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ORIGINAL ARTICLE

The Biomechanical Behaviour and Life Span of a Three-rooted Maxillary First Premolar with Different Access Cavity Designs: A Finite Element Analysis

Nehal ALSHAZLY,[1] Nawar Naguib NAWAR,[1] Gianluca PLOTINO,[2] Shehabeldin SABER,[1,3]

[1]Department of Endodontics, Faculty of Dentistry, The British University in Egypt, Cairo, Egypt
[2]Private Practice, Rome, Italy
[3]Center for Innovative Dental Sciences (CIDS), Faculty of Dentistry, The British University in Egypt, Cairo, Egypt

ABSTRACT

Objective: The present study aimed to evaluate the influence of different access cavity designs on the biomechanical behaviour of a three-rooted maxillary first premolar using finite element analysis (FEA).

Methods: Three experimental FEA models were generated: the intact tooth (IT) model, the traditional access cavity (TAC) model, and the conservative access cavity (CAC) model. In both TAC and CAC models, root canals preparation was simulated as follows: the mesiobuccal and distobuccal canals with a final tip size of 30 and taper of 0.04 and the palatal canal with a final tip size of 35 and taper of 0.04. Cyclic loading of 50 N was simulated on the occlusal surface of the three models. The number of cycles until failure (NCF), the location of failure, stress distribution patterns, maximum von Mises (VM), and maximum principal stress (MPS) were all evaluated and compared.

Results: Both types of access cavity preparation caused a reduction in the lifelog of the tooth; when compared to the IT model the TAC model had a lifelog of 94.82% while the CAC model had a lifelog of 95.80%. The maximum VM stresses value was registered on the occlusal surface of the TAC model (7 MPa), while the minimum was on the occlusal surface of the IT (6.2 MPa). MPS analysis showed that the highest stress value was recorded on the occlusal surface of the CAC model (7.71 MPa), while the least was recorded on the occlusal surface of the TAC model (3.77 MPa). Radicular stresses were always of minimal value regardless the model.

Conclusion: The relation between the access cavity margins and the functional load points is a deciding factor that influences the biomechanical behaviour and fatigue life of endodontically treated teeth.

Keywords: Biomechanical behaviour, conservative access, finite element analysis, maxillary premolars, tooth life span, traditional access

HIGHLIGHTS

- Conservative access cavity differs from Traditional access cavity in terms of soffit preservation. This accounts for a 28.7% less volume of dentine removed.
- For a three-rooted maxillary premolar, the aforementioned extra step of preservation did not reflect in terms of a substantial increase in the life expectancy of the tooth.
- Access cavity designs should be customized for each individual tooth according to its occlusal functional relations.
- Heavy static and dynamic occlusal contacts should be included or excluded from the outline form to avoid failure.

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Address for correspondence:
Shehabeldin Saber
Department of Endodontics, Faculty of Dentistry, The British University in Egypt, Cairo, Egypt / Center for Innovative Dental Sciences (CIDS), Faculty of Dentistry, The British University in Egypt, Cairo, Egypt
E-mail: shehabeldin.saber@bue.edu.eg

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INTRODUCTION

The biomechanical behavior of endodontically treated teeth (ETT) is affected by the amount of lost dental tissues before, during and after treatment (1). Loss of tooth structure, changes in collagen fibril cross-linking, and loss of pulp vitality predispose ETT to fractures (2). Unfortunately, most fractures are non-restorable (3).

Tooth fracture after root canal treatment has many predisposing factors including tooth position and alignment in the oral cavity, the occlusion in terms of magnitude and direction of the functional loads, root number and morphology, the quality of the coronal seal, and the amount of remaining sound tooth structure (4, 5).

Maxillary premolars have a high incidence (6) and the greatest susceptibility to fracture under occlusal loading (7). Their narrow cervical thickness, presence of a concavity on the mesial aspect of the root, and a radicular groove on the palatal aspect of the buccal root predispose them to cusp fractures and vertical root fractures (8–10). The presence of three roots in maxillary first and second premolars has been reported for different populations and ranged from 0.9% to 9% (11–15).

