***ORIGINAL ARTICLE*** */ ARTICLE ORIGINAL*

***Endodontics*** */ Endodontie*

# WOULD ACCESS CAVITY DESIGN AFFECT THE MECHANICAL BEHAVIOR OF TOOTH: A FINITE ELEMENT STUDY

**Muhammad Ashraf Elhusseini[1] | Hala Fayek Khalil[2] | Engy Medhat Kataia[3]**

**Introduction**: Two distinct access cavity designs were used to access Two simulated finite element models (FE) Lingual (LAC) and incisal (IAC)). Three experimental FE models, including the IT model, were developed: LAC and IAC.

**Methods**: For every simulated model, one distinct radicular preparations was carried out of size #30/.04. The incisal edge was subjected to an occlusal cycle load of 120 N. The maximum von mises stresses (VMS), maximum principal stresses (MPS), and stress distribution patterns were assessed and calculated quantitatively.

**Results**: The traditional access design showed slightly higher fracture resistance to loading than the conservative incisal access cavity design.

**Conclusion**: Although the access cavity design affected the biomechanical behavior of the mandibular central incisor, the post endodontic restoration had the greater impact.

**Keywords**: incisal access cavity design, lingual access cavity design, canal preparations, finite element analysis.

---

**Corresponding author**:
Muhammad Ashraf Elhusseini, School of Dentistry, The British University in Egypt, El Sherouk City , Suez Desert Road , Cairo 11837 - P.O. Box 43. E-mail: PG.muhammad919400013@bue.edu.eg

**Conflicts of interest**:
The authors declare no conflicts of interest.

1. Endodontic Department, School of Dentistry, The British University in Egypt.
   E-mail: PG.muhammad919400013@bue.edu.eg
2. Endodontic Department, School of Dentistry, The British University in Egypt.
   E-mail:Hala.Fayek@bue.edu.eg
3. Endodontic Department, School of Dentistry, The British University in Egypt.
   E-mail: Engy.medhat@bue.edu.eg

# *LA CONCEPTION DE LA CAVITÉ D'ACCÈS ET LA TAILLE DE LA PRÉPARATION DU CANAL AFFECTERAIENT-ELLES LE COMPORTEMENT MÉCANIQUE DE LA DENT : UNE ÉTUDE PAR ÉLÉMENTS FINIS.*

**Introduction:** Deux conceptions de cavités d'accès distinctes ont été utilisées pour accéder à deux modèles d'éléments finis (EF) simulés. (Linguel (LAC) et incisal (IAC)). Trois modèles FE expérimentaux, dont le modèle IT, ont été développés : LAC et IAC.

**Méthodes:** Pour chaque modèle simulé, une préparation radiculaire distincte de taille #30/.04 a été réalisée. Le bord incisif a été soumis à une charge de cycle occlusal de 120 N. Les contraintes maximales de von mises (VMS), les contraintes principales maximales (MPS) et les modèles de répartition des contraintes ont été évalués et calculés quantitativement.

**Resultats:** Le comportement biomécanique de l'incisive mandibulaire est significativement influencé par la taille du modèle d'accès. Un aspect critique influençant le comportement biomécanique des dents traitées endodontiquement est la corrélation entre les sites de charge fonctionnelle et les marges de la cavité d'accès.

**Conclusions:** bien que la conception de la cavité d'accès ait affecté le comportement biomécanique de l'incisive centrale mandibulaire ; la restauration post-endodontique a eu le plus grand impact.

**Mots clés :** conception de cavité d'accès incisif, conception de cavité d'accès lingual, préparations canalaires, analyse par éléments finis.

## Introduction

Finite element analysis (FEA) uses the material properties of complicated structures to perform a numerical study of them. Recently, in endodontics, FEA has been used to examine how stresses are distributed when a structure is subjected to forces [1, 2].

Fracture resistance of tooth is reduced by removal of anatomic tooth structures like edges, cusps, and the pulp chamber roof during caries removal and access cavity preparation, as well as removal of root dentine during shaping and instrumentation. Moreover, it has been suggested that the most important factor influencing the teeth's resistance to fracture is the quantity of dentine that is left over following endodontic therapy. Consequently, it was shown that maintaining the pericervical dentin was essential to the survival of the teeth that had undergone endodontic treatment [3, 4].

Excavation at the cingulum and coronal third in anterior teeth should be minimal as possible as these structures affect its mechanical behavior. In the normally used traditional access cavity removing the caries and any existing restorations, including the pericervical dentine that reaches the apical constriction, and only leaving the healthy tooth components in place result in reduced fracture resistance and increased cuspal flexure [3-7].

