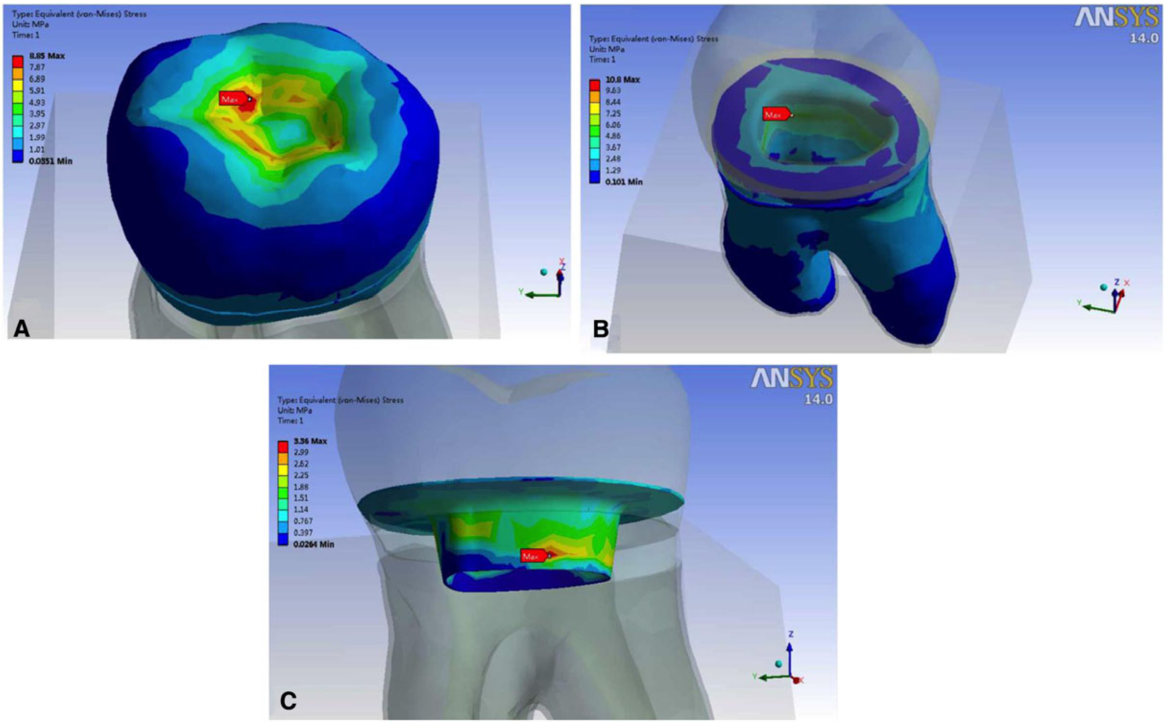

Figure 4 Distribution of the mvM stresses in molar tooth model B with ceramic endocrown during the masticatory load (MPa). (A) The mvM stresses in ceramic endocrown; (B) the mvM stresses in dentin; (C) the mvM stresses in composite resin luting cement.

