Effect of proximal caries-driven access on the biomechanical behavior of endodontically treated maxillary premolars

Engy M. Kataia
engy.medhat@bue.edu.eg

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Nawar Naguib Nawar, BDS, MSc, PhD, Lecturer, Roaa Abdelwahab Abdelfattah, BDS, Mohamed Kataia, BDS, MSc, PhD, Professor, Shehabeldin Mohamed Saber, BDS, MSc, PhD, Professor, Engy M. Kataia, BDS, MSc, PhD, Professor, Hyeon-Cheol Kim, DDS, MS, PhD, Professor

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Effect of proximal caries-driven access on the biomechanical behavior of endodontically treated maxillary premolars

Running title: effect of proximal caries-driven access on biomechanical behavior

Nawar Naguib Nawar[1], Roaa Abdelwahab Abdelfattah[1], Mohamed Kataia[1], Shehabeldin Mohamed Saber[1,2,3], Engy M. Kataia[1,4]*, Hyeon-Cheol Kim[5]*

[1]*Department of Endodontics, Faculty of Dentistry, The British University in Egypt (BUE), El Sherouk city, Egypt*

[2]*Center for Innovative Dental Sciences (CIDS), Faculty of Dentistry, The British University in Egypt (BUE), El Sherouk city, Egypt*

[3]*Department of Endodontics, Ain Shams University, Cairo, Egypt*

[4]*Restorative and Dental Materials Department, National Research Centre, Doki, Egypt*

[5]*Department of Conservative Dentistry, Pusan National University School of Dentistry, Dental Research Institute, Dental and Life Science Institute, Yangsan, Korea*

Nawar Naguib Nawar, BDS, MSc, PhD, Lecturer

Roaa Abdelwahab Abdelfattah, BDS

Mohamed Kataia, BDS, MSc, PhD, Professor

Shehabeldin Mohamed Saber, BDS, MSc, PhD, Professor

Engy Medhat Kataia, BDS, MSc, PhD, Professor

Hyeon-Cheol Kim, DDS, MS, PhD, Professor

* Corresponding authors:

Dr. Engy Medhat Kataia, BDS, MSc, PhD, Professor

Department of Endodontics, Faculty of Dentistry, The British University in Egypt, Cairo, Egypt

Tel: +2 01001859898, Email: Engy.Medhat@bue.edu.eg

Dr. Hyeon-Cheol Kim, DDS, MS, PhD, Professor

Department of Conservative Dentistry, School of Dentistry, Pusan National University

Geumo-ro 20, Mulgeum, Yangsan, Gyeongnam, 50612, Korea

Tel: +82-55-360-5222, e-mail: golddent@pusan.ac.kr

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Effect of proximal caries-driven access on the biomechanical behavior of endodontically treated maxillary premolars

ABSTRACT

Introduction: This study investigated the effects from the carious cavity and access from it on the fracture resistance of endodontically treated maxillary premolars using finite element analysis (FEA).

Methods: A maxillary premolar was used to compare three types of access cavity related to having a proximal carious defect: Caries-driven access (CDA), Conservative access that has a mesial component (MCA) as well as traditional access with the same mesial component (MTA). Cyclic loading was simulated on the occlusal surface and number of cycles till failure (NCF) was compared to the intact tooth model (IT). Mathematical analysis was done to evaluate the stress distribution patterns and calculated maximum von Mises (vM) and maximum principal stresses (MPS), with emphasis on pericervical region as a specific area of interest.

Results: Maximum vM registered on the IT was 6.14 MPa. The CDA provided the highest NCF with 92.28% of the IT, followed by MCA (84.90%) and MTA (83.79%). The vM and MPS analysis showed that the stress values and patterns are affected more by the proximity of the occlusal load to the tooth/restoration interface. Concerning the pericervical region, maximum vM was registered for IT (4.11 MPa), followed by the CDA (4.85 MPa), then MCA (8.13 MPa) and MTA (8.61 MPa). While the MPS analysis revealed that the CDA showed the highest magnitude of tensile stresses.

