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Influence of different access cavity sizes on the direction of stress distribution in endodontically treated uniradicular maxillary premolar: a finite element analysis

Influência de diferentes tamanhos de cavidades de acesso na direção da distribuição das tensões em pré-molares superiores unirradiculares tratados endodonticamente: uma análise de elementos finitos

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ABSTRACT

Objective: This study aimed to evaluate the influence of different access cavity sizes on the stress distribution in an endodontically treated maxillary premolar model compared to an intact one using finite element analysis (FEA). Materials and Methods: The distributions of maximum and minimum principal stress were calculated. In the intact tooth, the maximum principal stress was located in the enamel-dentine junction and the minimum principal stress was in the cervical area. Results: In large-sized access, the maximum principal stress (tensile) increased by 41% compared to the contracted access model. This tensile strength was concentrated on interface tooth/restoration. Medium-sized access caused an increase of 27% of the minimum principal stress (compressive strength) on the apical region compared to the contracted access cavity. There was also an increase of 15% of the maximum principal stress (tensile strength) when comparing medium and minimum-sized cavities. Conclusion: The endodontic access cavity design modified the value and the direction of principal stress distribution of endodontically treated uniradicular maxillary premolar compared to the natural one.

Keywords:

Elastic modulus. Endodontics. Finite element analysis.

RESUMO

Objetivo: Este estudo teve como objetivo avaliar a influência de diferentes tamanhos de cavidades de acesso na distribuição de tensões em um modelo de pré-molar superior tratado endodonticamente em comparação com um do mesmo dente hígido, usando análise de elementos finitos (FEA). Materiais e Métodos: Foram calculadas as distribuições de tensão principal máxima e mínima. No dente hígido, a tensão principal máxima ficou localizada na junção esmalte-dentina e a tensão principal mínima na região cervical. Resultados: Em acessos de grande porte, a tensão principal máxima (tração) aumentou 41% em comparação com o modelo de acesso mínimo. Esta resistência à tração foi concentrada na interface dente/restauração. O acesso de médio porte causou um aumento de 27% da tensão principal mínima (resistência à compressão) na região apical em relação ao da cavidade de acesso mínima. Houve também um aumento de 15% da tensão principal máxima (resistência à tração) ao comparar cavidades de tamanho médio e mínimo. Conclusão: O desenho da cavidade de acesso endodôntico modificou o valor e a direção da distribuição das tensões principais de pré-molares superiores unirradiculares tratados endodonticamente quando comparado com o modelo do mesmo dente hígido.

Palavras-chave:

Endodontia. Analise de Elementos Finitos. Módulo de Elasticidade.

1 INTRODUCTION

Endodontically treated teeth are known for their high biomechanical failure rate when compared to natural ones [1]. This failure is associated with a significant difference in the mechanical properties of dental structures compared to restorative materials used to replace the lost structure. This difference in characteristics causes different stress distribution in the restored substrate [2].

It was observed that endodontically treated maxillary premolars are more prone to mechanical failure. They have the highest fracture rate in the oral cavity due to shearing loads. These can lead to catastrophic fractures of the non-functional cusp. Its anatomical shape and crown volume as well as unfavorable crown/root ratio favor this occurrence [3].

Access cavity sizes remained unchanged for several years [4]. Significant changes were proposed to promote dental structure preservation [4,5]. Also, the introduction of magnification in endodontics enabled smaller access cavities [4-7]. There is a growing interest in such access sizes due to the possibility of preserving the remaining structures, thus providing long-lasting clinical results after endodontic treatment [5,6]. A recent study showed that contracted access cavities compromised root canal disinfection because it might restrict the file amplitude movement inside the canal, limiting surface debridement [7].

Mechanical laboratory tests have some limitations like being destructive, showing only the fracture strength, and not enabling to perform analysis of stress distribution along with the structure [8]. Thus, computational simulation is suggested such as, the finite element analysis – FEA [8,9]. The standardization of FEA would be impossible in tests with real biological samples. It reproduces the biomechanical behavior of teeth when subjected to functional and parafunctional loads [9]. The wide anatomical variation and consequently different mechanical properties are difficult to be standardized in clinical situations as well [10]. Therefore, FEA allows to vary only what is interesting to compare [8-10].