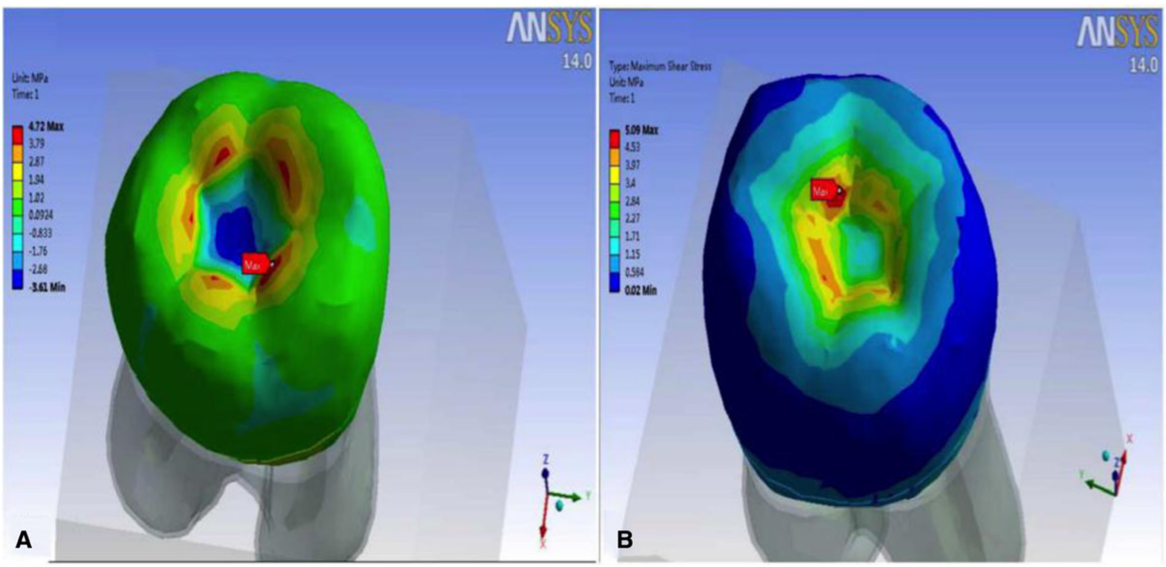

Figure 5 Distribution of contact stresses in molar tooth model B with ceramic endocrown during the masticatory load (MPa). (A) Contact tensile stresses in the ceramic endocrown; (B) contact shear stresses in the ceramic endocrown.

The highest mvM stress values in the enamel and dentin for the tooth restored by ceramic endocrown were lower in the crown ceramics than those in tooth restored with FRC posts and all-ceramic crown; however, in the resin/cement interface, they were lower for the ceramic crown supported by FRC posts than those in the ceramic endocrown restoration (Table 2). The maximum contact shear and tensile stress values along the restoration/tooth interface of the ceramic endocrown were lower than those with ceramic crown supported by FRC posts (Fig 7 Table 3).