Conclusion: A proximal CDA benefits the mechanical properties of maxillary premolars, however its impact on the biological aspect should be assessed to provide a ruling for/against it.

KEYWORDS: cyclic fatigue; finite element analysis; fracture resistance; maxillary premolars; caries-driven access

INTRODUCTION

Many investigations are directed towards the biomechanical behavior of endodontically treated teeth (ETT)[1-4] because most fractures after endodontic treatment are non-restorable[5-7]. This unfortunate sequalae motivated the proposal of access cavity designs that target better dentin preservation[8]. The newly introduced access cavity designs varied in their complexity; from a simple deviation from complete pulp chamber deroofing to the more demanding orifice-directed ones[9]. The new designs gained interest among clinicians before sufficient evidence could support or refute them[4,9], and it was not surprising that as controversial evidence about access cavity designs accumulates, both the complexity of the issue and the need for more research got clearer.

The concept of minimally invasive dentistry or endodontics with minimal sacrifice of coronal structure was suggested for better prognosis of ETT. For this purpose, conservative and ultraconservative access cavities were tried[2,3,9]. Moreover, access to the canal space through the caries lesion (caries-driven access; CDA) with minimal removal of intact dentin has also been suggested and tried[9]. These attempts of dentin conservation should prevent or at least reduce the fracture incidence of ETT[2,8].

Maxillary premolars are recognized to be more susceptible to vertical root fractures[10]. Their narrow cervical thickness, presence of a mesial root concavity predisposes them to cusp and/or vertical root fractures upon lateral occlusal loads[11-13]. However, many studies have shown no benefit when the buccolingual dimension of their access cavity preparation is reduced from a traditional to a conservative or even an ultraconservative access[9,14].

In some clinical scenarios where a neighboring tooth is missing, proximal caries-driven access may be an option. Such design would preserve much of the pulp chamber roof, and it seems logical to assume it can provide a reinforcing quality to the tooth. Though a proximal design will only provide a curved trajectory to the root canals[2,9], this issue is becoming less of a challenge with the advances in shaping instruments in terms of metallurgy, design, and safe kinematics[15,16].

For proper selection of the access cavity design, research evidence is highly required. Unfortunately, laboratory tests using extracted teeth are almost impossible to standardize, due to uncontrollable factors such as teeth morphology, age, extraction forces and storage conditions[7,17]. Therefore, a numerically controlled test that allow fixation of contributing factors, such as the finite element analysis (FEA) can isolate the effect of a specific variable in a scenario that mimics the clinical situation as much as possible[3,4].

This study aimed to evaluate whether the proximal caries-driven access cavity approach will enhance the biomechanical behavior of maxillary premolars by the FEA method[2-4]. The null hypothesis was that proximal caries-driven access would not significantly affect the fatigue life of maxillary premolars.

MATERIALS AND METHODS

Finite Element Analysis Model Generation

An intact mature single-rooted human maxillary premolar was selected for the study. The tooth was scanned in a high-resolution cone beam computed tomography machine (Planmeca ProMax 3d MID; Planmeca, Helsinki, Finland) with a voxel dimension of 75 µm. Materialize interactive medical image control system (MIMICS version 21; Materialise, Leuven, Belgium) was used to identify the dental structures and to convert the generated DICOM format images into 3D models by forming masks and automatically growing threshold regions. Data was then optimized using the 3-Matic Medical 11.0 software (Materialise, Leuven, Belgium). SolidWorks (Dassault Systemes, France) was used to combine enamel and dentin and establish the surrounding periodontal ligaments and bone. Lastly, the mathematical model was validated in the same manner used by Nawar et al[4].

