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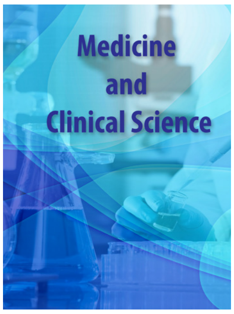
Original Article

Influence of Reconstructive Technique and Ferrule Height on Stress Distribution in Endodontically Treated Molars: A 3D Finite Element Analysis Study



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Keywords

endodontically treated molar (ETM), finite element analysis (FEA), three-dimensional model (3D model).

Abstract

Background: *Endodontically treated teeth restored with a different type of restorative technique may experience a fracture. Accurate information about the stress distribution of endodontically treated lower first molars restored with different techniques is needed. This study was conducted to investigate and analyze the influence of reconstructive technique and ferrule effect on the stress distribution of endodontically treated molars (ETM).*

Methods: *six three-dimensional finite elements (FE) models of a mandibular first molar were constructed (via MIMIC and Solid Works software). Based on the reconstructive methods used and the presence of a ferrule, Models have been divided into model 1 with a 2mm ferrule and model 2 without a ferrule. The models were restored with cast-made posts (A1 and A2), fiber posts (B1 and B2), and endocrown (C1 and C2). A vertical, oblique, and horizontal load of 200N was applied to each 3D model, and Von Mises stress was analyzed using ANSYS software.*

Results: *all stress values were within physiological limits under all cases of load application. Areas of maximum stress concentration were located at the loading points of the crowns for all models except the A2 model, in which maximum stress lies on the middle of the distal root. Models C1 and C2 showed the highest stress, followed by models A1 and A2. while, models B1 and B2 showed the lowest stress. The ferrule group showed more satisfactory stress distribution.*

Conclusions*: All the reconstructive techniques can be considered adequate alternatives for restoring ETM. Models of fiber posts showed a homogeneous stress distribution while cast post and core models exhibited the highest stress. The endocrown models reduced stress in the root canal's inner wall in comparison with other models. Ferrule presence was shown a positive effect.*

Introduction

The restoration of endodontically treated teeth (ETT) is one of the main challenges in restorative dentistry. The volumetric loss of the hard tissues, changes in the properties of dentine, and changes in proprioception may result in modifications in the biomechanical properties of the teeth [1,2]. Endodontically treated teeth, with a large amount of coronal tooth structure loss, frequently require post placement [3]. Traditionally, non-adhesive posts and cores with cast or prefabricated metallic posts have been widely used with relative success [4,5]. However, those restorations have been associated with a high incidence of unfavorable root fractures due to their high elastic modulus [6]. With the need for esthetic materials and mechanical properties similar to those of root dentine, adhesive resin posts and core build-ups incorporating a fiber post are becoming popular [7]. Currently, due to the development of adhesive technologies and materials, the endocrown type of restoration has been developed. An endocrown is a monoblock restoration that is cemented to the internal portion of the pulp chamber and the remaining tooth margins using adhesive luting cement. The remaining coronal tooth structure (ferrule) is considered the crucial factor for the optimal biomechanical behavior of endodontically treated teeth [8]. To analyze the effects of the post and core systems on the stress distributions in endodontically treated teeth, several methods are available. The finite element analysis (FEA) is an upcoming and significant numerical modeling tool for the research method. The advantages of this method are that it more closely simulates the natural conditions, reduces experimentation cost, and avoids destructive experimentation. It also makes it possible to determine the position, strength, and direction of an applied force. Additional benefits include good reproducibility, accurate outcomes, and time savings [9,10].

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Materials and methods

A 3D static linear finite element analysis study (in silico study) was conducted to determine the influence of different reconstructive techniques and the presence or absence of ferrule in the stress distribution of endodontically treated mandibular first molar using FEA software. The study was conducted in the conservative department, Faculty of Dentistry, Sanaa University.

Model geometry

3-Dimensional geometry of a left mandibular first molar was obtained from a CT scan (Pax-i 3D Green 1515, Vatech, South Korea). The CT image was converted to Digital Imaging and Communications in Medicine (DICOM) format and imported into an interactive medical image control system software (Mimics® 19.0, Materialise, Leuven, Belgium). The different hard tissues visible on the scans were then identified using Mimics® based on image density thresholding. After creating the 3D model in Mimics® 19.0, it was saved as a (.SAT) file before importing into ANSYS/CAE software, Professional Version (ANSYS® 18.1, Inc., Canonsburg, PA 15317). The periodontal ligament (PDL) was created by filling the gap between the cementum and the alveolar socket with a thickness of 0.18 mm. Software (SolidWorks © 2001-2018 Luxology, LLC) was used to fabricate computer-aided design structures to simulate the clinical scenarios of endodontic treatment, root enlargement, reconstruction of the radicular walls, and prosthetic rehabilitation [11].

