The Effects of Different Endodontic Cavities on the Fracture Resistance of Endodontically Treated Mandibular First Molars- A Three-dimensional Finite Element Analysis

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Research Article

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Abstract

Objectives: The purpose of this study was to predict the fracture resistance of endodontically treated mandibular first molars (MFMs) with diverse minimally invasive endodontic access cavities using finite element models.

Materials and Methods: Based on microcomputed tomographic data of an MFM, five three-dimensional finite element models representing a natural tooth (NT) and 4 endodontically treated MFMs were generated using finite element analysis software (HyperWork 14.0, Altair, USA). Treated MFM models were with a traditional endodontic cavity (TEC) and minimal invasive endodontic (MIE) cavities, including a computer-aided designed guided endodontic cavity (GEC), contracted endodontic cavity (CEC) and truss endodontic cavity (TREC). Three loading conditions were applied, simulating a maximum bite force of 600 N vertically and a normal masticatory force of 225 N vertically and laterally. The distributions of von Mises (VM) stress and peak VM stress were calculated.

Results: The peak VM stresses of the NT model were the lowest under normal masticatory forces. In endodontically treated models, the distribution of VM stress in GEC model under all loads was the most similar to NT model. The peak VM stresses of the GEC and CEC models under different forces were lower than those of TREC and TEC models. The peak VM stresses of the GEC were lower than those of the CEC under normal masticatory loads but higher under maximum bite load. Under two vertical loads, the peak VM stresses of the TREC model were the highest, while under the lateral load, the peak VM stress of the TEC model was the highest. However, the VM stress in most part of the TEC model was higher than that in TREC model under all loads.

Conclusions: Compared with TEC, GEC and CEC could better improve the fracture resistance of teeth. TREC may have a limited effect on fracture resistance enhancement when compared to GEC and CEC.

Clinical Relevance: Our data demonstrated that compared with TEC and TREC, GEC and CEC access could better improve the fracture resistance of endodontically treated teeth, which may be an alternative balancing biomechanical properties and clinical convenience.

Introduction

The primary goal of endodontic treatment is the long-term retention of functional teeth, but increasing the long-term retention rate of endodontically treated teeth (ETT) is still a great challenge. For decades, dental practitioners have been looking for ways to enhance fracture resistance, because tooth fracture is considered one of the main reasons resulting in the extraction of ETT [1]. Benefitting from technological advances in optics, radiology, instrumentation, materials and computer systems over the last decades, the concept of minimally invasive endodontics (MIE) to preserve as much sound dentin as possible was proposed to enhance fracture resistance [2].

Even 10 years after the first proposed application and the religious support from proponents and influencers in the field of endodontology, MIE is still controversial because many critical aspects still remain to be studied, and no clear evidence shows that MIE is better than traditional endodontics in fracture resistance [3–5]. Some important factors may affect the fracture strength of ETT, such as structural integrity [6], morphology [7], sizes of root canal preparations [8] and prosthetic reasons [9]. Among them, structural integrity, in which marginal ridge and pericervical dentin (PCD) matter, was thought to be a crucial aspect [10]. MIE access cavities are applied to conserve structural integrity by using different cavity designs in building pathways to each root canal during endodontic treatment. Several designs of MIE cavities have been proposed, including contracted endodontic cavities (CECs) [5], which are also known as “ninja” or ultraconservative endodontic cavities [11], truss endodontic cavities (TRECs) [12], and computer-aided design guided endodontic cavities (GECs) [13].

Finite element analysis (FEA) is a promising theoretical stress analysis method because the sample demand is small and the stress inside the model can be displayed, indicating the fracture risk areas intuitively [14]. Additionally, it allows for good control of variables in experiments, overcoming some drawbacks of in vivo studies, such as bias in sample selection [5, 15].

To study whether or which MIE cavity can better improve the resistance of tooth fracture after endodontic treatment, different MIE cavity models of a mandibular first molar (MFM) were established using a three-dimensional finite element method. A 3-point vertical/lateral static force load simulating normal masticatory force and an 8-point vertical static force load simulating maximum bite force were applied on the occlusal surface of different models. The peak von Mises (VM) stress and three cross sections of different models were evaluated.