The conservative endodontic access cavity (CEC), another name for the less invasive endodontics idea, was introduced after developments in imaging, visual enhancers, and endodontic equipment, in order to protect the peri-cervical dentin. But this cavity design may cause problems with instrumentation, irrigation, and root canal obturation [3-7].

This research aims to investigate the impacts of two distinct access cavity designs: the traditional lingual and the incisal access cavity designs with root canal preparation size (apical size 0.30mm taper 0.04mm) on the stress build up and the fatigue life of the one rooted type II canal configuration mandibular incisor using finite element analysis in an attempt to try and settle the debate concerning the added value of new access cavity designs.

This study adopted the hypothesis that access cavity designs would affect the mechanical behavior or the teeth.

## Materials and Methods

### Ethical committee approval

The British University of Egypt's Faculty of Dentistry Research Ethics Committee has approved this study (FD BUE REC 21-005).

### Sample selection

An intact, recently extracted sound human mandibular incisor of unknown source or extracted due to periodontal or orthodontic purposes with a mature apex and normal root morphology was selected. Selected tooth was checked under magnification for any cracks or caries after thoroughly cleaning the teeth to remove any deposits.

### Finite Element Model Generation

This study used a machine with amorphous silicon flat panel sensor, 0.5mm focal spot size, 14 Bit gray scale resolution and a Cesium Iodide (CsI) scintillator that operates with a Field of view 4 cm, tube voltage 120 kVp, milliampere 7 mA, voxel size 0.125 mm, scanning time 26.9 seconds [8- 10]. Data were exported, transferred, and downloaded in DICOM format using CBCT a Next Generation iCAT scanner. personal computer via a Compact Disc (CD).

For analysis, the scanned objects were segmented into distinct elements using mimics software Materialize's Mimics Software (19.0) located in Leuven, Belgium [8- 10]. Next, thresholds were used to put up the enamel and dentin masks from top, bottom, right, left, front and posterior directions. By using the Solidworks software 2021 (Dassault Systèmes SolidWorks Corporation) and Geomagic-Design X, the generated STL files were examined, disassembled, and assembled for reverse engineering. For the creation of PDL layer a 200 micrometer-thick layer 1.5 millimeters was shown as the periodontal ligament (PDL). An alveolar bone cube enclosed the periodontal ligament [8-11].

### Intact Tooth Model Validation

Model validation was done according to Nawar et al., (2022) [11].

### Access Cavity Design

After creation of the 3D solid model, the endodontic access cavities were designed as follows:

**Lingual access cavity (LAC**) [12-14]: The crown's lingual surface, located one millimeter above the cingulum, was the first point of entry. The cavity expanded until the pulp chamber roof was completely removed, both cervico-incisally and mesiodistally. Next, direct access to the root canal was established by partially removing the pericervical dentine in the lingual region.

**Incisal access cavity (IAC)** ) [12-14]: The bur was held parallel to the teeth's long axis until it entered the pulp chamber, and the point of entry was relatively short at the incisal edge on the lingual surface of the crown. The pulp chamber roof and pericervical dentine were preserved because the cavity was not enlarged. (Figure 1, Table 1)

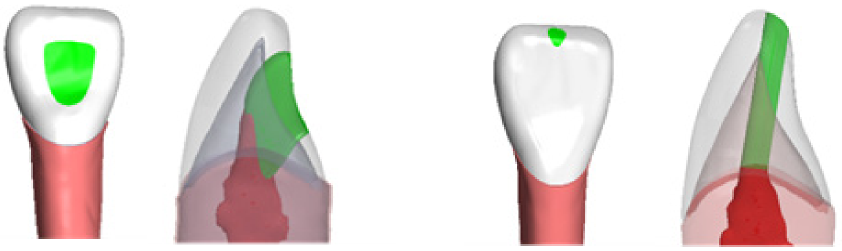

Figure 1. a- lingual access cavity design model (LAC). b- incisal access cavity design model (IAC).

Table 1: includes the volumes and dimensions of the access cavities.

| Case | volume ($mm^3$) |
|---|---|
| **Lingual** | **9.46** |
| **Incisal** | **4.14** |

**Root Canal Preparation**

Root canals were simulated of diameter size 0.30 mm with taper 0.04 mm following the development of the IT model and models with simulated access cavity designs.

Next, simulated gutta percha filling materials were used to fill the root canals up to canal orifices, which were 0.5 mm short of the root apices. Simulated resin composite restorative materials were then used to fill AC designs.