This study evaluated the influence of different endodontic access cavity sizes in stress distribution in a two-dimensional model of endodontically treated uniradicular maxillary premolar using FEA.

2 MATERIALS AND METHODS

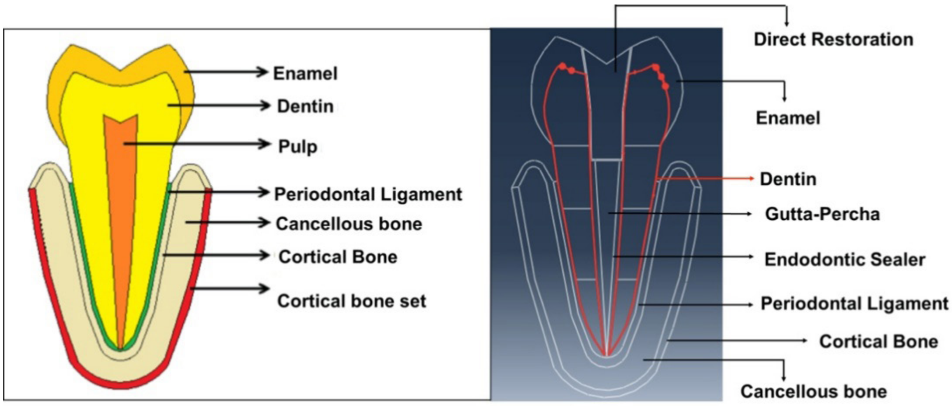
2.1 Computational Simulation

Three steps were developed to conduct FEA: A) construction of a model to be studied during the pre-processing; B) the development of loads; C) the analysis of results after the simulation in the post-processing. Ethics committee approval and informed consent were not applicable.

2.2 Model Construction

SolidWorks 2015 (SolidWorks Corp., Massachusetts, USA) was the software where the models of maxillary uniradicular pre-molar were elaborated. A two-dimensional drawing was performed in the sagittal section to be satisfactory in the stress analysis. Figure 1 shows the model used. It presents the discretized structures, including enamel, dentine and pulp space besides restorative material, and endodontic filling. Additionally, periodontal ligament and alveolar bone (cortical and cancellous) were created.

Figure 1 - Schematic drawing of the discretized structures in the computational model: a) intact tooth; b) tooth with endodontic treatment and root dentine divided into the cervical, middle, and apical thirds.



Source: authors, 2023.

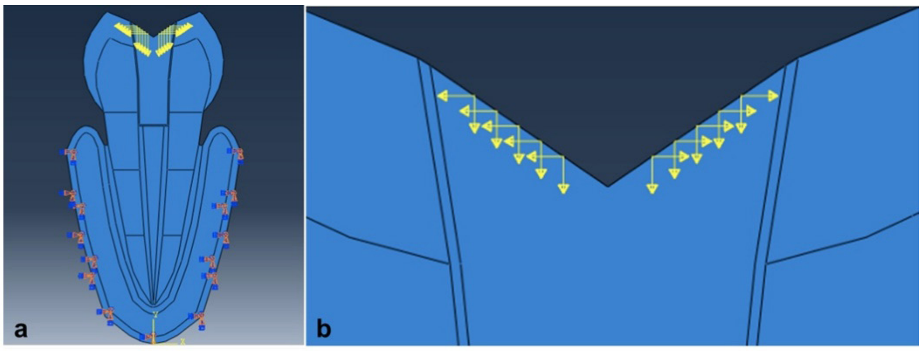
All elements used in the study were considered isotropic [9]. Enamel was considered an isotropic material. Consequently, all materials were assumed to have linear, elastic, and isotropic properties. The data used to provide different properties to the draw structure are represented by the Young modulus (E) and Poisson ratio.