Materials And Methods

Subjects

With consent of the patient and approval of the local research ethics committee, a fresh, intact, non-carious, lightly wear, mature human MFM with three canals was obtained and scanned with a micro–computed tomographic scanner (Y. Cheetah, Germany). The scanning parameters were as follows: 80 kV, 10 W, and 1.5 μm slice thickness. The image data were exported in DICOM format. A MIMICS 16.0 interactive medical imaging system (Materialise; Belgium) was used to identify the different hard tissues and design different endodontic cavities. Three-dimensional (3D) objects (enamel and dentin) were automatically created in the form of masks and exported as STL files. These files were refined with reverse engineering software (Geomagic Studio 10, NC). The enamel and dentin were combined using 3-Matic Research 12.0 (Materialise; Belgium).

Access Cavity Designs

In this research, a natural tooth (NT) and 4 endodontically treated MFM models were investigated. According to the volumes of removed coronal dentin and PCD, 4 cavity preparations were adopted, including the GEC, CEC, TREC and traditional endodontic cavity (TEC). (Fig. 1.A)

All MIE cavities in this study were designed with MIMICS, retaining the advantage of reducing the loss of hard tissues in the pulp chamber roof and PCD. The pathways of the GEC model were three separating cylinders in the direction of the coronal 1/3 of every root canal so that the PCD could be preserved as much as possible. The CEC outline was determined with three cylinders straight into the root canal orifices meeting the occlusal surface. The outline of TREC was determined with three cylinders straight to the root canals and vertical to the partially overlapping occlusal surface.

Geometry Acquisitions

With the appropriate modifications of the microcomputed tomographic data, 3-dimensional models of endodontically treated teeth were created based on the access cavities described previously. The distal root canal was enlarged to 0.40 mm/0.06 taper files based on the canal geometry. The missal root canals were enlarged to 0.25 mm/0.04 taper. The working length was set at 0.5 mm coronal to the apical foramen. The enlarged root canals were filled with gutta-percha. From the root canal orifice to the pulp chamber roof, every access cavity was restored with flowable bulk resin (3M ESPE-Filtek Bulk-Fill Flowable, USA). The rest of the access cavity was restored with bulk fill composite resin (3M ESPE-Filtek Bulk-Fill Posterior Restorative, USA).

The periodontal ligament was generated by creating a uniform 0.25 mm layer around the root [16]. Meanwhile, the alveolar bone was modelled as a 20-mm cube around the periodontal ligament. Overall, the finite element models were constituted by 7 fundamental parts (Fig. 1.B). The number of tetrahedral elements for the models ranged from 443,973 to 526,923. The volumes of dentin and enamel in each model were recorded.

Model Generation

The FEM was performed using HyperMesh 14.0 (Altair, USA) to calculate VM stress in the enamel and dentin. The analysis was based on the following assumptions:

(1) Each material was presumed to be homogeneous, isotropic and linearly elastic;

(2) There was perfect bonding between each component;

(3) There was no flaw in the initial model;

(4) There were rigid constraints on the base and lateral surfaces of the alveolar bone. The material properties were referenced from the literature and are listed in Table 1

Table 1
Mechanical Properties of the Investigated Materials*

Material	Young’s modulus (GPa)	Poisson’s ratio
enamel	84.1	0.30
dentin	18.6	0.31
pulp	0.002	0.45
periodontal ligament	0.0689	0.45
gutta-percha	0.0069	0.45
cortical bone	13.7	0.3
bulk fill composite resin	13.46	0.18
flowable bulk fill composite resin	12.0	0.25

*According to Eskitaşcioğlu et al.2002[17], Correia et al.2018 [18] and Ausiello et al.2017[19].