The minimally invasive endodontics (MIE) concept was introduced to preserve dental tissues and decrease the frequency of post-operative fractures. The conservative endodontic cavity (CEC) was suggested to preserve the pericervical dentine by incomplete deroofing of the pulp chamber. Nevertheless, other versions of extreme conservatism were also advocated; collectively referred to as the ultra conservative access designs. This included: (a) the orifice directed dentine conservative access (Truss access), (b) the ninja access (point access), and (c) some caries driven access cavities. Such designs diverge from the concept of straight-line access in the traditional access cavity (TAC) (16).

The impact of such designs on the biomechanical behavior of ETT is rather contradictory (17). Many *in-vitro* studies reported an improved fracture resistance in teeth with minimally invasive access cavities (17). However, other studies have shown no significant difference between the TAC design and the CAC designs in maintaining fracture strength (17).

The three-rooted variation of maxillary premolars is seldom studied and there is scarce evidence for the influence of this anatomical variation on its biomechanical behaviour after endodontic treatment using different access cavity design. The present study sought to investigate, using the finite element analysis (FEA) method, the impact of different access cavity designs on the biomechanical behaviour of an endodontically treated three-rooted maxillary first premolar.

MATERIALS AND METHODS

The study proposal was reviewed and approved by the research ethics committee at The British University in Egypt (approval number: 21-004 on 23/2/2021). This study was conducted in accordance with the Declaration of Helsinki.

Finite Element Model Generation

A recently extracted, non-carious, three-rooted maxillary first premolar with mature apices, normal root morphology and canal curvatures less than 20 degrees was selected. The tooth was anonymous and was extracted for periodontal reasons not related to this study. The tooth was cleaned and examined under 16X magnification by a dental operating microscope (Zeiss Extaro 300, Germany) to confirm the absence of any fractures or resorption defects. The selected premolar was scanned with a high-resolution Cone Beam Computed Tomography machine (Planmeca ProMax 3d MID; Planmeca, Helsinki, Finland), with endodontic mode, operating at 90 kV, 12 mA with a voxel dimension of 75 µm. A total of 668 images were generated and the data was obtained in the DICOM format images. Materialize interactive medical image control system (MIMICS 19.0; Materialise, Leuven, Belgium) was then used to identify enamel and dentine, as well as produce the 3-dimensional (3D) model by forming masks and automatically growing threshold regions. Data were then optimized using the 3-Matic Medical 11.0 software (Materialise NV). SolidWorks (Dassault Systems, France) was used to combine enamel and dentine as well as to establish the surrounding bone.

Model Validation

Finite Element (FE) model was validated in the same manner as described by Nawar et al. (18). The scanned natural tooth was used for direct validation of the FE model. A 3D printed plastic block and high-fusion wax (Galileo; Talladium Inc, Valencia, CA) were used for compensation of the periodontal ligament and bone. Load was applied then displacement was measured using a universal testing machine (Lloyd instruments LRX-plus; Lloyd Instruments Ltd, Fareham, UK). Testing loads were precalculated to apply linear static load and to allow for multiple elastic testing. The load was applied by three-dimensional negative shaped parts to ensure correct contact area. With a 3% maximum error percentage, three trials of 10, 20, and 30 N were performed (18).

Access Cavity Design

After producing the intact tooth (IT) model, the accessed models were generated (Fig. 1). The traditional access cavity (TAC) was designed by removing the entire roof of the pulp chamber ensuring a straight-line path from the access opening to the root canal orifice (19). As for the conservative access cavity (CAC), a line was drawn from the center of the root canals' orifices at the furcation level and extended to the occlusal surface resulting in two cross-points that are then connected to produce the access outline (19). The volume of CAC was 57.61 mm^3 while that of the TAC was 80.72 mm^3.

Root Canal Preparation

Root canal preparations were virtually simulated using the software SolidWorks (Dassault Systems, Cedex, France) by drawing a central axis in the root canal and then creating a conical shape around it using the following dimensions: the mesiobuccal and distobuccal canals were prepared with a final tip size of 30 and taper of 0.04 and the palatal canal with a final tip size of 35 and taper of 0.04. The prepared root canals of the TAC and CAC models were then filled with simulated gutta-percha filling materials, 0.5 mm short from the apex of roots up to 2 mm from the canal orifices. Flowable resin composite was then used above the gutta-percha till the level of the pulp horns. The access cavities were finally filled with simulated composite resin materials.