2.3 Loads and Boundary Conditions

The software used for computer simulation by FEA was ABAQUS/CAE (Version 6.14-5; Simulia, Providence, RI).

Ten nodes of 9 N were used yielding a load of 90 N (Fig. 2). In the loading model, a sphere was used on the occlusal surface to obtain force distribution and avoid concentration at a single point [11].

Figure 2 - Computational model: a) drawing showing movement-free set in the outer portion (orange arrows); b) zoom of the occlusal portion showing the distribution of forces in x and y directions, representing the physiological occlusal load (yellow arrows).



Source: authors, 2023.

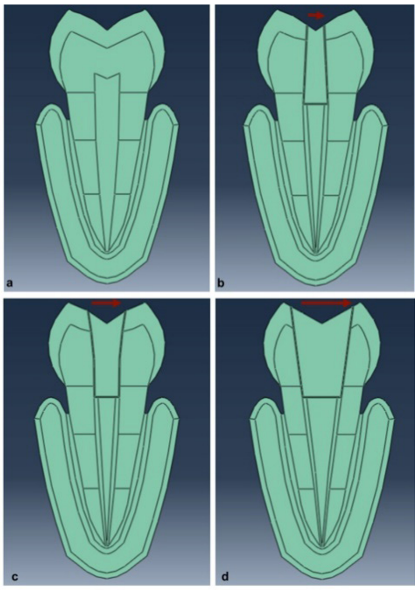
Simplifications inherent to the static analysis and the displacements caused by external actions were considered very small compared to the tooth. Therefore, displacement of the sample was disregarded. As a boundary condition, it was considered that the tooth was rigidly set in the outer portion of the cortical bone, movement-free, as highlighted in red.

The mesh generated for the analysis was 0.2 mm in size with 7786 nodes, 7654 elements, 7530 linear quadrilaterals type CPS4R, and 124 linear triangular CPS3 kinds. All models had their mesh created with the same size and type parameters.

2.4 Simulation Varying Geometry Size of Access in Endodontically Treated Teeth

For this analysis, four two-dimensional models were constructed for computational simulation showing an intact tooth and three other models with endodontic cavities. These cavities were simulated to be restored with resin composite in three clinically different access sizes (Fig. 3).

Figure 3 - Computational model with a red arrow highlighting the size of dental wear: a) intact tooth, b) minimal-sized access c) medium-sized access, and d) large-sized access.



Source: authors, 2023.

The minimum-sized access simulates a contracted endodontic access cavity with a convergent inclination of walls (Fig. 3b). Its opening is concentrated on the central third portion of the occlusal face. The medium-sized access simulates a cavity with sufficient opening with slightly divergent walls and corresponding to one-third of the distance between cusp tips (Fig. 3c). A large-sized access model presents significant tooth structure loss with clearly divergent walls, almost reaching cusp tips (Fig. 3d). The Young modulus and Poisson ratio used are described in Table 1.

Table 1- Mechanical property of dental materials and structures.

Material	Young Modulus (GPa)	Poisson Ratio
Pulp chamber	0.002 (11)	0.45 (11)
Dentine Crown	20 (12)	0.3 (13)
Enamel	80 (14)	0.3 (13)
Periodontal Ligament	0.0118 (15)	0.45 (15)
Cortical Bone	13.7 (16)	0.3 (16)
Cancellous bone	1.370 (16)	0.3 (16)
Adhesive System	4 (12)	0.3 (17)
Resin Composite	10 (12)	0.3 (18)
Gutta-Percha	1.7 (19)	0.45 (20)
Endodontic Sealer	1.7 (19)	0.45 *

*estimated value

Source: authors, 2023.

For the stress distribution analysis of all simulations, the maximum and minimum principal stress values were considered as in materials with fragile behavior.