Access Cavity Design and Root Canal Preparation

A list of acronyms used throughout the manuscript is detailed in Table 1. After producing the intact tooth model (IT), three accessed models were generated (Fig. 1); one with a caries-driven mesial access (CDA), another with the same mesial cavity along with a conservative occlusal access that preserves the soffit (MCA), and finally a model with the same mesial cavity along with a traditional occlusal access (MTA). To create a traditional endodontic access cavity, the entire roof of the pulp chamber was removed to create a straight-line path from the access opening to the root canal orifice[2]. To create the digital design with a conservative access, an arbitrary line was drawn from the center of the root canal orifice at the furcation level, then extended to the occlusal surface resulting in two cross-points connected to produce the access outline[18]. To create the CDA, the middle 1/3 of the buccopalatal width of the tooth in the mesial one third was removed including the marginal ridge thus entering the pulp chamber as a tunnel with an occlusogingival depth of 1.5-2 mm on the outer surface[19,20]. The junctions between the occlusal and the proximal cavities in the MCA and MTA were made to be smooth and curvy to avoid establishing stress concentration areas.

The access cavity was filled with simulated composite resin material. The volume of the access cavity for CDA was 39.24 mm^3, 51.83 mm^3 for the MCA, and 58.37 mm^3 for the MTA. After measuring the apical diameter of the root canal, the root canal preparation was determined accordingly. Root canal preparation was simulated by drawing an arbitrary line in the central axis of the root canal, then creating a conical shape around it with the target dimensions[2-4]. The radicular morphology of the premolar was Vertucci type II[21], with an apical diameter of 0.27 mm at its minor constriction, thus the radicular preparation was simulated to have #40/.04 sized lumen. The preparations were overlapped, and the prepared root canals were filled with simulated gutta-percha filling materials 0.5 mm short from the radiographic apex of the root canal up to 2 mm from the canal orifices.

Meshing and Set Material Properties

All models were imported into the Cosmos software package (SolidWorks) for meshing. The hard dental structures and the materials used were considered homogeneous, linear, and isotropic. The elastic moduli and Poisson's ratio of structures used to set up the FEA models are listed in Table 2 and their validity was checked according to Dorado et al[22], while the SN curve of enamel and dentin was set according to Gao et al[23] and Kinney et al[24]. The numbers of nodes ranged from 63715 (IT model) to 67652 (MTA model) and the number of tetrahedral elements ranged from 38411 (IT model) to 39610 (MTA model). Finally, the cancellous bone block was constricted from buccal and palatal sides, and all components were simulated to have bonded contacts (Fig. 1*D*).

Finite Element Analysis

To simulate the clinical conditions (Fig. 1*D*), all models were subjected to cyclic occlusal loading according to the pattern employed by Lim et al[25] with a magnitude of 50 N until failure[3,4,26]. The number of cycles until failure (NCF) was then registered as well as the failure location. The life span was calculated as the percentage of the NCF for each experimental model compared with the intact model[3,4,26]. Mathematical analysis of the stress distribution patterns, maximum von Misses (vM) stresses and maximum principal stress (MPS) were also assessed. In addition to the maximum values recorded for all models, further analysis was done to the cervical region of the teeth, being an important area of interest (AOI).

RESULTS

Maximum vM stress, NCF, and the life span of various models compared to the intact model are presented in Table 3, while vM and MPS stress distribution patterns are shown in Figure 2, and MPS range is shown in Figure 3. The CDA provided a considerable advantage with an 8-9% higher NCF than MCA and MTA, while the buccal extension of the occlusal portion did not provide much significance. Maximum vM ranged from 6.14 MPa in the IT model to 9.01 MPa in the MTA (Fig. 2). Concerning the location of the maximum vM stresses, they were located on the buccal cusp slope in the IT, CDA and MCA, however, in the MTA model, stresses were located on the palatal cusp slope in proximity to the tooth/restoration interface. Concerning MPS, the widest range of compression/tension stress values was found in the MCA with a range of -8.81 MPa to 4.3 MPa (Figs. 2 and 3). Both vM and MPS showed almost no radicular stresses.

Concerning the AOI, maximum vM ranged from 4.11 MPa in the IT model near the mesiobuccal line angle to 8.61 MPa in the MTA just buccal to the mesiopalatal line angle (Fig. 2). Also, the widest range of compression/tension stress values was found in the MCA with a range of -2.03 MPa to 3.73 MPa (Figs. 2 and 3). It is also notable that in the MTA model, the area showing the maximum MPS near the cervical line is wider than MCA but with lower stress values.