According to the presence or absence of a ferrule, the ETM model was replicated into two models: model 1, which has a 2mm ferrule area, and model 2, which has no ferrule. Regarding the type of reconstructive technique, each model was subdivided into A, B, and C models. Model A was restored with a metallic cast-made post and core. Model B was restored with a fiber post with a composite core. Model C was restored with a zirconia endocrown (Figure 1). The dimensions of the geometric three-dimensional models are shown in Table 1.

Finite element analysis:

The models were generated and analyzed using ANSYS software (Computer-aided engineering software developed by ANSYS® 18.1, Inc., Canonsburg, 2001-2018). The finite element mesh was obtained using the free meshing technique and linear tetrahedral elements with quadratic displacement shape functions and 3 degrees of freedom per node, type C3D4. The C3D4 was used with fine meshes to obtain accurate data. The final models present a specific number of nodes and elements through the convergence test until obtaining a number unable to interfere with the study outcome. The convergence was considered acceptable when the relative errors became less than 1% before mechanical simulation. The tetrahedral mesh of all models was as follows: model A1 has 290044 nodes and 181213 elements, model B1 has 286200 nodes and 179195 elements, model C1 has 285482 nodes and 179600 elements, model A2 has 290044 nodes and 181213 elements, model B2 has 666064 nodes and 420878 elements, model C2 has 280354 nodes and 177589 elements. Mechanical properties of the restorative materials were created for each part of the FE model. All model structures are assumed to be completely joined, which means no failure in adhesion and interposition between them [12].

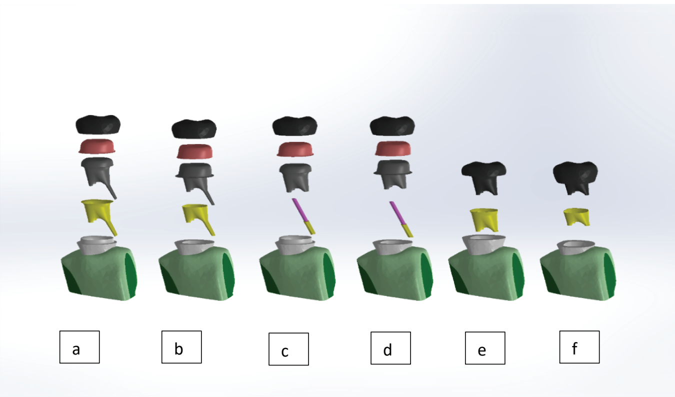

***Figure 1**. Schematic illustration of three-dimensional geometric models.*

***Table 1.** Dimensions of the geometric three-dimensional models [26,27]*

Part			Dimension (mm)
Crown	Height		7.5
	Thickness at the top		1.5
	Thickness at the bottom edge		1.0
Core	Height		4.0 for group 1 models
			6.0 for group 2 models
	Diameter		8.0
Ferrule height	Group 1 models		2.0
	Group 2 models		0.0
PDL	Thickness		0.18
Bone	Thickness		3.5
Cast-made post and core			
Post In the distal canal	Length		9.0
Gutta-percha	Length		5.0
	Diameter		1.5
Fiber-post			
Core	Height		4.0 for group 1
			6.0 for group 2
	Diameter		8.0
	Thickness over the post		2.0
Post In the distal canal	Length		14
	Diameter		1.5
Endo-crown			
Crown height	Group 1 models		5.5
	Group 2 models		7.5
Pulp chamber part	Height		4.0 for group 1
			2.0 for group 2
	Diameter	Mesio-distal	
		Buccolingual	
Gutta-percha	Length		12
	Diameter		1.5

The boundary conditions will be applied on the nodes of the root surface, at the bottom end line of the cortical bone supporting the ETM, to give them 0° of freedom in all directions. A 200 N load was applied on the occlusal surface of the mandibular first molar at five points of contact with the opposing upper molar in three directions, which are vertical (0°), oblique (45°), and horizontal (90°) direction to simulate the physiologic masticatory forces and external traumatic forces, respectively [13-16].

Results

A convenient way of reporting stress is in the form of a color representation of the stress distributions. The color-coding ranges from dark blue (minimum stress) to red (maximum stress).

Stress distribution in the tooth and the posts

Vertical load

Maximum stress is concentrated at the areas around the loading points on the crown surface, irrespective of the restoration type and the ferrule effect except for model A2 in which it is concentrated in the distal root at the level of the end of the post, Figure 3. Higher stress distribution in the remaining tooth structure was observed at the cementoenamel junction (CEJ) in all models.