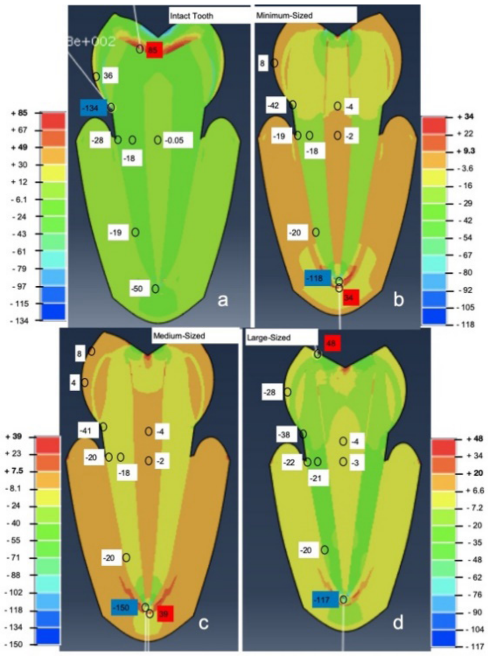
This study was based on the simulation development of four clinical situations for just one model of drawing. Therefore, the data volume generated was not enough for applying statistical analysis and only inferential analysis was made.

3 RESULTS

The pattern of stress distribution within the dental structure for all evaluated models was based on the color variation. Each color corresponds to the range of stress value in MPa. The red color represents the highest stress value. The blue color at the bottom of the bar represents the lowest stress value. The positive value is related to the maximum principal stress (tensile strength). The negative value is related to the minimum principal stress (compressive strength).

Figure 4 shows the values of the maximum and minimum principal stresses of the intact tooth and each kind of access cavity size.

Figure 4 - Sketch of the results of the simulations by the FEA, and distribution of the minimum and maximum principal stresses (MPa) along with the intact tooth (a) endodontically treated tooth with the variation of the geometry of the internal coronal-root access: (b) the minimum-sized access; (c) the medium-sized access and (d) the large-sized access.



Source: authors, 2023.

In the intact tooth, the maximum principal stress was located in the enamel-dentine junction and the minimum principal stress was in the cervical area. In the endodontically treated tooth, the size of access changed the direction of stress distribution. In large-sized access, the maximum principal stress increased by 41% compared to the contracted access model. This tensile strength was concentrated on interface tooth/restoration. Medium-sized access caused an increase of 27% of the minimum principal stress (compressive strength) on the apical region compared to the contracted access cavity. There was also an increase of 15% of the maximum principal stress (tensile strength) when comparing medium and minimum-sized cavities.

4 DISCUSSION

High values of the maximum principal stress were observed in the main groove of the occlusal region between the buccal and lingual cusp. More specifically in the center of places where loading was applied (Fig. 4). The dental structure removal during the cavity access procedure and the replacement by restorative materials altered stress distribution when compared to the intact tooth. Thus, differences in the Young modulus of each material and the access size generated other points of the maximum principal stress. For instance, endodontically treated teeth had the pulp tissue (E=2 MPa) [12] replaced by gutta-percha and endodontic sealer (E=1700 MPa), i. e., much greater E than the biological tissue provoking the wedge effect. This effect implies distributing the tension resulting from the load applied along the entire length of the tooth and restorative material towards the apex region of the root.

The greatest result of the minimum principal stress in all simulations was in the apical region. It mechanically has flexibility and resilience of the alveolar bone and periodontal ligament, reducing the possibility of failure. Also, the periodontal ligament can adapt to functional changes. When the functional demand increases, its width can increase by up to 50% as well as the thickness of its fiber bundles [17].

Our research observed that the maximum value of the maximum principal stress was reduced when the tooth was restored with a different Young modulus material than dental structure (Fig. 4), as found in another study [15]. The difference can be attributed to the dependence of stress distribution according to the material E value.

The enamel compressive strength is 262 MPa and the dentine is 298 MPa [18]. The results of the principal stress of all simulations in this work did not reach the known values for causing fractures. Besides, the dental structure behavior under the action of occlusal loads allows it to receive a wide variation in the magnitude of loads and distribute stresses without suffering a fracture.