**Meshing and Set Material Properties**

Each model was put into the Mechanical APDL ANSYS 18.2 software in order to mesh. During the meshing process, many tetrahedral components were joined at nodes, resulting in different meshes depending on how complicated each preparation was. The Mechanical properties of the materials for FEA are set in Table 2.

Table 2: Mechanical Properties of the Materials for Finite Element Analysis [10- 12]

| Material | Elastic modulus (MPa) | Poisson ratio |
|---|---|---|
| Enamel | 84100 | 0.30 |
| Dentin | 18,600.0 | 0.31 |
| Periodontal-ligaments | 68.90 | 0.45 |
| Guttapercha | 140 | 0.45 |
| Alveolar-bone | 13,700.00 | 0.30 |
| Composite-resin | 7000.00 | 0.30 |

**Finite Element Analysis**

Following the creation of the 3D models, a boundary condition was created to replicate the connection between the PDL, the bone, and the tooth. A boundary condition (zero displacement) in all directions (X, Y, and Z) was therefore built for every cortical bone node for analytical purposes. To analyze the stress state, a cyclic load of 120 N [15] was applied to the incisal Edge. A 3D finite element ball model applied a load to the area of the incisal ridge. The same load application and boundary condition were used to analyze each model. FEA was utilized to process the stress distribution and concentration regions of the 3D solid models. Mechanical APDL ANSYS 18.2 software was utilized to conduct a mathematical analysis of the models. The resulting graphical representation was color-coded bars. The quantitative analysis is derived from these bars. The colors go from blue to red. The MPS and the maximum VMS into the dentin core and crown are shown numerically. The maximum compressive stresses area in the MPS is represented by blue, and the maximum tensile stresses area is represented by red.

## Results

SolidWorks software was used to evaluate the biomechanical behavior of the tooth structure, after preparation with different coronal cavity designs and the same radicular preparations. Equivalent von mises stresses (VMS) and maximum principal stresses (MPS) were calculated for each model under vertical loading. The simulation of the intact model under loading and the number of cycles till failure (NCF) were completed first and the location of failure was recorded. After that, other models' life spans were simulated, and they were estimated as a proportion of each model's NCF relative to the IT model

1- **Intact tooth (IT)**

a. **Von-mises stresses:**
The Maximum VMS recorded were 105.82 MPa where the stress distribution on the incisal ridge, the marginal ridges and the lingual fossa, and directed cervically toward the root (Figure 2).

b. **Maximum principal stresses:**
The MPS recorded were 62.948 MPa where the maximum compressive stresses were located at the incisal ridge and decreased at the cervical line of the tooth. The maximum occlusal tensile stresses were located on the lingual surface and lowered at the radicular area (Figure 3).

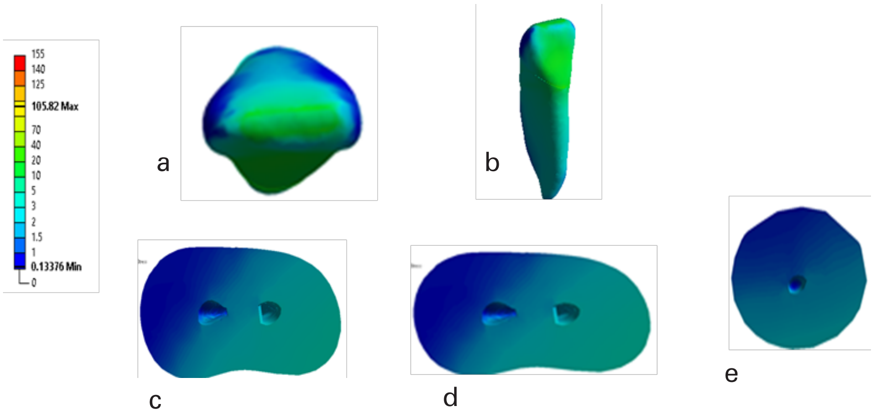

Figure 2. Composite figure showing the VMS of each view for the sound model: (a) occlusal, (b) Isometric, (c) coronal part of the root (d) middle root, (e) apical root.

