Biomechanical Behavior of Two-Rooted Maxillary Second Premolar with Different Access Cavities and Apical Preparations (A Finite Element Analysis)

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Abstract:
Aim: This study evaluated the influence of different access designs on maxillary two-rooted premolar teeth to assess their biomechanical behavior using finite element analysis. **Methodology:** Three simulated FEA models were accessed with three main different access cavity designs: the intact tooth (IT) model, the traditional access cavity (TAC), and the conservative access cavity (CAC). Two different radicular preparations were done for each simulated model. The buccal and palatal canals were prepared to the apical sizes #30/.04, and #40/.04. A cyclic load of 50 N was applied on the occlusal surface. The patterns of stress distribution, the maximum von Mises (VM), and maximum principal stresses (MPS) were evaluated and determined mathematically. **Results:** According to VM analysis, the occlusal surface of the CAC/30/.04 model recorded the highest VM stresses value (10.428 MPa), whereas the occlusal surface of the TAC/30/.04 recorded the lowest (7.576 MPa). According to MPS analysis, the occlusal surface of the CAC/40/.04 model had the greatest recorded stress value (3.7684 MPa), whereas the occlusal surface of the TAC/30/.04 model had the lowest value (3.0415 MPa). Radicular stresses were always of minimal value regardless of the model. **Conclusion:** The biomechanical behavior of endodontically treated teeth is influenced by the relationship between the access cavity margins and the functional load locations. Depending on each tooth's static and dynamic occlusal relationships, a specific access cavity design is recommended.

Keywords: Biomechanical behavior, conservative access, traditional access, finite element analysis, maxillary premolars, traditional access

Introduction:

Tooth fracture is still a significant consequence with endodontic treatment. Endodontic therapy is considered to be the most practical method for preserving the tooth when most of the hard dental tissue is damaged by trauma, caries, previous restoration, access cavity and root canal preparation. Endodontically treated teeth (ETT) are more brittle and prone to fracture than untreated teeth. According to several studies, the main cause is the drying out of ETT over time and changing their collagen cross-linking (1–3). Fracture risk increases with the removal of anatomical structures like the pulp chamber roof, pericervical dentin, and one or both marginal ridges (4). It was postulated that the amount of residual coronal dentin appears to be the most crucial factor in the prognosis of an endodontically treated tooth (5,6).

Nowadays, the goal of all restorative techniques, particularly in endodontics, is to maintain strength and stiffness that resists structural deformation. This could be possible by adopting the minimally invasive dentistry concept (MIC) which was promoted by **Clark and Khademi** in 2010. Since then, the traditional endodontic access cavities (TEC) are not the only option anymore, as options now include the conservative and ultra-conservative endodontic access cavities (CEC and UEC respectively) (7). MIC aims to preserve the soffit and peri-cervical dentin by incomplete deroofing of the pulp chamber that increase the fracture resistance in endodontically treated teeth (8). These cavities have gained popularity among endodontists (8–11). This is made possible by improving visibility with dental loupes or a microscope, instrument flexibility, integrity, design, and metallurgy (12).

There is a conflict between many in-vitro studies regarding the MIC. Some studies showed that the fracture resistance improved in teeth with conservative and ultra-conservative access cavities than that in traditional access cavity (8–10,13–16), while, other studies showed that there was no difference between the different access cavities regarding the fracture strength of the tooth (11,17–22). However, most of these studies were performed on molar teeth and there is a gap of knowledge concerning premolars.

Maxillary premolar teeth present an unfavorable anatomic shape, crown size, and crown/root proportion, making them more susceptible to fractures than other posterior teeth, when submitted to occlusal load application(23). The prevalence of two rooted maxillary premolar is the highest among all the other root configurations (24).

This study aimed to evaluate the biomechanical properties of two-rooted maxillary premolars that have undergone various combinations of coronal cavity designs and radicular preparations using finite element analysis (FEA).

