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INFLUENCE OF ENDOCROWN PULPAL EXTENSION ON STRESS DISTRIBUTION IN ENDODONTICALLY TREATED MAXILLARY PREMOLARS. A THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

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ABSTRACT

Purpose: Although endodontically treated molars restored with endocrowns have been reported to be clinically successful, clinical and in vitro studies indicated more frequent problems with endodontically treated premolars restored with endocrowns. The aim of this finite element study was to evaluate the influence of the pulpal extension on the stress distribution in endodontically treated maxillary premolars restored with endocrowns.

Materials and methods: An intact maxillary first premolar tooth without any obvious abnormalities or decay was scanned using Planmeca ProMax 3D Mid cone-beam CT machine, the 3D models of enamel and dentin were then segmented using MIMICS software. Three design models were created as follow: Model (A) represented the classical ceramic crown with glass fiber reinforced post and a composite resin core , model (B) represented the endocrown preparation of a circular butt-margin with the depth of the central retention cavity extending 5 mm in depth from the occlusal floor, and model (C) represented the endocrown preparation of a circular butt-margin with the depth of the central retention cavity extending 3 mm in depth from the occlusal floor. Bone geometry was simplified and simulated as a cylinder that consisted of an outer shell of compact bone and an inner core of trabecular bone. All the design models where remeshed and exported to Ansys Workbench as volume meshes for the finite element analysis. The base of the bony cylinder was selected as a fixed support, and an axial oblique load of 100 N was applied to each model. Material properties were assigned for every model, and static structural analysis was performed.

Conclusions: Within the limitations of this finite element study, it was concluded that endocrowns offered a viable alternative for restoration of endodontically treated maxillary premolars, and increasing the pulpal extension to 5 mm significantly increased the stress distribution in the endocrown under axial forces.

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INTRODUCTION

The rehabilitation of severely damaged coronal hard tissue of endodontically treated teeth is always a challenge in reconstructive dentistry. Clinical concepts regarding the restoration of non-vital teeth are controversial and are based on profuse and inconclusive empirical literature. The primary reason for reduction in stiffness and fracture resistance of endodontically treated teeth is the loss of structural integrity associated with caries, trauma, and extensive cavity preparation, rather than dehydration or physical changes in the dentin.[1,2,3,4] Additionally, the lack of vitality greatly restrains the sensory feedback during peak loads and results in non-vital teeth being more prone to fracture.[5]

Restoration of endodontically treated teeth with extensive coronal loss has always followed a strict protocol, with the fabrication of total crowns supported on metal cores and/or glass fiber posts.[6-9] Initially, it was believed that this procedure would provide better reinforcement of the remaining dental structure.[10,11] However, it has been observed that the use of intracanal retainers only promoted retention of the prosthetic crown. As a result of removing a healthy dental structure to enable the placement of rigid elements devoid of mechanical behaviors similar to those of the tooth,[12-15] the remaining tooth could be weakened.

With the advent of adhesive dentistry, the need for using posts and filling cores has become less evident. Moreover, the appearance of ceramics that had high mechanical strength and were capable of being acid etched (such as those reinforced with leucite or lithium disilicate), allied with the adhesive capacity of adhesive systems and resinous cements, made it possible to restore posterior teeth, especially molars, without cores and intra-radicular posts.[16] Thus, it became feasible to restore posterior teeth with extensive coronal destruction by means of onlay and/or overlay restorations and, more recently, with endocrowns, without the use of radicular posts and while using the entire extension of the pulp chamber as a retentive resource.[17,18] **Pissis**[17] was the forerunner of the endocrown technique describing it as the ‘‘monoblock” porcelain technique.

The recent innovations in ceramic materials and CAD/CAM technologies are developed to enable the accomplishment of high aesthetic demands and to limit the shortcoming of conventional materials and methods; i.e., low tensile strength, sintering shrinkage, excessive brittleness, wear of antagonist, crack propagation, and marginal gaps.[19] Recently, Celtra Duo (Sirona Dentsply, Milford, DE, USA) is a material classified as a zirconia reinforced lithium silicate CAD/CAM material that may be optionally heat treated. It contains 10% dissolved zirconia in a silica-based glass matrix. Although heat treatment is not necessary for crystallization of the material, flexural strength of fired Celtra Duo has been reported to be considerably greater than the milled material. [20]

Previous studies have shown that molars restored with complete crowns or posts, cores, and crowns have satisfactory long-term survival rates.[21,22] The smaller crowns and pulp chambers of premolars result in weaker retention of foundation restorations after tooth preparation for a complete crown. Therefore, an endodontically treated premolar should usually be restored using a post, core, and crown.[23] However, because of the oval root canals in premolars, more dentin is removed during preparation for a circular prefabricated post, and root perforation may occur.[24]

Clinical studies reported no significant difference in survival rates between the molars restored with endocrowns versus those restored with traditional techniques.[25] However, the clinical performance of endocrown restored premolars is inferior to that of molars restored with endocrowns.[25,26] Cohesive failure of bonding is the main reason for failure in premolars restored with endocrowns.[25] The clinical fracture of endocrown restored teeth has also been reported.[27] In order to estimate the feasibility of restoring endodontically treated premolars with endocrowns, their stress distributions must be analyzed.