The maximum stress concentration was seen at the post end of the custom-made post and core as well as at the zirconia endocrown. However, lower stress concentrations were observed for fiber posts with composite core models.

a)

b)

c)

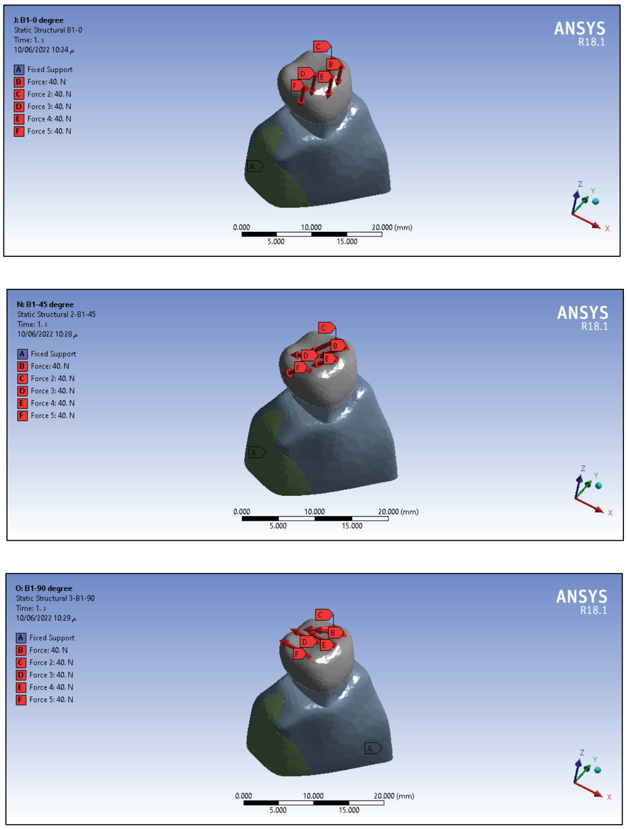

Figure 2. *Different load directions on the mandibular first molar model*

a) vertical loading; b) oblique loading; c) horizontal loading

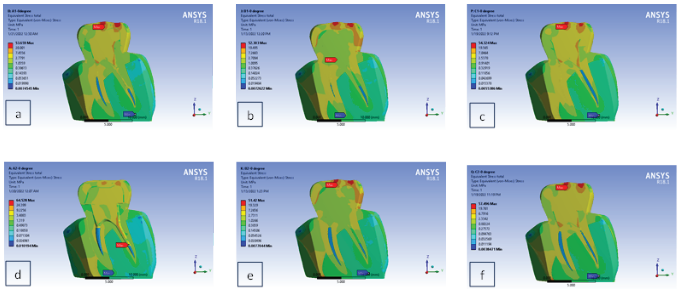

Figure 3*. von Mises stress distribution under vertical loading for all models:*

b) A1 b) A2 c) B1 d) B2 e) C1 f) C2

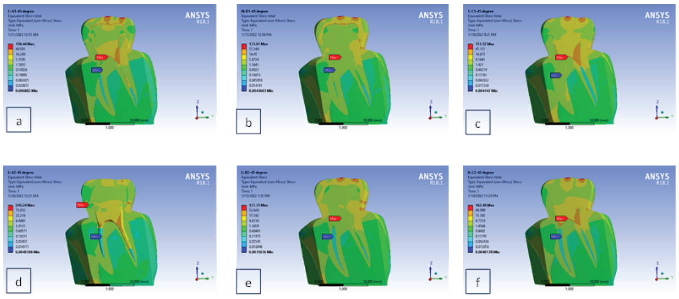

Figure 4*. von Mises stress distribution under oblique loading for all models:*

a) A1 b) A2 c) B1 d) B2 e) C1 f) C2

The ferrule presence decreases the stress in the custom-made post models and slightly in the zirconia crown models. However, it almost has no effect in fiber post models.

Oblique load

Maximum stress was concentrated in the areas around the loading points on the crown surface in models A1, B1, C1, and C2, however, in model A2 it was concentrated in the mesial margin of the crown as well as B2 in which it is concentrated at the lingual margin of the crown, Figure 4.

The magnitude of the stress distribution under oblique loading was higher than vertical loading. In the remaining tooth structure, a higher stress distribution was seen at the CEJ in all models. The stress was slightly higher in group one than in group two.

The maximum stress concentration was seen at the custom-made post and core in the model without ferrule effect A2 followed by zirconia endocrowns. However, lower stress concentrations were observed for fiber posts with a composite core.

Horizontal load

Stress under horizontal loading was similar to oblique loading, Figure 5. However, the magnitude of the stress under horizontal loading was higher than vertical and oblique loading.

In the remaining tooth structure, higher stress distribution was seen at the CEJ level in all models with maximum stress in model C1.

The maximum stress concentration in posts under horizontal load was as in oblique load. The presence of ferrule decreases the stress in all restorative techniques.