Materials and methods:

The tooth selected was an intact upper premolar with two separate roots of normal morphology, and well-developed apices, and no cracks or cavities were seen. The tooth was cleaned from all deposits, then examined under 16X magnification of a dental operating microscope (Zeiss Extaro 300, Germany) to confirm the absence of any structural defects. The selected specimen was scanned with a high-resolution Cone Beam Computed Tomography (CBCT) machine (Planmeca ProMax 3d MID; Planmeca, Helsinki, Finland), with endodontic mode, operating at 120 kVp, 7 mA, Voxel size 0.125 mm, scanning time 26.9 seconds, and field of view 4 cm. After the acquisition, data were exported and transferred in DICOM format and downloaded via a Compact Disk (CD) to a personal computer for analysis, where, mimics software (version 17; materialize, Leuven, Belgium) was used to identify enamel and dentine and the scanned sample images were imported. First; a new project wizard was started to load and open the high-resolution CBCT images in Mimics 19.0. Second, the directions were set up; top, bottom, right, left, anterior, and posterior. Then, the masks of enamel and dentin were set up by thresholding and region growing, and finally, 3D objects were calculated. The data was optimized and then exported STL files so that they could be edited by the Computer-Aided Design Programs CAD (software package SolidWorks) (Dassault Systems, Cedex, France) to produce the 3D model surrounded by simulated periodontal ligaments and bone.

Model validation:

The finite Element (FE) model was validated in the same way as described by Nawar et al. (20). Direct validation of the FE model was performed using the scanned natural teeth. Four strain gauges were fixed on the tooth surfaces just above the cemento-enamel junction. The periodontal ligaments and bone were compensated for by using a 3D-printed plastic block and high-fusion wax (Galileo; Taladium Inc, Valencia, CA). The load was applied using a universal testing machine (Llyod Instruments LRX-plus; Llyod Instruments Ltd, Fareham, UK), and then the displacement was measured. Testing loads were previously determined to apply a linear static load and enable many elastic tests. Three 10, 20, and 30 N trials with a 3% maximum error percentage were carried out (20). The ball attachment was fixed on the occlusal surface of the tooth while applying a load of 50 N until the plateau was reached. The stress distribution pattern of the IT model following the application of load is shown in the resulting graph.

Access cavity design:

The intact model (IT) prepared different endodontic access cavities. Traditional access cavity (TAC) is created by removing the dental roof of the crown, including the paracervical dentin, to create smooth, straight access to all of the root canals (25,26). While Conservative access cavity (CAC) always begins at the occlusal surface’s central fossa and extends smoothly with converging axial walls to the occlusal surface. It only removes the dental tissue required to expose the canal orifices, leaving the PCD and soffit intact (25,27–29) (Fig.: 9c). After finishing the preparation, all internal edges were smoothed and rounded (30).

Root canal preparation:

After creating a solid model for the original tooth and coronal variations, the root canals were virtually prepared with two different apical sizes with the same root canal taper (30/.04 and 40/.04 respectively). To prepare the root canal, a spline was drawn in the center of it, followed by a conical shape with dimensions equal to the file’s dimensions (28,29). The models’ prepared root canals were then filled with simulated gutta percha filling materials 0.5 mm short from the apices of the roots up to canal orifices, and coronal cavity designs were filled with simulated resin composite restorative materials (28,29,31) .

Meshing and set material properties:

All the models were imported into **(Mechanical APDL ANSYS 18.2 software (ANSYS, Canonsburg, PA, USA)** for meshing. The meshing process resulted into different meshes according to each preparation complexity using tetrahedral elements. The number of nodes and tetragonal elements ranged from 785731 and 450813 respectively (IT model), to 723556 and 259685 (MOD model). It was assumed that teeth and all materials used were homogeneous, isotropic, and linearly elastic. The modulus of elasticity and poisson's ratio of structures used to produce the FE model are listed in Table (1) (29,31–33). Following the creation of the 3D meshes, a boundary condition was defined that simulated the relationship between the natural tooth, the periodontal ligaments (PDL) and bone. As a result, for analysis purposes, a boundary condition (zero displacement) was defined at all cortical bone nodes that were constrained in the mesial and distal directions (X, Y, and Z) (33).