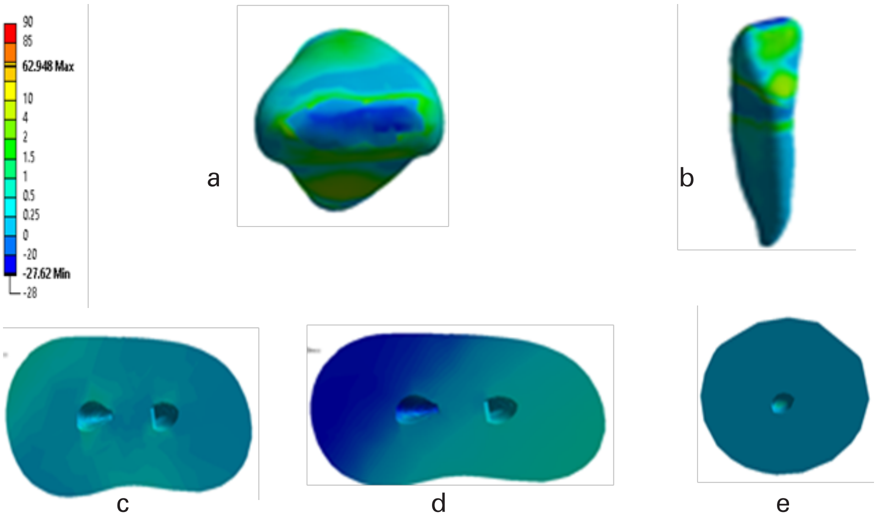

Figure 3. Composite figure showing the MPS of each view for the sound model: (a) occlusal, (b) Isometric, (c) coronal part of the root (d) middle root, (e) apical root.

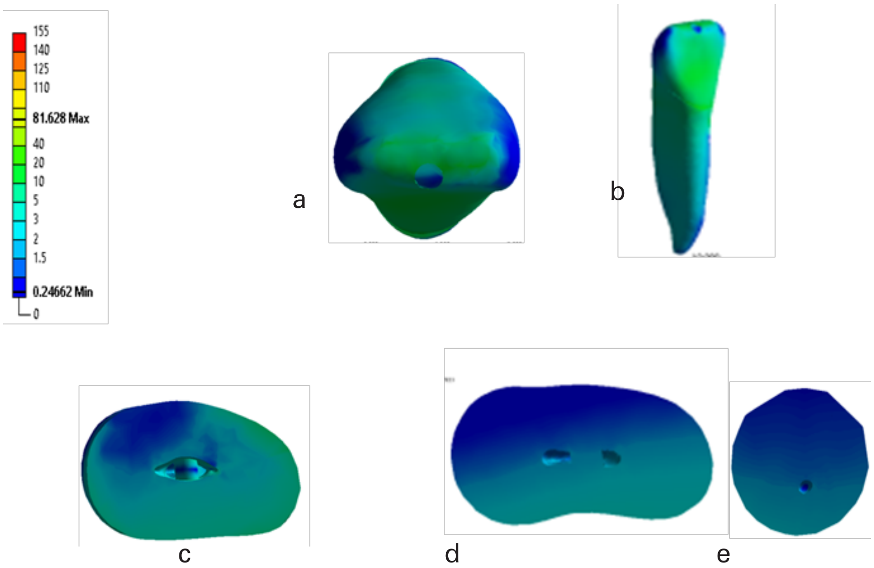

Figure 4. Composite figure showing the VMS of each view for LAC/30/.04 model: (a) occlusal, (b) isometric, (c) coronal part of the root (d) middle root, (e) apical root.

1- **Lingual access cavity (LAC):**

a. **von-Mises stresses:**

**For LAC/30/.04:** the tooth structure at the restoration edges had a stress distribution, with the highest VMS observed being 81.628 MPa. On the outside of the root, there was a band that represented the cervical stresses. There were very little radicular stresses (Figure 4).

b. **Maximum principal stress**

**For LAC/30/.04:** MPS recorded were 51.898 MPa, (Figure 5, Table 3) into which:

a. The maximum compressive stresses were located at the incisal ridge and lowered at the cervical line of the tooth.
b. The maximum occlusal tensile stresses were located on the lingual surface and lowered at the radicular area.

1. **Incisal access cavity (IAC):**

a. **von-Mises stresses:**

**For IAC/30/.04:** the tooth structure at the restoration edges experienced stress dispersion, with in a maximum VMS of 96.989 MPa being measured. On the outside of the root, there was a band that represented the cervical stresses. There were very little radicular stresses (Figure 6).

b. **Maximum principal stresses:**

**For IAC/30/.04:** the MPS recorded were 61.532 MPa, (Figure 7) into which:

a. The maximum compressive stresses were located at the incisal ridge and lowered at the cervical line of the tooth.
b. The maximum occlusal tensile stresses were located on the lingual surface and lowered at the radicular area.