DISCUSSION

Clinical scenarios in endodontics vary widely, however, the aim of endodontics remains the same, which is restoring the function of the tooth for the longest possible time. Given the fact that ETT exhibit a shorter life expectancy when compared to vital teeth[12], researchers have investigated different factors that can contribute to the ability of the tooth to withstand occlusal forces and remain in function[1,2]. Among the postulates brought forth to extend the survival of ETT was the general assumption that preserving more dentin reflects on how a tooth reacts biomechanically to its burden[8]. In 2010, Clark and Khademi[8] introduced new concepts and subsequently new types of access cavity variations arose and got adopted, especially boosted by the growth of social media[9]. However, when researchers started investigating the new concepts and designs, some were accepted such as the value of the pulp chamber soffit[2,3], some were revoked because they cause more harm than benefit such as the ultraconservative cavity designs[2,3,9,14], and some are still debatable such as the criticalness and even the definition of the pericervical dentin[4].

One of the bio-minimalistic access cavity designs is the caries-driven access[9,27]. The caries driven access aims at limiting the removal of dental structure to the diseased carious lesion and undermined enamel[27]. However, smaller access designs can complicate the process needed to achieve the primary endodontic objective, which is debridement of the root canal system[28]. Hence, the importance of evaluating whether or not such access design provides any biomechanical advantage in the first place, which this study sought to do.

This study attempts to assess NCF, maximum vM and MPS in its analysis because studying the dental biomechanical behavior is quite complex. It is important that the study parameters are set to employ inputs that are as relevant as possible, however, there is always the risk of oversimplification[22]. Studying the dental biomechanical behavior should take into consideration stress values, stress character and its distribution pattern[2,22].

The null hypothesis was rejected; the CDA provided a remarkable biomechanical advantage and showed the least reduction in a tooth's life expectancy as evident by the NCF values. Also, MPS analysis showed in all models that failure happened in areas where stresses had a more tensile character. This finding agrees with previous studies that found dentin to be three folds stronger under compression than under tension[29,30].

Maxillary premolars vary widely in the number and morphology of their radicular structure[31]. However, the single-rooted variation is the most common type; while the vast majority of second premolars are single-rooted, ethnicity determines whether the maxillary first premolar is predominantly single or double rooted[31]. Therefore, a single rooted premolar was chosen for this study.

In this study all models showed minimal radicular stresses. Stresses were consumed on the outer surface of the root barely ever reaching the inner surface of the root canal. This agrees with previous studies[2-4,32]. Tension areas did not appear between the two canals in the single-rooted tooth with Vertucci type II configuration. This may be attributed to the fact that this area is supported by dentin in the Y-plane and that stresses get consumed on the external root surface. Finally, varying the radicular preparation parameters was not tested in this study because cumulative evidence demonstrated that it plays a minor role in the tooth's biomechanical behavior[3,4,32].

Meanwhile, simulations showed that restricting the occlusal portion of the access to the conservative design did not increase significantly to the tooth's survival, i.e. limiting the buccolingual extension of the occlusal portion of the access cavity in premolars adds no reinforcement to the tooth but can rather have a negative effect if occlusion contact points were not taken into consideration. This goes along with Alshazly et al[33], and with Silva et al[14] who found that even the ultraconservative access did not reinforce premolars. However, previous studies have shown that the practice of preserving the soffit would benefit molars[9]. This can be attributed to the larger surface area of loading, volume of dentin preserved and even the much wider occlusal table that characterize molars. Also, the findings of this study along with others[14,33] suggest that access-related studies on a set of teeth can be applicable for its different radicular morphological variations. This highlights the need for more specified studies from which clearer guidelines that refrain from generalizations can be drawn.

When special focus was given to the AOI, it could be noted that interrupting the tooth's enamel in all accessed models changed the stress distribution patterns shifting the point of maximum vM / tensile MPS to a more palatal location. However, caries driven access kept the stress values nearer to the value recorded for the intact tooth, while it was approximately doubled for both access designs that included an occlusal component. When MPS is studied for the MCA and MTA models, it could be seen that cervical stresses were distributed over a larger area of the cervical area of the MTA model. This wider distribution brought stresses values down. This agrees with the findings of previous studies[2,4]. When this finding is put along the finding that both models had comparable NCF, it highlights the aforementioned point of how critical it is in FEA studies to correlate numerical findings with stress distribution patterns.