Meshing and Set Material Properties

The experimental models were imported into the Cosmos software package (Solid works software package; Dassault Systems) for meshing. This resulted in models with an element size ranging from 0.402637 to 2.01319 mm according to the complexity of the models. Teeth and all materials used were considered ho-

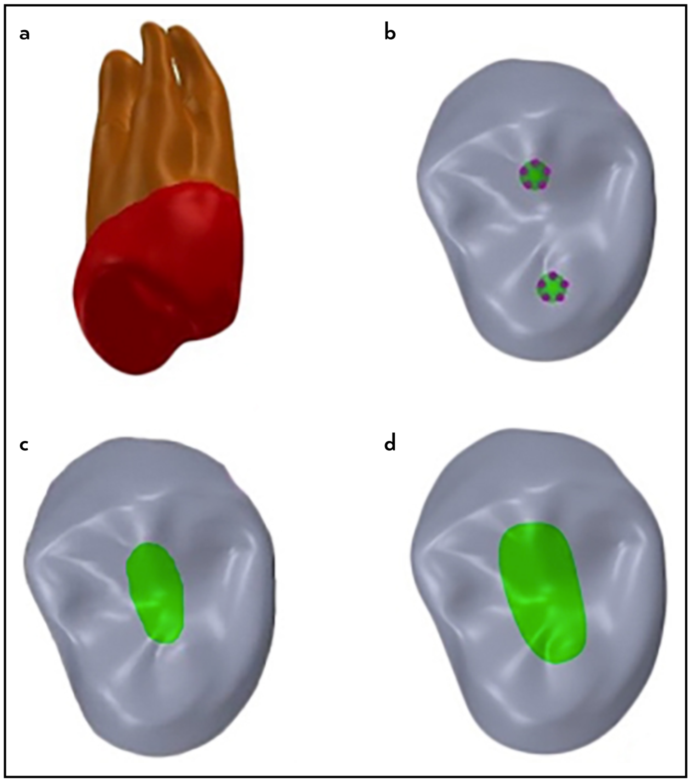

Figure 1. (a) The sound model of the intact three-rooted premolar; (b) The points of load application on the occlusal surface of the solid model; (c) The conservative access cavity (CAC) outline formed by removing the area between the projected long axis of the root canals yet preserving the soffit; (d) The traditional access cavity (TAC) outline that completely deroofs the pulp chamber

mogeneous, linear, and isotropic (20–22). The elastic modulus and Poisson's ratio of structures used to set up FEA models are listed in Table 1 (18, 20, 22), whereas the plot of stress/Number of cycles to failure (SN curve) for both of enamel and dentine was set according to Gao et al. (22) and Kinney et al. (23). The numbers of nodes and tetrahedral elements ranged from 68305 and 42530 respectively (IT model), to 72037 and 43212 respectively (TAC model). Considering the bounding conditions, the cancellous bone block was fixed mesially and distally and all components were simulated to have bonded contacts.

Finite Element Analysis

The three experimental models were subjected to simulated cyclic loading with a magnitude of 50 N to simulate the clinical masticatory loading (24, 25). Vertical load (vertical to the longitudinal axis of the models at 0°) was applied mid-way through the inclined planes of the buccal and palatal cusps, following the pattern of Lim et al. (26).