Finite Element Analysis:

The experimental models were subjected to vertical cyclic loading of magnitude 50 N to simulate the masticatory forces following the pattern produced from occlusal fingerprint described by Kullmer et al. (25). Cyclic occlusal loading was applied on the sound model as well as the simulated models following various root canal preparations, with the root canals filled with simulated gutta percha and the access cavities filled with simulated resin composite (28,29,31). Mathematical analysis of the stress distribution patterns, maximum von Mises (VM) stress, Maximum principal stress (MPS) were assessed by FEA using the Mechanical APDL ANSYS 18.2 software (ANSYS, Canonsburg, PA, USA).

Occlusal fingerprint analysis (OFA) :

Occlusal fingerprint analysis was performed to determine the loading areas on the subjected model while simulating clinical conditions. An intraoral scanner was used to digitally scan the original maxillary premolar with an occlusal antagonist (Medit i500; Medit, Seoul, Korea) (31). Exocad (Darmstadt, Germany) software was used to map and mark wear facets and occlusal contacts digitally. These areas were transferred to the FEA model, and loading was done on all of them simultaneously (31,34).

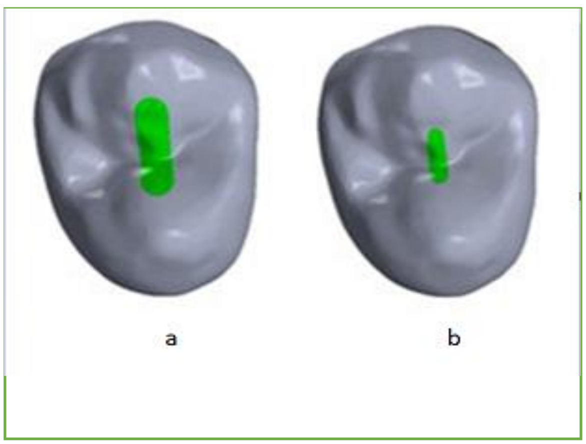

TABLE 1 – Mechanical properties of the materials for Finite Element Analysis

Material	Young's modulus (MPa)	Poisson's Ratio
Enamel	84.1	0.30
Dentin	18.6	0.31
Periodontal ligament	0.00069	0.45
Cortical bone	13.7	0.30
Cancellous bone	1.37	0.30
Pulp	0.002	0.45
Resin composite	12.5	0.30
Gutta percha	2	0.45

Figure 1. (a) The traditional access cavity design (TAC) that completely deroofs the pulp chamber; (b) The conservative access cavity design (CAC) that preserves the soffit.

Results:

VM stress distribution pattern and value are shown in Figure (2). Occlusally, the maximum VM stress values for the CAC/30/.04, TAC/40/.04, CAC/40/.04, TAC/30/.04, and IT model were recorded to be 10.428 MPa, 8.514 MPa, 7.682 MPa, and 7.576 MPa, 8.19 MPa respectively. Maximum VM stresses were located on the tooth structure around the restoration margins. Cervical stresses were located as a band on the outer surface of the root. Radicular stresses were limited to the external surface of the root and they were of minimal value.

The magnitude and distribution of MPS are shown in Figure (3). CAC/40/.04 had the highest MPS value (3.768 MPa), followed by TAC/40/.04 (3.5156 MPa), CAC/30/.04 (3.1686 MPa), and IT model (3.126 MPa). The TAC/30/.04 model recorded the least MPS value (3.0415 MPa). The pattern and values of MPS of the experimental models were comparable to each other and to the IT model.