Force Loading Processes

The force loading processes were according to D'Souza et al*[20]:

Load A (3-point vertical force load): The models received a vertical static force load of 225 N in total to simulate a normal vertical mastication force load. The force load was applied to the occlusal surface at 3 registered contact points (i.e., separately located at the mesiolingual cusp, mesiobuccal cusp and distal cusp) (Fig. 1. C-1, red arrow).

Load B (3-point lateral force load): A static force load of 225 N was applied laterally (45° to the tooth axis) at 3 registered contact points (i.e., separately located at the mesiolingual cusp, mesiobuccal cusp and distal cusp) to simulate the lateral mastication force load (Fig. 1. C-1, black arrow).

Load C (8-point vertical force load): A static force load of 600 N was applied vertically to 8 contact points registered (i.e., separately located at the mesiolingual cusp, the distolingual cusp, mesiobuccal cusp, the distobuccal cusp, and the distal cusp) on the occlusal surface to simulate the maximum bite force load (Fig. 1.C-2, red arrow).

The force load at each contact point was applied over a specified contact surface area. The peak VM stress and VM stress in each model were computed and analyzed. The distribution of VM stress on the cross-sectional images at the level of the cemento-enamel junction (CEJ), the pulp chamber floor (PCF), and the apical foramen (AF) was investigated [14].

Results

All five three-dimensional finite element models were established successfully. The VM stress diagrams of all the models are listed in Fig. 2. The VM stress value increases gradually from blue to red. In all models, the sites around the force load points and cervical regions were red, indicating higher VM stress (Fig. 2). The VM stress on the occlusal surface was spread in an approximate actinomorphic pattern from the force load points. The part with higher VM stress in one model is the area more prone to cracking of the model. The peak VM stress is the maximum value of VM stress in each model under different loads. Under certain stress load, the model with the highest peak VM stress was the one most prone to fracture in all models. The peak VM stress in all models occurred at the sites around the force load points on the occlusive surface of the model, and the values of peak VM stresses are listed in Fig. 3.

By calculating the difference in volume cavity preparation between ETT models and NT, the volumes of removed dentin in GEC, CEC, TREC, and TEC were 33.16 mm^3, 23.17 mm^3, 28.34 mm^3 and 45.57 mm^3, respectively.

Under the vertical 3-point force load, the peak VM stresses in the NT, GEC, CEC, TREC and TEC models were 203.1 MPa, 208.5 MPa, 210.2 MPa, 229.6 MPa and 210.6 MPa, respectively (Fig. 3). The peak VM stress of the NT model was the lowest in all models, while that of TREC was the highest. Both the peak VM stresses of the GEC model and CEC model were lower than those of the TREC model and TEC model. Although the peak VM stress of the TEC model was lower than that of the TREC model, the VM stress in the investigated sections and most part of the crown in the TEC model was higher than that in the TREC model (Fig. 2). The peak VM stress of the CEC model was slightly higher than that of the GEC model. The VM stress of the CEC model in the CEJ and PCF sections was higher than that of the GEC model, while in most parts of the crown, it was lower (Fig. 2).

Under the lateral 3-point force load, the peak VM stresses in the NT, GEC, CEC, TREC and TEC models were 340.2 MPa, 345.2 MPa, 353.9 MPa, 372.2 MPa and 452.3 MPa, respectively (Fig. 3). The peak VM of the NT model was the lowest, while that of the TEC model was highest in all models. The peak VM stress of the TREC model was higher than that of the CEC model and GEC model. The peak VM stress of the CEC model was higher than that of the GEC model. In the investigated sections, the VM stresses of the GEC and CEC were similar, but in certain parts of the crown, the VM stress of the GEC was remarkably higher (Fig. 2).

Under the vertical 8-point force load, the peak VM stresses in the NT, GEC, CEC, TREC and TEC models were 198.4 MPa, 195.5 MPa, 189.5 MPa, 232.2 MPa and 218.7 MPa, respectively (Fig. 3). The peak VM stress of the NT model was slightly higher than that of the CEC model and GEC model. The peak VM stress of the TEC model was lower than that of the TREC model but remarkably higher than that of the GEC model and CEC model. The peak VM stress of the TREC model was much higher than that of the other models, while that of the CEC was the lowest. The VM stress in the crown of the NT model was slightly higher than that in the GEC model and CEC model, but in the PCF and AF sections, it was lowest in the ETT models. Although the VM stress in the zones on the occlusive surface of the TEC model was lower than that in the TREC model, the VM stress in most parts of the TEC model was the highest (Fig. 2).