This study has its limitations that are mostly related to the process of FEA itself. Enamel and dentin are functionally graded with varying elastic models and creep-related behavior which is an input that is not yet incorporated in literature's FEA process as far as the authors' knowledge and is not known if or how it may affect the results[26,34,35]. Another limitation is this study is that it is limited to a specific set of dentition, premolars. The study also investigates a specific pattern of loading. Further studies are needed to investigate the validity of the results with other teeth and different loading parameters given the evidence that varying the loading conditions can affect the outcome. Finally, whether or not proximal caries-driven access cavities can negatively impact the biological objectives of endodontic treatment was outside the scope of the study[36] and should be assessed by future studies.

CONCLUSION

A proximal caries-driven access cavity that distances the occlusion contact areas from the tooth/restoration interface is feasible from a mechanical point of view to reduce the mechanical failure of ETT. On the other hand, limiting the buccolingual extension of the occlusal portion of the access cavity in premolars adds no reinforcement to the tooth, but can rather have a negative effect if occlusion contact points were not taken into consideration. These findings of FEA computer simulations need to be confirmed in clinical settings by well-designed randomized clinical trials.

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Figure legends

Figure 1. The simulated models and conditions. (A) Intact tooth and three different access cavity designs and (IT: intact tooth, CDA: accessed with a caries-driven mesial access, MCA: accessed with the same mesial cavity along with a conservative occlusal access, and MTA: accessed with the same mesial cavity along with a traditional occlusal access). (B) Loading conditions used in this study. (C) Trajectories to the canals: (CDA) Curved trajectory, (MCA) Oblique line access, and (MTA) Straight line access.

Figure 2. von Mises (vM) and maximum principal stress (MPS) values as well as distribution patterns in the simulated models (IT: intact tooth, CDA: accessed with a caries-driven access, MCA: accessed with caries-driven cavity along with a conservative occlusal access, and MTA: accessed with the caries-driven cavity along with a traditional occlusal access). The mesiopalatal isometric view shows the nodal point of maximum vM and MPS at the AOI, while red arrows indicate the nodal points of maximum vM and MPS stresses value detected in the whole model. Negative sign in MPS denotes compressive stresses.

Figure 3. Bar chart showing maximum principal stress (MPS) values in MPa where negative values denote compressive stresses and the positive values denote tensile stresses. Values in red represent at the area of interest (AOI) while the values in blue represent in overall MPS values.

Table 1. List of acronyms used throughout the manuscript in the order of their appearance