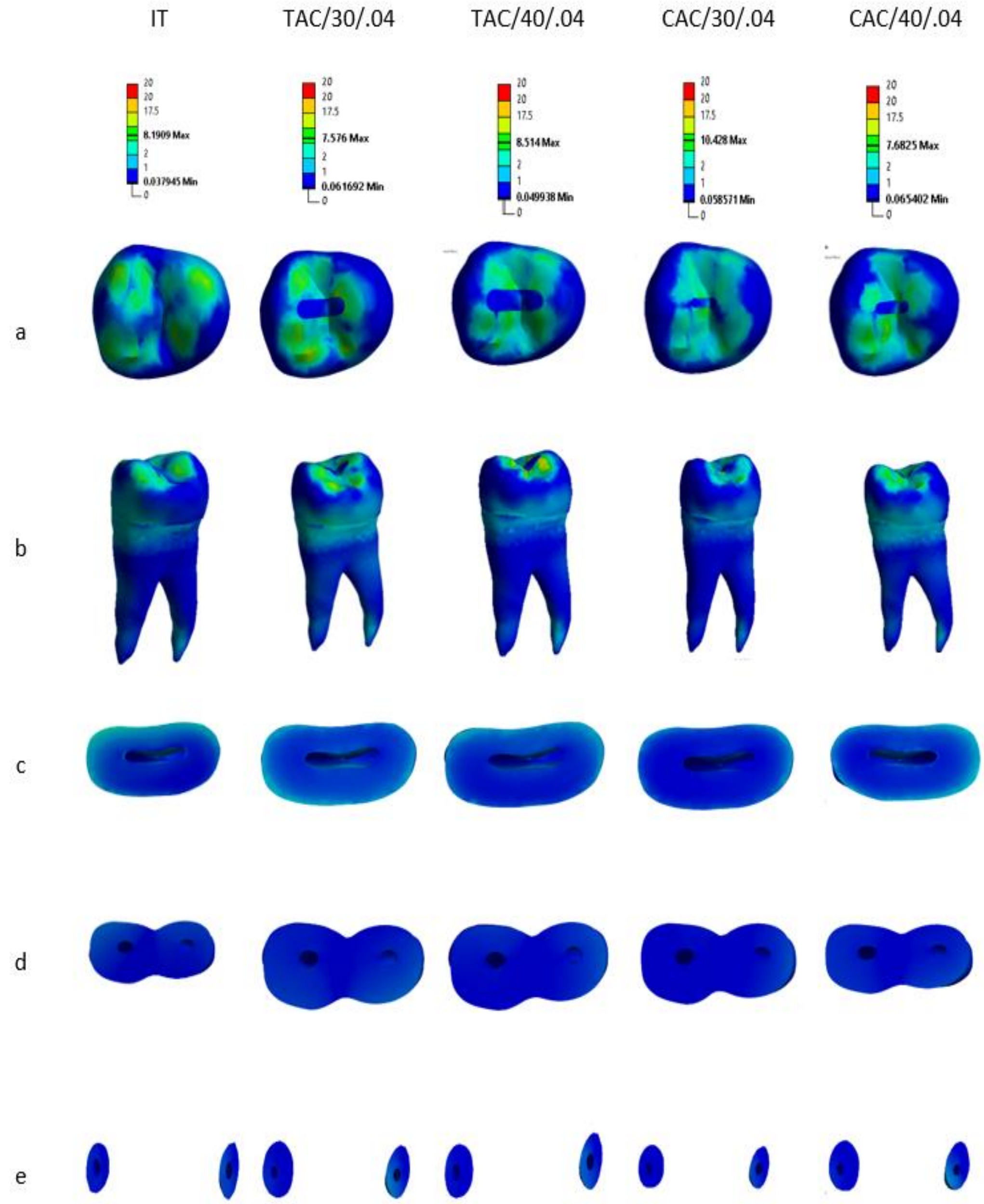

Figure 2. composite figure showing von Mises (VM) stresses distribution for the IT, TAC/30/.04, TAC/40/.04, CAC/30/.04, and CAC/40/.04 models under loading. (a) Occlusal view; (b) Isometric view; (c) Cervical cross section view; (d) Furcation cross section view; (e) Cross section 2 mm above the apex.