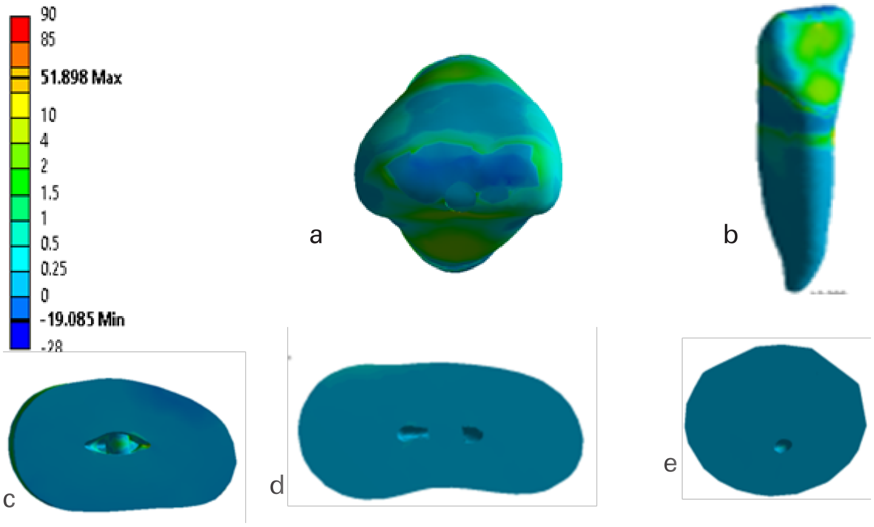

Figure- 5: Composite figure showing the MPS of each view for LAC/30/.04 model: (a) occlusal, (b) isometric, (c) coronal part of the root (d) middle root, (e) apical root.

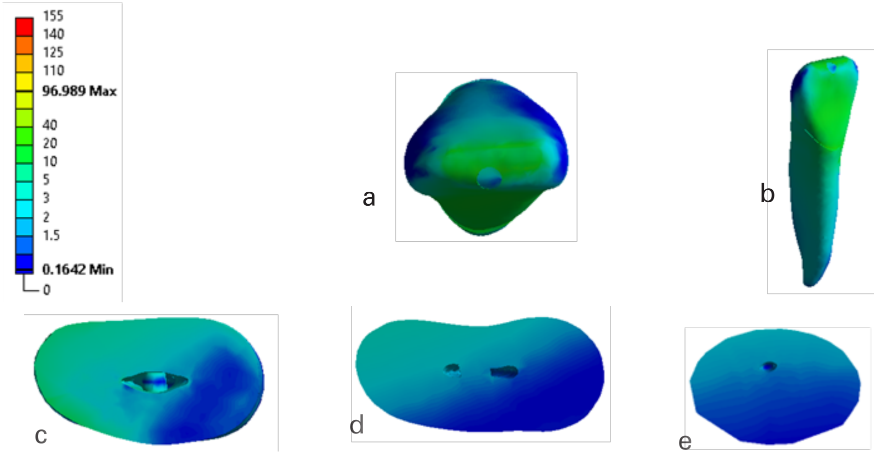

Figure 6. Composite figure showing the VMS of each view for IAC/30/.04 model: (a) occlusal, (b) isometric (c) coronal part of the root (d) middle root, (e) apical root.

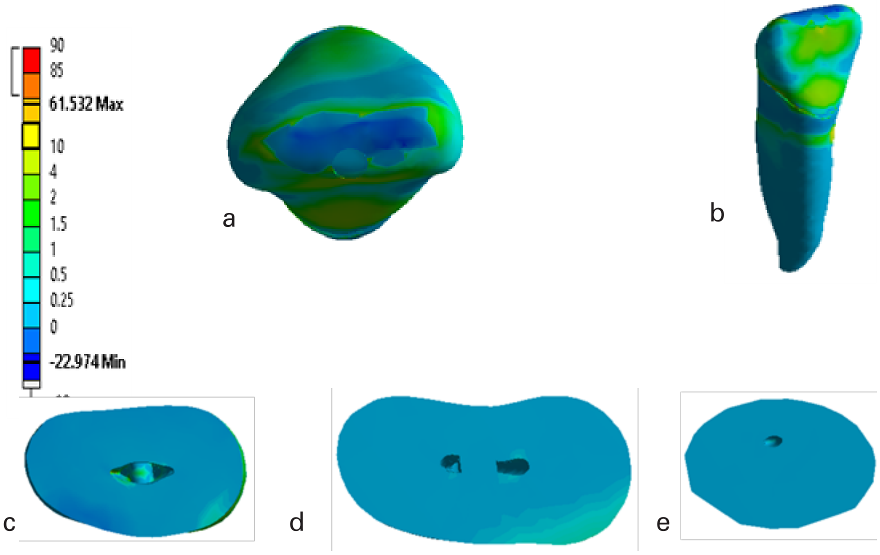

Figure 7. Composite figure showing the MPS of each view for IAC/30/.04 model: (a) occlusal, (b) isometric, (c) coronal part of the root (d) middle root, (e) apical root.