Simulations of the cyclic loading until failure of the three experimental models (IT, TAC, and CAC) were done, and the number of cycles to failure (NCF) was registered. The fatigue life for TAC and CAC groups was calculated as the percentage of the NCF in comparison to the IT model. Mathematical analysis of the stress distribution patterns, maximum von Mises (VM) stress, maximum principal stress (MPS) and fatigue life after load application to all models were assessed by FEA using the

TABLE 1. Mechanical properties of the materials for Finite Element Analysis (5-7)

Material	Young's modulus (MPa)	Poisson's ratio
Enamel	84100	0.33
Dentine	18600	0.31
Resin composite	12500	0.3
Gutta-percha	0.69	0.45
Periodontal ligament	68.9	0.45
Alveolar bone	13700	0.3

TABLE 2. Number of cycles to failure (NCF) and the life span of the TAC and CAC models compared to the IT model

Experimental model	NCF	Life span (%)
IT	1.37×10^{10}	100.00
TAC	4.092×10^{9}	94.82
CAC	5.15×10^{9}	95.80

IT: Intact model, TAC: Traditional access cavity, CAC: conservative access cavity

Cosmos software package (Solid works software Package; Dassault Systems). All values were tabulated and compared, and stress distribution patterns were analysed.

Statistical Analysis

Not applicable for finite element analysis studies (18, 20, 22).

RESULTS

The NCF of the TAC and CAC models and their fatigue life in comparison to the IT model are presented in Table 2.

The magnitude and distribution of VM stresses are displayed in Figure 2. At the occlusal surface (Fig. 2a), the maximum VM stresses were recorded for the TAC model (7 MPa) followed by the CAC model (6.84 MPa) and the IT model (6.2 MPa), respectively. The isometric view of the models (Fig. 2b) showed uneven distribution of stresses, with more stresses at the distopalatal line angle and the cervical line of the CAC model.

Regarding the cervical VM stresses, at the level of the cervical line (Fig. 2c), only the CAC model showed more stresses in the palatal root. Whereas at the root furcation level (Fig. 2d), and 2mm from the root apex (Fig. 2e), the magnitude of the observed stresses was minimal, and its distribution was comparable amongst all models.

The magnitude and distribution of MPS are displayed in Figure 3. At the occlusal surface (Fig. 3a), the CAC model had the highest MPS value (7.71 MPa), followed by the IT model (4.22 MPa), while the least MPS value was recorded in the TAC model (3.77 MPa). At all cervical levels (Fig.3 c-e), the magnitude of the observed stresses was minimal, and its distribution was comparable amongst all models. The cervical cross sections of all models showed the same pattern of stress distribution with tension concentrated on the external surface of the distobuccal root and compression on the external surface of the palatal root.

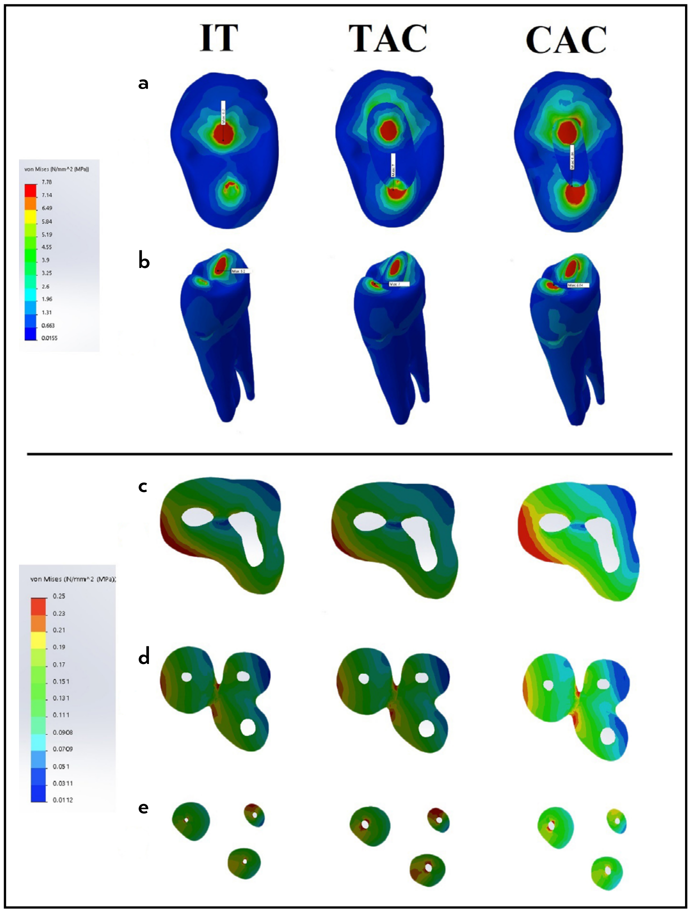

Figure 2. Composite figure showing von Mises (VM) stresses distribution for the IT, TAC, CAC models under loading. (a) Occlusal view; (b) Isometric view from the distopalatal line angle; (c) Cervical cross-section view; (d) Furcation cross-section view; (e) Cross-section 2 mm above the root apex