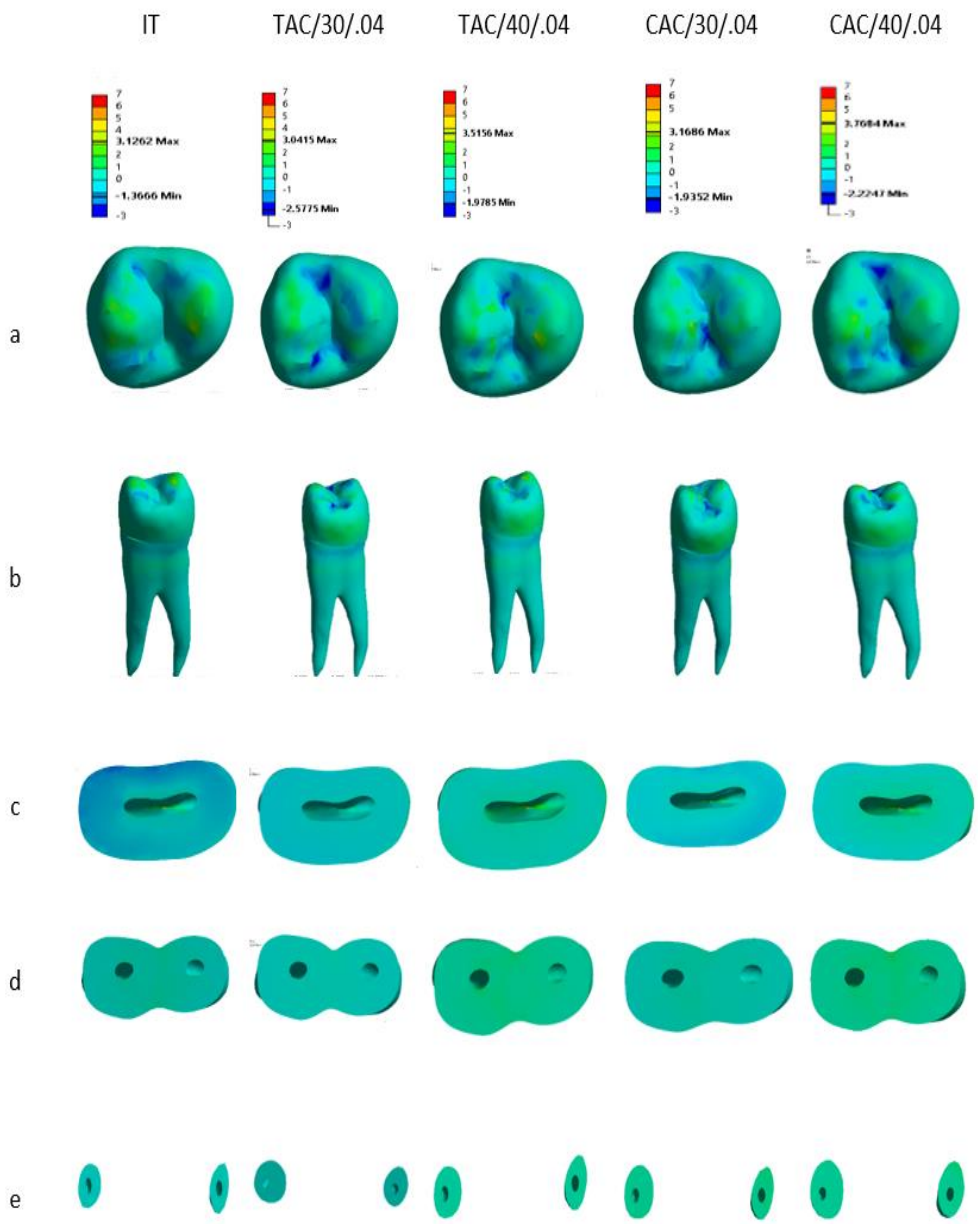

Figure 3. composite figure showing maximum principal stresses (MPS) distribution for the IT, TAC/30/.04, TAC/40/.04, CAC/30/.04, and CAC/40/.04 models under loading. (a) Occlusal view; (b) Isometric view; (c) Cervical cross section view; (d) Furcation cross section view; (e) Cross section 2 mm above the apex.