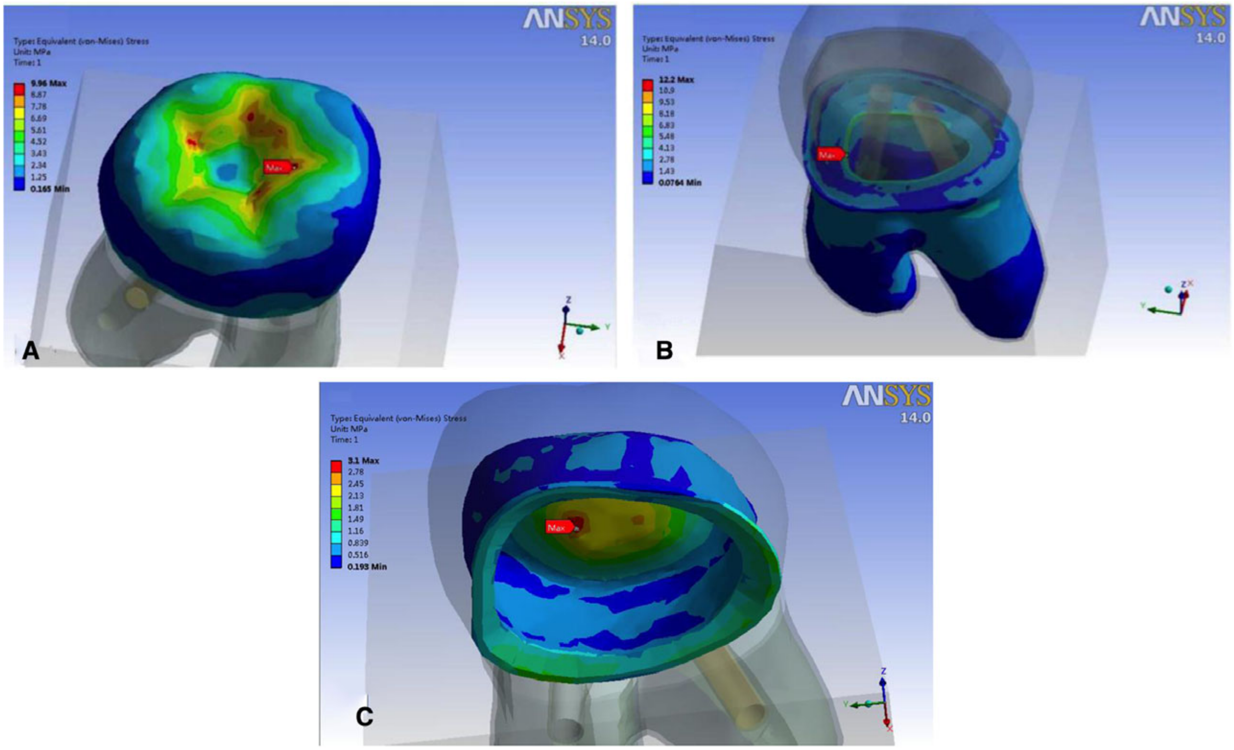

Figure 6 Distribution of the mvM stresses in molar tooth model C with FRC posts, composite resin core, and ceramic crown during the masticatory load (MPa). (A) The mvM stresses in ceramic crown; (B) the mvM stresses in dentin; (C) the mvM stresses in composite resin luting cement around post.

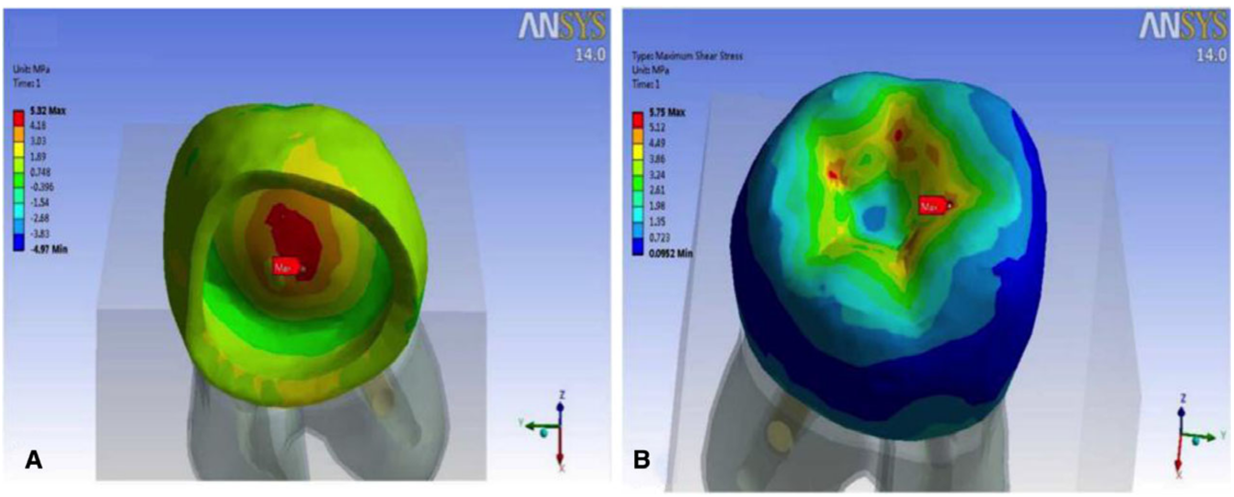

Figure 7 Distribution of contact stresses in molar tooth model C with FRC posts, composite resin core, and ceramic crown during the masticatory load (MPa). (A) Contact tensile stresses in the ceramic crown; (B) contact shear stresses in the ceramic crown.

Discussion

The restorative procedure performed with the conventional crown, the resin composite filling core, and the glass fiber post attempts to reproduce the biomechanical behavior and esthetics of enamel and the resilience of dentin.[31,32] Ceramic endocrown is a total crown that expands within the surface of the pulp chamber as a one-piece "monoblock" without the need for an intraradicular post.[33] The high bonding capacity of leucite-reinforced ceramics to the dental structure and the smaller number of bond interfaces probably make the dentin/enamel/ceramic group more resistant when compared with the dentin/enamel/post/resin/ceramic group.[34]

In vivo studies have also demonstrated the favorable performance of endocrown restorations.[6,33,35] In addition, endocrown restorations are easy to perform but only should be made with reinforced ceramics.[6,33,35]

According to this study's results, the mechanical response for the tooth restored by ceramic endocrown was superior to the tooth restored with ceramic crown retained by FRC posts. Therefore, the null hypothesis was rejected.