Due to the excellent combination of enamel and dentine, the intact tooth model has the perfect and unique union between hardness, resistance, and resilience [19]. Restorative procedures and changes in the structural integrity of teeth can easily violate this balance [20].

Preserving intact structure and the use of biomimicry principles during restorative procedures favor the greatest longevity of the tooth-restoration complex [20]. This was also confirmed by other studies which showed by using FEA, the removal of dental structure alters the pattern of stress distribution. It makes the dental structure more susceptible to fracture by reducing the stress distribution area [1,4-5,8,15,16,19,21]. The present research showed that the maximum principal stress (tensile strength) increased by 41% in teeth with large-sized access (48 MPa), compared to the minimal-sized access one (34 MPa).

Although medium-sized access provided a similar pattern and direction of stress distribution of contracted access cavity, it was also observed that it caused an increase of 15% in tensile strength and 27% in compressive strength on the periodontal ligament. Whether it may interfere with biological processes that take place after pulp extirpation and cleaning/shaping procedures, new researches should be addressed to understand the clinical consequences of such findings. Perhaps this difference might not be enough to justify a contracted cavity size, which can limit canal cleaning and shaping [7].

Clinically, posterior restored teeth may suffer deformations due to the application of occlusal loads. This may be associated with high levels of stress concentration within the tooth-restoration complex. However, if the deformations exceed the strength of the dental structures, it may cause compromised restoration, formation of cracks in the adhesive interface, microleakage, formation of structure (or structural) cracks, and even fractures [19,22]. This behavioral trend can be seen in Figure 4d. The greatest maximum principal stress (tensile) is located at the restoration-tooth junction in large-sized access cavity model which can cause structure fracture.

Endodontic access cavities size remained large and unchanged for several years. It was primarily focused on operator needs for identifying/locating structures and producing better disinfection. Nonetheless, such an access size is not ideal for preserving the dental structure. Remnants may suffer non-restorable fractures leading tooth to extraction [4,5].

The computer simulation does not predict the fracture, that is, the failure of the material [15]. This interpretation is made with a comparative analysis of the values of the stresses generated with the values found in the literature on strain strength, compression, and tensile.

The finite element method was chosen to accomplish this analysis due to the possibility of standardizing conditions. It can analyze stress distribution and reproduce the biomechanical behavior of teeth when subjected to functional and parafunctional loads [9]. The stresses generated with the application of load on the dental structure can result in structural deformations if they are higher than the elastic limit of the material. Rupture of the structure may occur. The endodontically treated tooth strength is lesser than that of the untreated tooth [1]. Therefore, the study of stress distribution in such teeth is important to identify the eventual fragilities and to embrace the clinical decision making process about the better suitable restoration to be accomplished. For instance, restorations with cuspid protection in large-sized access cavities are strongly recommended to avoid structure failure.

It was not feasible to compare quantitatively the values of the stresses generated in the computational tests with other studies due to a myriad of differences such as - A) tremendous methodological variation of the loading; B) tooth draw; C) tri- or two-dimensional model; D) variation of the Young modulus values of the materials used; E) greater or lesser discretization of the drawings, having more simple or more complex models; F) size and shape of the generated mesh [1,3,8,9,12,13-16]. Therefore, the comparison and discussion of our results were based on qualitative analysis of the stress distribution.

It must be considered that very conservative access may jeopardize the location of root canals and their cleaning and disinfection [7]. Besides, it may imply more significant deviation from the original canal path during preparation, due to space limitations [7]. All the mentioned drawbacks and the lack of a significant increase in mechanical resistance [5,6,20,23-26] may not justify the accomplishment of contracted access cavity design. Future researches are recommended to elucidate better restoration strategies to embrace clinical decision making process in different types of access cavities.

5 CONCLUSION

The size of endodontic access opening has a great influence on stress distribution when comparing with natural tooth due to the wear of dental structures and the consequent substitution of natural structures by filling materials for coronal and radicular portions.

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