Table 3: Maximum von mises stresses (VMS), maximum principle stresses (MPS), number of cycles till failure (NCF) and the life span of various models compare to the intact model.

| Model | Canal preparation | Maximum VM Stress (MPa) | Percentage (%) | Maximum principal stress (MPa) | Percentage (%) | NCF | Lifelog percentage (%) |
|---|---|---|---|---|---|---|---|
| Intact tooth | | 105.82 | 100.00% | 62.948 | 100.00% | 3.47E+09 | 100% |
| Lingual (LAC) | 30/0.04 | 81.628 | 91.47% | 51.898 | 31.67% | 3.82E+09 | 84.78% |
| Incisal (IAC) | 30/0.04 | 96.989 | 108.69% | 61.532 | 122.59% | 2.7E+09 | 77.8% |

## Discussion

Several studies have shown that the loss of sound structure during the endodontic access preparation procedure is the main cause of the brittleness and greater fracture risk of the treated tooth. The TAC, is used to facilitate the procedure and acquire a straight-line access. However, a significant amount of the tooth structure is destroyed [16-20].

The concept of minimally invasive endodontics (MIE) aims to preserve tooth structure by decreasing the size of the AC, which strengthens the tooth and increases its functional life as well as treatment outcomes. During endodontic treatment, some practitioners began utilizing different CAC designs with the aid of dental microscopes and CBCT imaging. Previous studies have produced conflicting results about the effect of MIE on the fracture resistance of treated teeth [21, 22].

FEA evaluates the biomechanics of structures under loads in order to investigate the failure mechanisms. FEA offers several benefits over experimental research and clinical trials, including cost and time savings, repeatability, and uniformity of applied force location, amplitude, and direction [23-24].

Due to the lack of information on the biomechanical behavior and stress distribution of mandibular incisors compared to molars, the lower lateral incisor was chosen as the experimental model for this study. When exposed to occlusal load application, these teeth are more prone to fracture than others due to their decreased size. Consequently, the kind of AC design may have a major impact on the tested teeth's strength, particularly in the case of conservative preparations [25].

To generate precise tooth models with realistic dimensions for our study, the chosen incisor was scanned using high resolution CBCT in the endodontic mode. Using Mimics 19.0 (Materialise NV), 3D models were created and a mask threshold was set to differentiate dentin from enamel. STL were then imported into SolidWorks software, where all parts were put together to create models with typical dimensions and component relationships, as assumed in the study methodology to simulate the clinical conditions [8-11]. Additionally, while meshing the 3D models of the teeth, the element size was lowered. Variable size mesh was then used to decrease the number of equations, thus simplifying the stress analysis process.

Two coronal access cavity designs were used in this study lingual, and Incisal [12-14]. Simulated composite resin was used to repair the access cavities to imitate the clinical situation. For each model (30/0.04), radicular preparation was virtually carried out.

To evaluate the stress state, a cyclic load of 120 N was applied to the incisal edge using a 3D finite element ball model, to determine the areas of stress concentration and distribution. All models were exposed to the same load application circumstances throughout the research [15].

The quantitative analysis is determined using color-coded bars (Red to blue to include all colors) that were produced graphically. The maximum VMS and MPS are quantitatively presented. Into which the maximum compressive stresses area is represented by blue, while the highest tensile stresses area is shown by red. By examining the distribution patterns and values of the maximum VMS and MPS for each model, it was discovered that the highest stresses were close to the loading sites and the restoration's boundaries, and decreased away from them. Also all of the models had the same pattern of stress distribution.

In the IT, the enamel received the majority of the VMS, while the pericervical dentin area and the root from the cervical region to the apex showed very little stress. Additionally, in the CAC models (incisal, face, and cervical) the enamel was better retained than that of the LAC model, allowing for better stress distribution on them. This occurs because the capacity of the enamel to sustain the occlusal load functions as a “compression dome” enabling appropriate internal stress absorption under compression more than the composite [26]. This finding agrees with Saber et al., 2020 [8] despite the different tooth model used in their study (mandibular first molar).