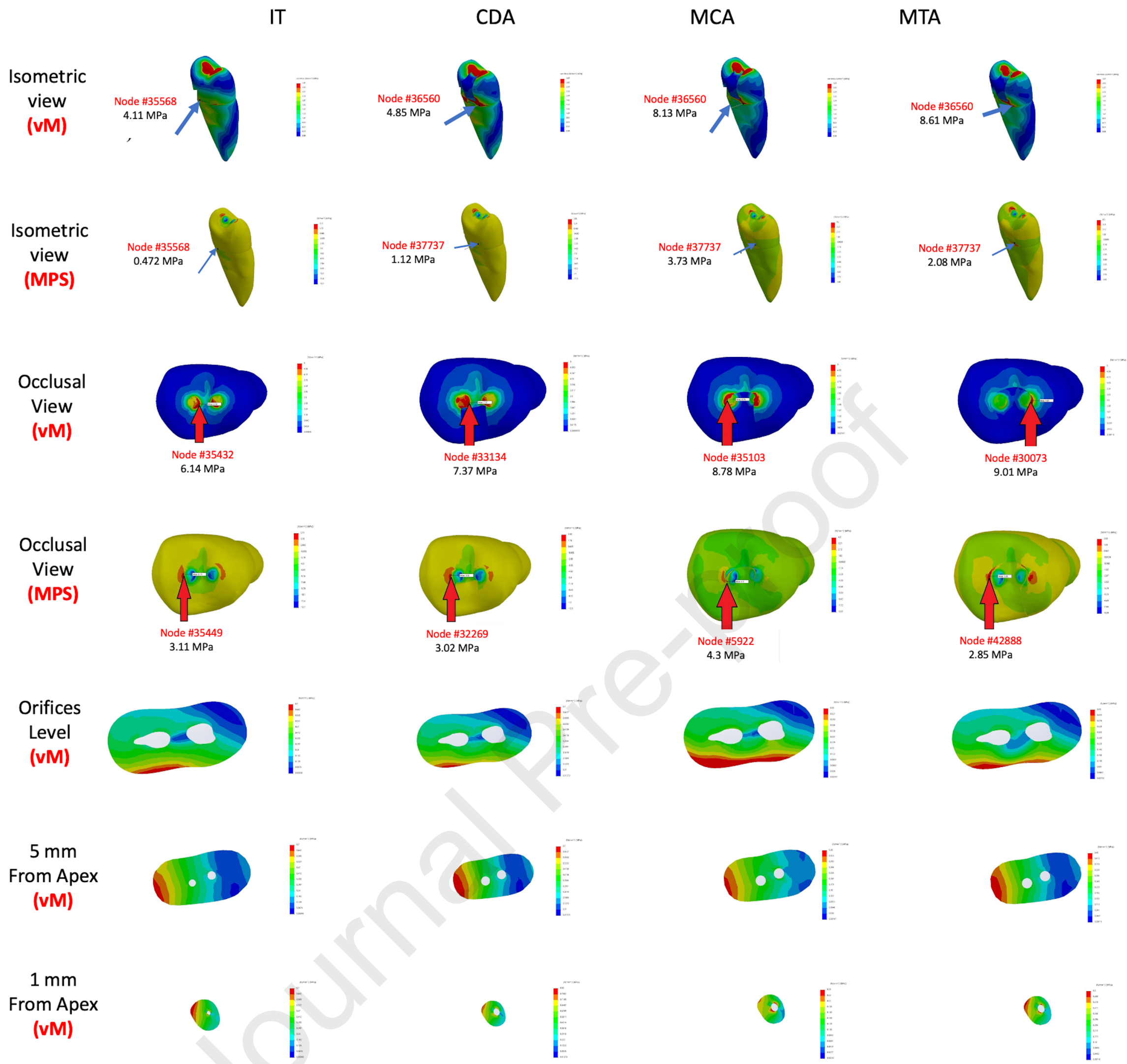
Full Text	Acronym
Endodontically treated teeth	ETT
Finite element analysis	FEA
Intact tooth	IT
Caries driven access	CDA
Conservative access with mesial component	MCA
Traditional access with mesial component	MTA
Number of cycles till failure	NCF
von Mises	vM
Maximum Principal Stress	MPS
Area of interest	AOI