IT: Intact tooth, TAC: Traditional access cavity, CAC: Conservative access cavity

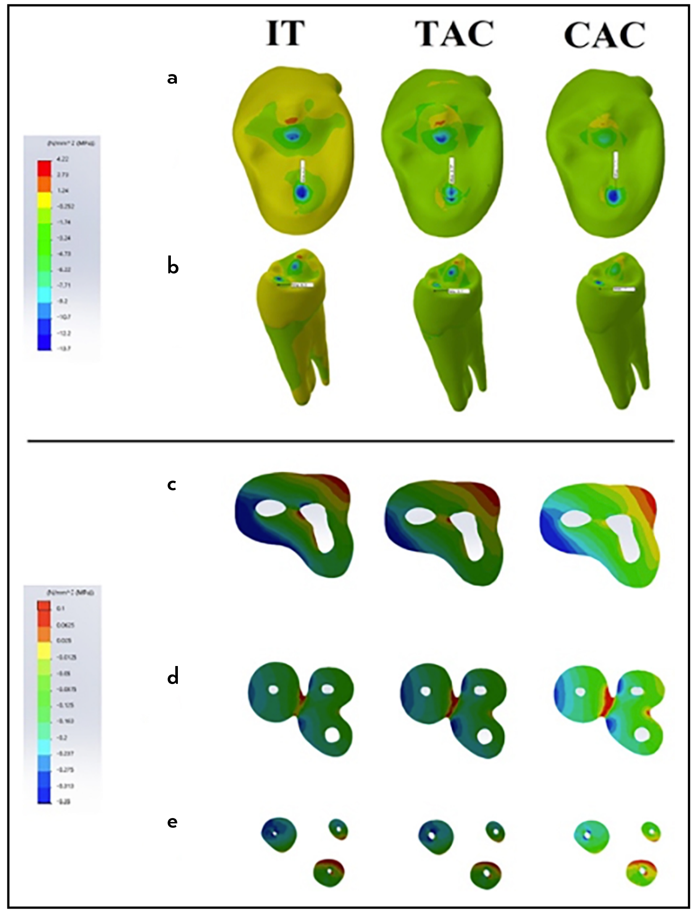

Figure 3. Composite figure showing maximum principal stresses (MPS) distribution of the IT, TAC, CAC models under loading. (a) Occlusal view; (b) Isometric view from the distopalatal line angle; (c) Cervical cross-section view; (d) Furcation cross- section view; (e) Cross-section 2 mm above the root apex

IT: Intact tooth, TAC: Traditional access cavity, CAC: Conservative access cavity

DISCUSSION

The biomechanical behaviour of ETT is dependent on the remaining amount of sound coronal and radicular tooth structures (9, 27, 28–31). Therefore, the current study sought to investigate the impact of different access cavity designs on an anatomic variant for a tooth with a high incidence of fracture susceptibility.

FEA was used for stress analysis in the present study because it has the merit of standardization through the evaluation of one tested variable while virtually fixating all other contributors, thus providing reliable results and numerically controlled testing to overcome limitations of *in-vitro* studies such difficulties in teeth storage and crack incidence (32).

Ultraconservative access cavity designs such as the ninja or point access were not included because literature does not support the notion that they provide any additional mechanical advantage beyond what is provided by conservative designs (19, 20). On the other hand, evidence suggests that the ultraconservative designs complicate the procedures and add to the inherent risks of procedural errors and the failure to achieve the biological objectives (33, 34).

In this study simulated cyclic loading was applied, given the fact that clinically most of the failures of the ETT are caused by cyclic fatigue with a subcritical load or fluctuating stresses which are much lower than the load capacity required to cause a catastrophic failure (18, 24, 33). Such repeated masticatory loading cycles cause fatigue failure due to the cumulative effect of crack initiation and propagation over time (27, 35).