In the investigated sections, the VM stresses of CECs and GECs were lower than those of TRECs and TECs. The VM stress in the CEJ and PCF sections of the CEC model was higher than that of the GEC, but in the crown, it was lower (Fig. 2).

Discussion

Since different designs of the MIE cavity have been proposed, many practitioners have already begun to apply them in clinical practice [2, 21]. Previous studies have reported conflicting results regarding the influence of access cavities on the fracture resistance of ETT. Many studies have shown that there are no statistically significant differences in resistance to failure between MIE access cavities and TECs [22–24]. However, some studies have shown that compared with TEC, TREC and CEC improved the fracture resistance [12, 25, 26]. The MFM is the first erupting permanent tooth, and as a result, it is susceptible to decay or caries; thus, in many cases, it requires endodontic treatment [27]. It also has the highest risk of tooth fracture and is extracted after endodontic treatment [1, 28]. Therefore, an MFM was selected as the object of the study.

In this study, different MIE cavity models were established using the three-dimensional finite element method and were compared with NT and TEC. The volume of removed dentin in GEC, CEC, and TREC was significantly lower than that in TEC. The MIE cavity designs significantly reduced the volume of tooth hard tissue removal compared with TEC. In this study, since all cavity models were computer-designed, the calculated hard tissue removal was ideal. From clinical perspectives, the root canal orifices of the teeth with CECs and TRECs could not be directly located, so it was almost certain to remove more hard tissue in the root canal detection than in the *in vitro* model. Thus, CECs and TRECs may increase the potential for deviations and/or instrument fracture [29]. However, in GEC, the volume of tooth hard tissue removal can be controlled within a certain range, and the difference between the long axis of the root canal under TEC and GEC is acceptable [30].

Under the 3-point vertical and lateral force loads, the peak VM stress and VM stress in all investigated sections of NT were the lowest. Therefore, NT may have the best fracture resistance under normal masticatory force loading. Under 8-point vertical load, the VM stress in the crown of the NT model was slightly higher than in the CEC model and GEC model; however, in the root, it was the lowest, which may indicate that under maximum bite force load, root fracture infrequently occurs in NT. However, the incidence of crown fracture in NT may be higher than ETT with CEC and GEC.

Consistent with previous studies [14, 15], the sites around force load points and the cervical region in each model had higher VM stress, indicating that apart from the sites of the force load, PCD is another stress concentration area. Compared to the GEC and CEC models, the VM stress of the TEC model were higher, while the thickness of PCD was obviously smaller. Hence, it is predictive that ETT with TECs seems more prone to fracture than those with CECs and GECs, especially in the cervical regions.

Most studies have demonstrated that no obvious difference was found between CEC and TEC in fracture resistance [29, 31, 32]. However, Özyürek. et al [33] observed that although there was no significant difference in the fracture strengths of teeth prepared using the TEC and CEC approaches, the teeth in the CEC group had more restorable fractures than teeth in the TEC group. The present study indicates that CECs may have better fracture resistance than TECs. The reason may be that in this experiment, all ETT cavities were computer-designed, and PCD and dentin in the pulp chamber roof were idealized to be preserved to the largest extent. In the clinic, it is almost certain that more PCD and dentin in the pulp chamber roof will be removed in CECs, which will weaken the fracture resistance of ETT with CECs.