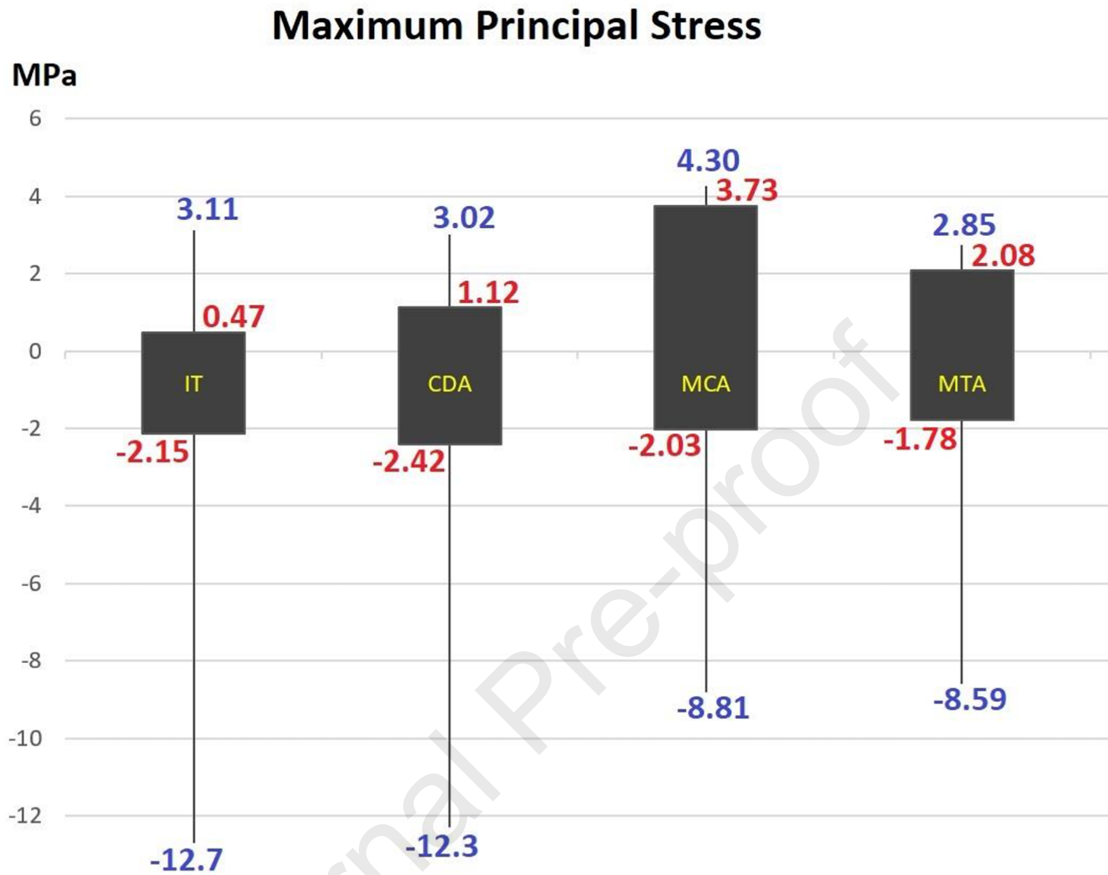
Table 2. Mechanical properties of the materials used for finite element analysis[2-4]

Material	Elastic modulus (MPa)	Poisson ratio
Enamel	84,100.00	0.33
Dentin	18,600.00	0.31
Periodontal ligament	68.90	0.45
Gutta-percha	0.69	0.45
Alveolar bone	13,700.00	0.30
Composite resin	12,500.00	0.30