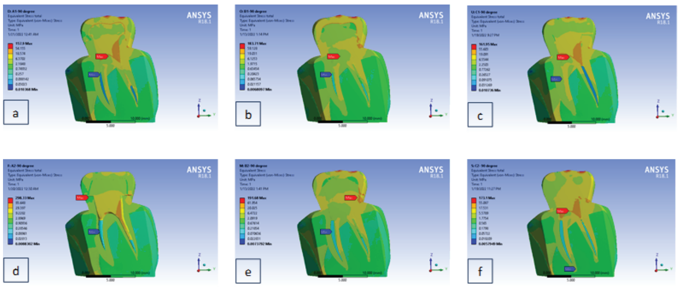

Figure 5. *von Mises stress distribution under horizontal loading for all models:*
c) A1 b) A2 c) B1 d) B2 e) C1 f) C2

Stress distribution at the post and surrounding structure interfaces

Stress distribution was investigated at the posts and the surrounding structures' interfaces for vertically loaded teeth. Model A1 showed a lower stress, while higher stress was seen in model C1. In the A2 model, the stress at the post/dentine interface increased markedly toward the apical part. However, in models B1 and B2 it decreased toward the apical end.

Similarly, when the tooth was loaded in the oblique direction, the same stress distribution was observed except for the lower stress, which was recorded in model B1. The magnitude of the stress was lower than the vertical loading

When the tooth was loaded horizontally, Model A1 showed a higher stress while the lower stress was seen in model B2. In all models, the stress at the post/dentine interface decreased toward the apical part. The maximum stress was lower than the oblique and vertical loading.

Discussion

This study evaluated the stress distribution in endodontically treated lower first molars restored with cast post-and-core, glass-fiber posts, and endocrowns, considering the influence of the ferrule. The interfaces' characteristics and material rigidity significantly affect the biomechanical behavior of these teeth. Understanding occlusal loads and selecting appropriate reinforcing techniques can help minimize failure risks [5].

In our study, posts were placed in the distal root canal, the widest and straightest, with a two-thirds insertion for maximum retention [7]. The parallel-sided fiber posts used were more retentive and distributed stress uniformly compared to tapered posts [6]. Zirconia is preferred for posterior all-ceramic crowns due to its superior mechanical properties.

Finite element modeling (FEM) has been widely used to analyze stress distribution in endodontically treated teeth under various loading conditions [8,11,12,17]. While FEM is beneficial for studying complex systems, it faces challenges in accuracy and validity. Our convergence tests confirmed the model's accuracy, and the mandibular first molar model was created from a CT scan, enhancing its clinical relevance.

The study simulated complex loading conditions by applying a mean masticatory force of 200 N at three angles (0°, 45°, and 90°) [15,16,18,19]. All deformation and stress values remained within physiological limits, indicating that the residual roots would not fracture under normal occlusal forces after restoration.

VMS distributions showed maximum stress concentrations at crown loading points, with increased stress in the cervical third when changing from oblique to horizontal forces, consistent with previous studies [17]. The highest stresses were observed in zirconia endocrowns, followed by custom-made posts, while fiber posts concentrated stress within the root dentine [8,11,12,17]. The lower stiffness of glass fiber posts likely contributes to better stress distribution [5,6].

The study also found that maximum stress in endocrowns was due to zirconia's high modulus of elasticity, with VMS levels not exceeding zirconia tensile strength [20]. The results align with findings that stress concentrates at material interfaces [21,22]. Lower elastic modulus materials generated less stress concentration at the post-dentine interface, with GFP showing balanced stress distribution [23,24].

When a tooth has a ferrule, more dental tissues are preserved, leading to increased peak VMS in the cement layer while reducing stress in coronal dentine [25]. The ferrule effect provides a protective mechanism, concentrating stress in the pulp chamber rather than at the finish line margin, thereby relieving the root from high stress [5-8].

Finally, the loading angle significantly influences stress distribution. Changing the load direction can increase stress on remaining dentine and enlarge high-stress areas [18,19]. Thus, horizontal loading should be minimized.

Conclusions

This study highlights the stress distribution in endodontically treated lower first molars restored with cast post-and-core, glass-fiber posts, and endocrowns, emphasizing the influence of ferrule presence. All restorative techniques evaluated are viable options, with zirconia endocrowns exhibiting the highest stress concentrations, followed by custom-made posts, while glass-fiber posts demonstrate a more favorable stress distribution within the root dentine.

The presence of a ferrule significantly enhances the biomechanical stability of restorations, reducing stress concentrations and providing protection against fractures. Finite element modeling (FEM) proves to be an effective tool for simulating complex loading conditions and assessing the biomechanical behavior of restored teeth.

In summary, the choice of restorative technique and ferrule presence are critical factors in optimizing stress distribution and improving the longevity of endodontically treated molars. Future research should further investigate the long-term performance of these restorative options under various clinical conditions.

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