Compared to CECs, GECs seem to be more operable and predictable, because GECs allow more predictable and expeditious location with significantly less substance loss [13]. Although there were some reports about the accuracy and dentin loss of a GEC [30, 34], few reports about the effect on fracture resistance were found. The peak VM stress and the distribution of VM stress of the GEC model under all force loads were the most similar to those of NT model in all ETT models. It is reasonable to believe that the fracture resistance of teeth in the GEC group is most similar to that in the NT model. Under two vertical loads, the VM stress of a GEC in the crown was higher than that of a CEC, but in the root, it was similar or lower. Hence, compared with CECs, GECs may increase the probability of crown fracture but reduce the risk of root fracture. This is probably because pathways of root canals were in the different directions in the GEC, and the transmission of the stress was dispersed. Less stress was transmitted to the PCD and the root of the tooth, and more stress concentrated in the crown may have led to more restorable fracture in teeth with GECs than in those with CECs. Further study is still needed to determine whether CECs and GECs are more beneficial to the long-term retention of ETT.

Compared to TECs, TRECs seem to have better fracture resistance under vertical force loads, but under the lateral force load, the result is the opposite. Thus, the peak VM stresses of TREC model under all forces were higher than those of GEC and CEC models. A recent study showed that teeth with TRECs have better fracture strengths than those with CECs [26]. However, the present study shows that more solid evidence is still needed to prove that TRECs have a positive effect on fracture resistance enhancement than TECs. Compared to GECs and CECs, TRECs may have a limited effect on tooth resistance enhancement.

Although different cavities were compared in this study, FEA cannot fully simulate the real oral environment and our study only carried out for different situations of the same tooth model, may resulting in less convincing results [35]. More in vitro and clinical randomized controlled trials are still needed to verify the results of this study.

Conclusions

Within the limitations of this study, it could be concluded that MIE cavity design significantly reduced the volume of hard tooth tissue removal. In all models, the cervical region was a stress concentration area. Compared with TECs, GECs and CECs could better improve fracture resistance, but further study is still needed to determine whether CECs and GECs are more beneficial to the long-term retention of ETT. Compared to GECs and CECs, however, TRECs may have a limited effect on tooth resistance enhancement.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Author Contribution

X.W. and W.W. performed the experiment, analyzed the data and wrote the manuscript. D.W. and Y-R.W. contributed significantly to the analysis and manuscript preparation. X-Y. Q., X-G.C. and L-X.N. participated in the design of the MIE access cavity and establishment of the three-dimensional finite element model; Y.T. was the main supervisor and initiator of this study. All authors reviewed, revised, and finalized the paper.