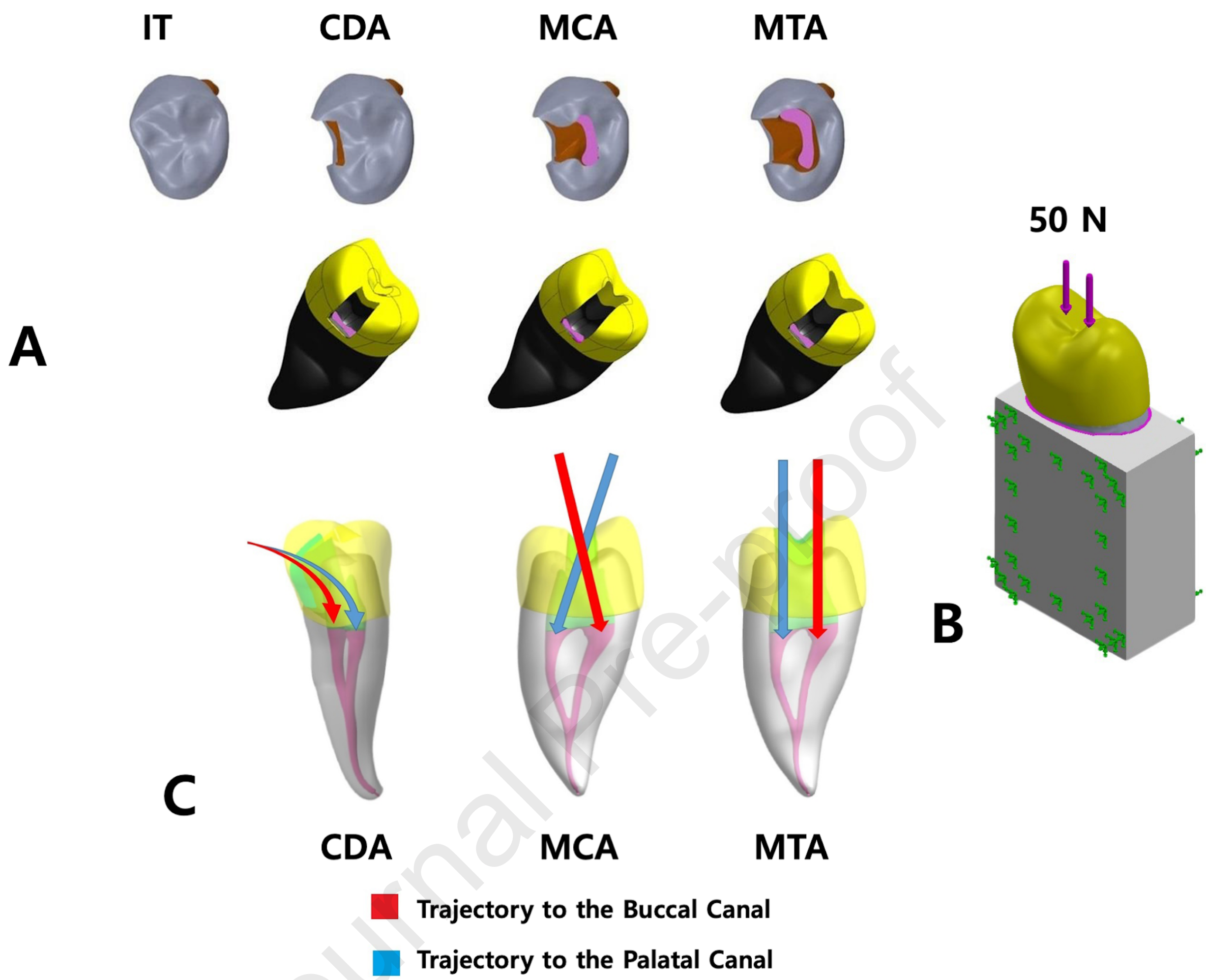
Table 3. Maximum von Mises (vM) stress, number of cycles till failure (NCF), and the life span of various models compared to the intact model

Model	Maximum vM Stress (MPa)	Maximum vM Stress at AOI (MPa)	NCF	Lifelog percentage (%)
IT	6.14	4.11	1.50×10^{10}	100.00%
CDA	7.37	4.85	2.46×10^{9}	92.28%
MCA	8.78	8.13	4.36×10^{8}	84.90%
MTA	9.01	8.61	3.36×10^{8}	83.79%


IT
CDA
MCA
MTA
Isometric view (vM)
Node #35568
4.11 MPa
Node #36560
4.85 MPa
Node #36560
8.13 MPa
Node #36560
8.61 MPa
Isometric view (MPS)
Node #35568
0.472 MPa
Node #37737
1.12 MPa
Node #37737
3.73 MPa
Node #37737
2.08 MPa
Occlusal View (vM)
Node #35432
6.14 MPa
Node #33134
7.37 MPa
Node #35103
8.78 MPa
Node #30073
9.01 MPa
Occlusal View (MPS)
Node #35449
3.11 MPa
Node #32269
3.02 MPa
Node #5922
4.3 MPa
Node #42888
2.85 MPa
Orifices Level (vM)
5 mm From Apex (vM)
1 mm From Apex (vM)



Maximum Principal Stress
MPa
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
3.11
0.47
IT
-2.15
-12.7
3.02
1.12
CDA
-2.42
-12.3
4.30
3.73
MCA
-2.03
-8.81
2.85
2.08
MTA
-1.78
-8.59


IT
CDA
MCA
MTA
50 N
A
B
C
CDA
MCA
MTA
Trajectory to the Buccal Canal
Trajectory to the Palatal Canal