Furthermore, regardless of cavity design, the fracture strength, failure mechanism, or stress distribution of a mandibular incisor restored with resin composite and a CAC that maintains the integrity of the marginal ridge will not change in comparison to the IT model. This would provide support to the theory placed out by Nawar et al. in 2022 [11] that the dental architecture might be able to distribute pressures over a larger area while staying within certain bounds. The value of stresses on the composite restoration were directly correlated with its size, but the value of stresses on enamel was inversely correlated with the size of the composite restoration, as the stresses will be concentrated within the composite, and the tooth restoration interface will limit the amount of loads that can pass further through the tooth structure. In agreement of other studies it was proven that it’s crucial to take into account how load sites and the location of the access cavity boundary relate to one another. [8-11].

Again in agreement with previous studies it was found that even though there were no particularly high stress values in the cervical region, the cervical stress values increased as the AC size decreased, this pattern of stress distribution was seen in all conservative designs [8-11].This may be explained by the fact that LAC had more composite in which the stresses were consumed.

The distribution of the radicular stresses in all experimental models followed a consistent pattern, with higher values cervically and gradually decreasing apically. It was mostly on the outside of the root, with very little amount traveling into the root canals.

Furthermore, the MPS analysis was carried out to show how loading pressures cause the models to experience tension and compression. On the other hand, MPS on the radicular section was extremely small. The same pattern of stress distribution was seen into which, the incisal ridge had the maximum compressive stresses, the lingual surface had the highest occlusal tensile stresses, whereas the radicular area had the lowest.

However, FEA has limitations and might not accurately mimic the clinical situations because it is a computer-based virtual approach. The results can only be understood qualitatively since the dentin’s hardness is not the same within the tooth. Furthermore, it was shown that dentin’s mechanical behavior declines with age due to a decrease in fracture toughness and crack propagation resistance. For this reason, it would be helpful to investigate if the study’s findings hold true for older dentin [27].

The adopted hypothesis that access cavity designs would affect the mechanical behavior or the teeth was proven.

## Conclusion

Within the confines of this study, the following conclusions can be reached:

1. The mandibular incisor’s biomechanical behavior is significantly influenced by the size of the access design.
2. From a biomechanical point of view, radicular preparation has very little effect on the tooth.
3. The connection between the functional load points and the access cavity margins influences the biomechanical behavior of the teeth that have undergone endodontic treatment.

## Recommendation

Based on the occlusal relationships, a unique design for the access cavity is advised into which stress and clinical failure should not be concentrated in this design. This study indicated that the post-endodontic restoration played a significant role. Therefore, if the marginal ridges were lost, a complete coverage restoration may be recommended. This study also examines particular groupings of loading elements, further research is encouraged to assess different loading scenarios. This might require changing the modelling of chewing simulator models, amplitudes, and orientations in order to simulate clinical occlusion.

**Source of funding:** The study did not receive any financial support.

**Authorship statement:** we confirm that all listed authors meet the authorship criteria and that all authors agree with the manuscript’s content.