In the present study, the maximum VM was located occlusally at the site of load application regardless of the access design. This finding agrees with Saber et al. (19) and Jiang et al. (36). Though the difference in stresses magnitude was minimal, it was unevenly distributed, as the IT model showed maximum VM stresses on the buccal cusp slope while the TAC and CAC models showed a palatal location. This can be attributed to the structure receiving the loading force, as in the IT model the simulated occlusal forces landed on enamel, while in the other models they landed on the enamel-composite interface. This highlights the importance of the relation between the location of loading points and the extent of the access cavity margins.

Both the cervical and radicular stresses were inversely proportional to the size of the endodontic access cavity. The

CAC model showed higher cervical stresses when compared to the TAC model and the IT model, and almost double the radicular stress values of the TAC model. Regarding radicular stresses, maximum VM was mainly on the external surface of the root and the inward transmitted stresses to the root canal walls were of a minor value and this pattern was similar in all experimental models, with higher values at the cervical cross-section that gradually decreased toward the apices. These findings concerning radicular and cervical stresses agree with Saber et al. (19) and Nawar et al. (18) and disagree with Wang et al. (20) who used static loading of 800 N. This may be understood in the light of how the buccolingual dimension of the CAC was less than that of the TAC, thus causing the load to fall near the tooth-composite interface, which hinders smooth stress transition. On the other hand, the TAC design had a wider area of access, so the stresses were within the coronal composite restoration.

Stress analysis of the models especially the IT one adds to the growing body of evidence to the concept that enamel acts like a "compression dome" protecting the tooth (37). Enamel has a higher modulus of elasticity (tougher) in comparison to resin composite and thus can accommodate higher stresses internally (19). Therefore, preserving the tooth structure, especially enamel, was associated with consumption of stresses coronally rather than their propagation to the roots (19), i.e., stresses are either trapped coronally with a higher magnitude or disperse towards the root on a larger surface area to bring their magnitude down. This is in agreement with Saber et al. (19), Elkholy et al. (21), and Nawar et al. (18).

MPS values raised when the access cavity margin approached the functional load points and all the MPS values on the radicular portion were of a minor value. Tension was found at the furcation level of all the models; however, it was also of a minor value.

In this study, loss of coronal enamel and dentine reduced the tooth's lifespan. This goes in agreement with three studies (18–20). Also, in the present study, the volume of CAC was 29% less than that of the TAC resulting in preservation of more sound tooth structure which agrees with Saber et al.(19) and Isufi et al (38). However, this considerable amount of structural preservation did not reflect on the NCF or lifelog percentage. This agrees with Silva et al (34), Xia et al (39), Roperto et al. (40), and Periera et al. (41) who, desipte using different methodologies, concluded that the access cavity design did not have an impact on the fracture resistance of premolars.

Limitations of this study include that the FEA simulation did not embrace the impact of thermocycling on the bond strength and life span of different simulated materials. Moreover, the anatomical uniqueness of the investigated tooth did not allow for much difference in size between the traditional and conservative access designs which may have contributed to insignificant differences. Finally, FEA studies assume that dental structures are uniform isotropic materials, when in fact dental structures are functionally graded materials with varying elastic moduli and creep-related behaviour (42, 43).

It is recommended to perform further research to evaluate more dynamic loading situations because this study only investigates specific sets of loading parameters. It is also advisable to study the impact of marginal ridge(s) loss for enhanced clinical simulation.

Within the limitations of this study, it can be concluded that the biomechanical behaviour and fatigue life of ETT were mainly influenced by the relation between the location of load points and the extent of the access cavity margins. Therefore, it is recommended that a custom access design is recommended for each tooth according to its static and dynamic occlusal relations, preferably excluding or including the antagonistic contact points to avoid stress concentration and clinical failure.

Disclosures

Conflict of interest: The authors deny any conflict of interest.

Ethics Committee Approval: This study was approved by The British University in Egypt Ethics Committee (Date: 23/02/2021, Number: 21-004).

Peer-review: Externally peer-reviewed.

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