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Figures

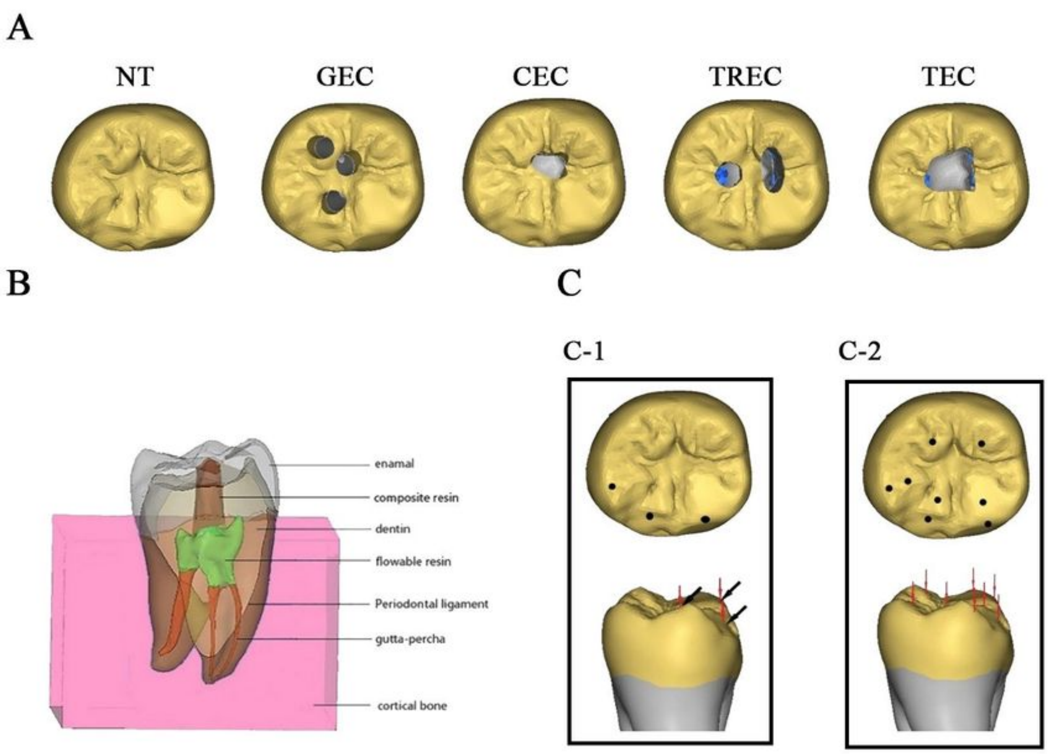

Figure 1

Schematic diagrams of different finite element models, components in one model and 3 force loading conditions.

A. Representative schematic diagrams of different finite element models: NT (natural tooth), GEC (guided endodontic cavity), CEC (contracted endodontic cavity), TREC (truss endodontic cavity), and TEC (traditional endodontic cavity) models.

B. Representative schematic diagram with different components in one finite element model.

C. Representative schematic diagram of different force load patterns: vertical and lateral static force loads (three contact points, 225 N in total to simulate normal vertical mastication force load) were applied on the occlusal surface (**C-1**), and vertical static force loads (eight contact points, 600 N in total to simulate the maximum bite force load) were applied on the occlusal surface. (**C-2**).

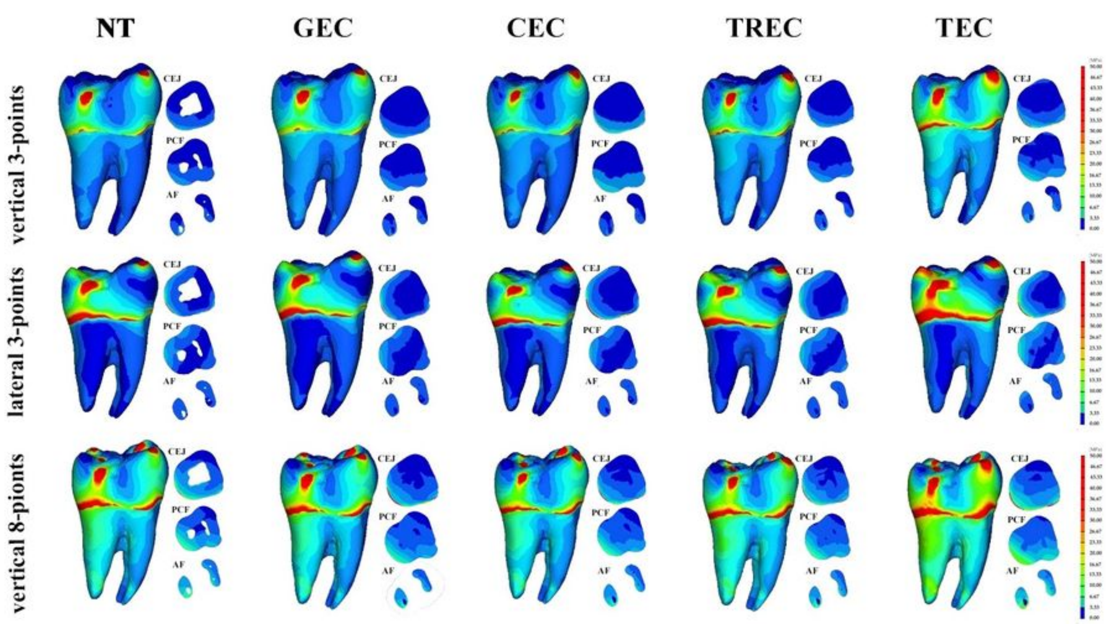

Figure 2

Diagrams of VM stress in different finite element models under three force loads.

Figure 3

The peak von Mises stress values (MPa) in each model.