## References

1. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: a review of the literature. J Prosthet Dent. 2001 Jun; 85(6):585-98.
2. Trivedi S. Finite element analysis: A boon to dentistry. J Oral Biol Craniofac Res. 2014 Sep-Dec; 4(3):200-3.
3. Saeed M, Al-Obadi M, Salim A, Alsawaf AY, Hadi K. Impact of Access Cavity Design on Fracture Resistance of Endodontically Treated Molars: A Systematic Review. Clin Cosmet Investig Dent. 2021 Jan 7; 13:1-10.
4. Monga P, Sharma V, Kumar S. Comparison of fracture resistance of endodontically treated teeth using different coronal restorative materials: An in vitro study. J Conserv Dent. 2009 Oct; 12(4):154-9.
5. Acharya N, Hasan MR, Kafle D, Chakradhar A, Saito T. Effect of Hand and Rotary Instruments on the Fracture Resistance of Teeth: An In Vitro Study. Dent J (Basel). 2020 Apr 29; 8(2):38.
6. Motiwala MA, Gul M, Ghafoor R. Effect of different access cavity designs on fracture toughness of endodontically treated teeth: a systematic review and network meta-analysis. Evid Based Dent. 2022 Dec 2.
7. Marvaniya J, Agarwal K, Mehta DN, Parmar N, Shyamal R, Patel J. Minimal Invasive Endodontics: A Comprehensive Narrative Review. Cureus. 2022 Jun 16; 14(6):e25984.
8. Saber SM, Hayaty DM, Nawar NN, Kim HC. The Effect of Access Cavity Designs and Sizes of Root Canal Preparations on the Biomechanical Behavior of an Endodontically Treated Mandibular First Molar: A Finite Element Analysis. J Endod. 2020 Nov; 46(11):1675-1681.
9. Silva EJNL, De-Deus G, Souza EM, Belladonna FG, Cavalcante DM, Simões-Carvalho M, Versiani MA. Present status and future directions - Minimal endodontic access cavities. Int Endod J. 2022 May; 55 Suppl 3:531-587.
10. Elkholy MMA, Nawar NN, Ha WN, Saber SM, Kim HC. Impact of Canal Taper and Access Cavity Design on the Life Span of an Endodontically Treated Mandibular Molar: A Finite Element Analysis. J Endod. 2021 Sep; 47(9):1472-1480.
11. Nawar NN, Kataia M, Omar N, Kataia EM, Kim HC. Biomechanical Behavior and Life Span of Maxillary Molar According to the Access Preparation and Pericervical Dentin Preservation: Finite Element Analysis. J Endod. 2022 Jul; 48(7):902-908.
12. Shabbir J, Zehra T, Najmi N, Hasan A, Naz M, Piasecki L, Azim AA. Access Cavity Preparations: Classification and Literature Review of Traditional and Minimally Invasive Endodontic Access Cavity Designs. J Endod. 2021 Aug; 47(8):1229-1244.
13. Silva EJNL, Pinto KP, Ferreira CM, Belladonna FG, De-Deus G, Dummer PMH, Versiani MA. Current status on minimal access cavity preparations: a critical analysis and a proposal for a universal nomenclature. Int Endod J. 2020 Dec; 53(12):1618-1635.
14. Dos Santos Miranda ARL, de Moura JDM, Calefi PHS, Amoroso Silva PA, Marceliano-Alves MFV, Lopes RT, Vivan RR, Rodrigues PA. Influence of conservative endodontic access cavities on instrumentation of oval-shaped straight root canals. Int Endod J. 2022 Jan; 55(1):103-112.
15. Dorado S, Arias A, Jimenez-Octavio JR. Biomechanical modelling for tooth survival studies:mecvhanical properties , load and boundary conditions a narrative review. Materials (Basel) 2022;15 7852.
16. Rezaei Dastjerdi M, Amirian Chaijan K, Tavanafar S. Fracture resistance of upper central incisors restored with different posts and cores. Restor Dent Endod. 2015 Aug; 40(3):229-35.
17. Lang H, Korkmaz Y, Schneider K, Raab WH. Impact of endodontic treatments on the rigidity of the root. J Dent Res. 2006 Apr; 85(4):364-8.
18. Tsesis I, Tamse A, Lustig J, Kaffe I. [Vertical root fractures in endodontically treated teeth part I: clinical and radiographic diagnosis]. Refuat Hapeh Vehashinayim (1993). 2006 Jan; 23(1):13-7, 68. Hebrew.
19. Cheron RA, Marshall SJ, Goodis HE, Peters OA. Nanomechanical properties of endodontically treated teeth. J Endod. 2011 Nov; 37(11):1562-5.
20. Silva EJNL, Pinto KP, Ajuz NC, Sassone LM. Ten years of minimally invasive access cavities in Endodontics: a bibliometric analysis of the 25 most-cited studies. Restor Dent Endod. 2021 Jul 21; 46(3):e42.
21. Clark D, Khademi J. Modern molar endodontic access and directed dentin conservation. Dent Clin North Am. 2010 Apr; 54(2):249-73.
22. Yuan K, Niu C, Xie Q, Jiang W, Gao L, Huang Z, Ma R. Comparative evaluation of the impact of minimally invasive preparation vs. conventional straight-line preparation on tooth biomechanics: a finite element analysis. Eur J Oral Sci. 2016 Dec; 124(6):591-596.

23. Lanza A, Aversa R, Rengo S, Apicella D, Apicella A. 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor. Dent Mater. 2005 Aug; 21(8):709-15.
24. Darbar UR, Huggett R, Harrison A. Stress analysis techniques in complete dentures. J Dent. 1994 Oct; 22(5):259-64.
25. Moore B, Verdelis K, Kishen A, Dao T, Friedman S. Impacts of Contracted Endodontic Cavities on Instrumentation Efficacy and Biomechanical Responses in Maxillary Molars. J Endod. 2016 Dec; 42(12):1779-1783.
26. Chiba A, Hatayama T, Kainose K, Nakajima M, Pashley DH, Wakabayashi N, Tagami J. The influence of elastic moduli of core materials on shear stress distributions at the adhesive interface in resin built-up teeth. Dent Mater J. 2017 Jan 31; 36(1):95-102.
27. Nazari A, Bajaj D, Zhang D, Romberg E, Arola D. Aging and the reduction in fracture toughness of human dentin. J Mech Behav Biomed Mater. 2009 Oct; 2(5):550-9.