Finite element analysis(FEA) has been used in dentistry as it represents detailed simulated tooth mechanical behavior under occlusal loads. Stress, strain, and some other qualities could be calculated in every point of the structure. FEA offers several advantages: variables can be changed relatively easily, no costly prototypes are needed to be manufactured, and the simulations can be performed in vitro.

MATERIALS AND METHODS

An intact maxillary first premolar tooth without any obvious abnormalities or decay was scanned using Planmeca ProMax 3D Mid cone-beam CT machine (Planmeca Inc, Helsinki, Finland). The equipment was adjusted to scan the whole tooth with a beam accelerating voltage of 90 kV and an X-ray beam current of 12 mA with a voxel dimension of 75 μm. The total scanning time was 15 seconds, and a total of 668 slices were scanned for the modelling, The 668 slices were imported into MIMICS software (MIMICS 14.0, Materialise, Leuven, Belgium) for the construction of the surface model. Masks for enamel and dentin were then created using thresholding and region growing tools; the enamel mask colored red, and the dentin mask colored yellow (Figure 1). The formed masks were then used to generate the enamel and dentin 3D models as displayed in Figure1A.

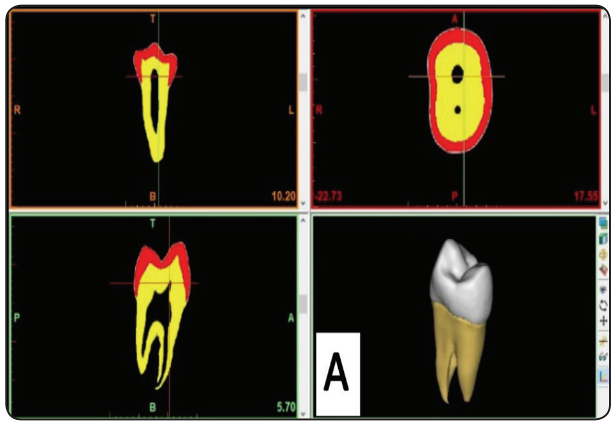

Fig. (1) Masks were applied to enamel (red) and dentin (yellow); A: A 3D representation of the whole tooth.

By using orthogonal cutting planes and Boolean operations (volume addition, intersection, or subtraction) in the simulation module in MIMICS, five preparation design solid models were generated based on the sound maxillary premolar model as follow:

Model (A): The classical ceramic crown with glass fiber reinforced post and a composite resin core with a 1.0 mm wide circumferential shoulder finish line at the CEJ and a 3 mm ferrule (Fig. 2A).

Model (B): The endocrown preparation consisted of a circular butt-margin of 1.0 mm with the depth of the central retention cavity extending 5 mm in depth from the occlusal floor with a rounded internal line angles (Fig. 2B).

Model (C): The endocrown preparation consisted of a circular butt-margin of 1.0 mm with the depth of the central retention cavity extending 3 mm in depth from the occlusal floor with a rounded internal line angles and a 2 mm composite seal (Fig. 2C).

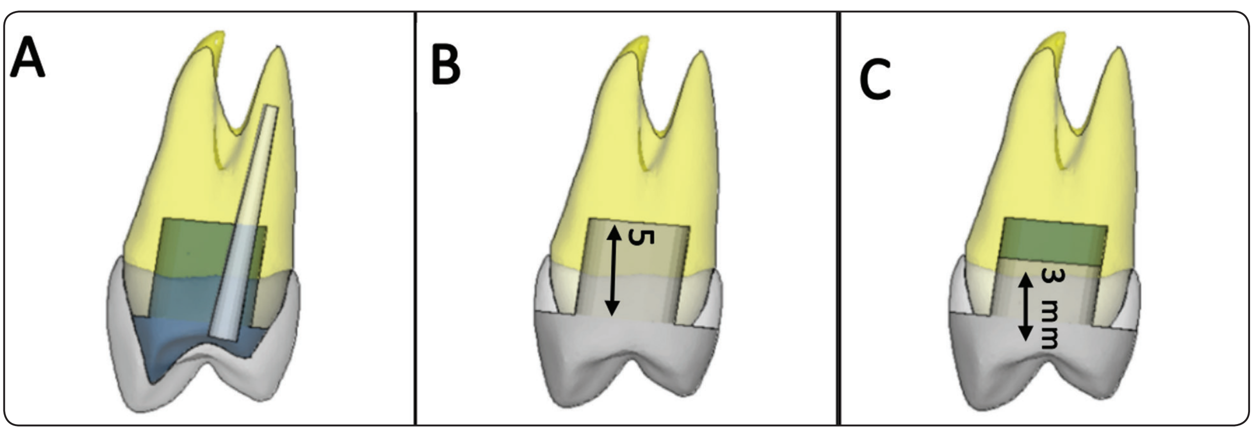

Fig. (2) Schematic representation of the three preparation designs; (A) Model A; (B) Model B; (C) Model C