Posterior teeth are liable to various directions and values of both functional and para-functional loads. The highest masticatory load in the posterior region for normal adults is 580 N according to Tortopidis et al.[36] In another study Bakke et al[37] reported that the average magnitude of highest masticatory load varies among females (441 N) and males (522 N). In this study, the applied axial load was 300 N. This is not as much as the maximum masticatory load, but simulates the normal masticatory load, in view of the complexity of displaying the complicated maximum occlusal loads in various restorations by numerical simulations. Thus, different load values and directions were not applied in this study.[8]

In the present study, the mechanical behavior of ceramic endocrown and ceramic crown supported by FRC posts to normal masticatory force were assessed by FEA. The dentin mvM stress values of ceramic endocrowns were lower than stress values in ceramic crowns with FRC posts. Therefore, ceramic endocrowns seem to be more beneficial in restoring molar teeth; however, the highest tensile stresses obtained in the three models were lower than the dentin tensile strength, 105.5 MPa.[38]

Morgano[39] found that the indication for posts is to retain the core and not to reinforce the root canal treated tooth. According to Forberger and Göhring's[40] study, the fracture strength values for both endocrowns and conventional crowns with post are almost the same. Although another study performed by Biacchi and Basting[7] showed that ETT restored with ceramic crowns retained by FRC posts and core are more prone to fracture than those restored with endocrowns.

Different studies have demonstrated that a ceramic endocrown restoration in molar teeth is more beneficial than in premolar teeth, because of the large surface inside the pulp chamber of molars compared to premolars, which will improve the micromechanical retention given by the adhesive system. Thus, ceramic endocrowns must be limited to restoring ETT molars in order to obtain a satisfactory performance in terms of bond strength and response to occlusal loads.[35] According to Dejak and Mlotkowski[41] root canal treated molar teeth restored with FRC posts and ceramic crowns are more prone to failure than root canal treated molars restored with ceramic endocrowns.

With regard to material failures, several studies reported that material failure susceptibility will increase following a high number of stress applications, despite the fact that the stress is lower than its yield strength.[42-44] To obtain predictable data about the material vulnerability to fatigue failure, which is widely recognized in the oral area, a static linear FEA can be used.[45]

Our results were compared with Dejak and Mlotkowski's[41] findings in terms of mvM stresses among the different restorations, and the stress level in the luting resin cement in our study was higher for ceramic endocrown restorations than in FRC posts and ceramic crowns restorations, which is not consistent with the other study results. In this study, the values of contact tensile and shear stress along the restoration/tooth interface under various restorations were calculated to simulate the natural masticatory process, which includes contact stresses that could be received by the teeth, as neither is always well tolerated by the PDL as an axial load, and could be received by the tooth as either tensile or shear forces on the restoration/tooth interface, aligned with the assessment of fragile material failure such as resin cements, crown ceramic, and remaining tooth structures.[46] Contact tensile and shear stress values around ceramic crowns supported by FRC posts and core were higher than around ceramic endocrowns (Table 3).

According to our study results, considering that the adhesive bonding procedure was properly done, ceramic endocrown restorations must not be fractured or damaged during normal masticatory load in mandibular molars. In clinical work, to achieve ideal cementation between an all-ceramic restoration and teeth, many steps are required to be done properly, including: perfect isolation to prevent any contamination from saliva and/or blood, acid etching,[47] silane coupling agent,[48] and applying bonding system between ceramic and tooth structure.[47-50] Moreover, the temperature fluctuations and periodic occlusal loads will affect the bond strength between crown ceramics after some time.[51,52] These steps are basics for the longevity of the restoration, since microleakage is a common cause for failue.[5] Although our study results support the favorable performance of an endocrown restoration over a ceramic crown supported by FRC posts and core, in vitro studies have limitations over attempts to produce a real clinical situation. This study's results do not necessarily reflect the clinical performance of the restorative approaches tested. Therefore, it might be considered from the achieved results that ceramic endocrown restorations are a restorative option for ETT molar teeth with severe loss of dental tissue. They are able to replace conventional crowns supported by posts and filling cores and provide advantages in terms of mechanical performance, cost, and clinical time.

Conclusions

Bearing in mind the limitations of this study, the following conclusions were drawn:

1. Ceramic endocrown restoration presented a lower mvM stress level in dentin than the conventional ceramic crown supported by FRC posts and core. Ceramic endocrown restorations in molars are less susceptible to damage than those with conventional ceramic crowns retained by FRC posts.
2. A ceramic endocrown that is properly cemented in molars might not be fractured or loosened under the masticatory load levels presented in this investigation. Therefore, ceramic endocrowns are advised as a practicable, minimally invasive, and esthetic restorations for root canal treated mandibular molars.

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