Discussion:

The contributing factors to the fractures commonly attributed to endodontically treated teeth include too much pressure on the tooth structure caused by heavy masticatory forces, traumatic injury, severe loss of tooth structure by carious defects, radicular preparation, and coronal access cavity which is considered to be the most important one (28,35,36). It was claimed that the main reason for brittleness of endodontically treated teeth was the moisture and nutritional loss. However, many studies proved that the moisture and nutrition loss impaired the fracture strength of the tooth by 9% only. Moreover, studies have shown that the most important factor that caused vertical root fracture was the amount of remaining intact tooth structure (28,37–41).

FEA theoretically assesses the biomechanical behavior (stress and strain) of nonhomogeneous structures while applying loading forces. On the contrary to experimental research and clinical trials, FEA has the benefit of being able to standardize the position, magnitude and direction of applied forces, it is also repeatable and saves time. It also has the advantage of allowing systematic testing of individual and groups of variables, which is not achievable by the experimental method (28,42,43).

MIE concept seeks to make endodontically treated teeth more resistant to breakage, extending their functional life and enhancing overall treatment results (7,9,36). Some practitioners began to use some contracted coronal access cavity designs during endodontic treatment, helped by CBCT imaging and dental microscope (28). However, there is a contradiction among the results of in-vitro studies about the effect of different coronal designs on the fracture resistance of endodontically treated teeth (26,44).

The loading sites on the subject model were identified using occlusal fingerprints analysis following the method of Kullmer et al. 2009. Occlusal fingerprints have the advantage of simulating the clinical scenario in contrast to studies that simply determines two points of load application regardless the actual clinical loading areas. These areas were added to the FEA model, and simultaneous loading was applied to each of them. The load applied was 50 N cyclic loading because cyclic loading in the form of mastication over time has been linked to crack initiation and spread (29,31,34,45–48).

Regardless of the access cavity design used in this study, the maximum VM was occlusal positioned at the location of the load application. Jiang et al. (49) and Saber et al. (28) both support this conclusion. The variation in stress magnitude was rather slight. In the IT model, the simulated forces occluded on the enamel, whereas in the other models, they occluded on the enamel-composite interface, which can be attributed to the structure receiving the loading force. This emphasizes the significance of the relationship between the positioning of loading points and the size of the access cavity margins.

Radicular stresses were mainly on the external surface of the root, and a negligible value was transmitted to the root canals. This agrees with the previous study of Maravić et al. (50). Moreover, the distribution of radicular stresses followed a consistent pattern throughout all experimental scenarios with higher values cervically and gradually decreased apically. This finding agrees with Saber et al. (28) and Nawar et al. (29) and disagrees with Wang et al. (15) but they used static loading of 800 N. There were more stresses at the cervical cross-section in CAC designs than that in TAC designs. This may be explained as the bucco-palatal dimension of the CAC was less than that of the TAC, making the load fall at or close to the tooth-restoration margin. Moreover, the TAC had more composite volume in which the stresses were consumed.

MPS values increased as the access cavity margin reached the functional load areas.
All MPS values on the radicular part were of a minor value. In all the models, tension was detected at the level of the furcation, but it likewise had very little significance.

Limitations of this study include that the FEA simulation only provided data for one specific anatomical configuration. This can represent a drawback in FEA studies regardless the tooth given the wide variation of anatomical features such as the presence of extra canals (51,52), C-shaped canals (53) and how stress localizations and values may be influenced by the root trunk's height, external root shape, and other factors (28). Also, the mechanical characteristics of materials are specified as uniform, linearly elastic, and isotropic with a tissue young's modulus. The Poisson's ratio and young's modulus aren't always the same inside the dentin since the hardness of the dentin diminishes from the outer surface to the tooth pulp cavity. It is also important to emphasis that this study did not explore the biological impact of the access cavity on the cleaning and shaping procedure that usually dictates irrigant activation with different methods (54).

Within the limitations of this study, it can be concluded that reducing the size of the access cavity does not necessarily reflect positively on the biomechanical behavior of the tooth. Moreover, the relationship between loading sites and access margins can take precedence over buccolingual conservation in terms of importance. It is advised that access should be regarded as a case-specific scenario with a unique access cavity whose design is based on its static and dynamic relationships of occlusion.

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