Bone geometry was simplified and simulated as a cylinder that consisted of two parts. The inner part represented the trabecular bone (diameter 12 mm and height 13 mm), and the outer part-shell of 1 mm thickness-represented the cortical bone (diameter 14 mm and height 15 mm). The shape of the socket was then formed using Boolean subtraction. (Figure 3)

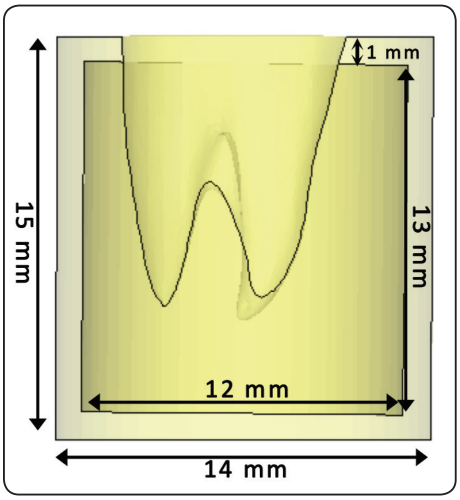

Fig. (3) Longitudinal section showing compact and trabecular bone with dimensions

Using the STL+ module in MIMICS, all the 3D models were exported to 3-Matic software (3-Matic7.01, Materialise, Leuven, Belgium) and converted into stereo lithography triangulated (STL) files that formed the surface meshes. In 3-Matic software, the "*Remesh module*" was then used to automatically improve the quality of the triangles and reduce their number simultaneously while maintaining the geometry. The solid models were then constructed by using the "*Create Volume Mesh*" tool in 3-Matic software. The volume meshes were created using a four-node linear tetrahedral elements, and then the finished volume meshes of all components were input into ANSYS workbench software (ANSYS workbench 14.0, ANSYS Inc., Houston, USA) as STL file format for the finite element analysis; the total number of elements were 189090, 191852, and 192392 for models (A), (B), and (C) respectively. (table 1)

TABLE (1) The number of nodes and element*

		Model (A)	Model (B)	Model (C)
Enamel	Elements	X	3432	3411
	Nodes	X	6195	6165
Dentin	Elements	17862	19031	18928
	Nodes	27765	29143	28997
Cortical Bone	Elements	58181	58601	58630
	Nodes	91917	92268	92342
Trabecular Bone	Elements	93797	94566	94670
	Nodes	132807	133921	134010
Endocrown (Crown)	Elements	11765	16222	14070
	Nodes	18797	24250	20979
Composite Core	Elements	6551	X	X
	Nodes	10623	X	X
Fiber Post	Elements	934	X	X
	Nodes	1717	X	X
Composite Seal	Elements	X	X	2683
	Nodes	X	X	4393
Total	Elements	189090	191852	192392
	Nodes	283626	285777	286886

In ANSYS workbench, the material properties were assigned using the elastic modulus and Poisson's ratio. In our study, Celtra Duo (Sirona Dentsply, Milford, DE, USA) (Zirconia reinforced lithium silicate) was the material of choice for both the conventional crown and the endocrowns. Enamel, dentin, cortical and trabecular bone, composite, and Celtra Duo were assumed to be linear, elastic, homogenous and isotropic. The material properties (Elastic modulus and Poisson's ratio) are presented in table 2.

* Cells with the cross(X) mark represent zero nodes and elements for the corresponding components in the assigned models

The fiber post was considered made up of long glass fibers embedded into a polymeric matrix. This composite material was considered orthotropic so that it showed different mechanical properties along the fiber direction (x-direction) and along the other two normal directions (y- and z-directions), the mechanical characteristics of the glass fiber post are reported in Table 3. E_x, E_y and E_z represented the elastic moduli along the three-dimensional directions while n_{xy}, n_{xz}, and n_{yz} and G_{xy}, G_{xz}, and G_{yz} were the Poisson's ratios and the shear moduli in the orthogonal planes (xy, xz, and yz), respectively.

TABLE (2) Isotropic material properties

Material	Elastic modulus (GPa)	Poisson's ratio
Enamel[28]	84.1	0.33
Dentin[28]	18.6	0.32
Trabecular bone[29]	1.37	0.30
Cortical bone[29]	13.7	0.30
Filtek supreme plus composite core (3M, ESPE,St. Paul, MN, USA)	22	0.22
Celtra Duo (Dentsply DeTrey)	108	0.22

TABLE (3) Orthotropic properties of the fiber post

Elastic modulus (GPA)	Poisson's ratio	Shear modulus
$E_x = 37$	$\nu_{xy} = 0.27$	$G_{xy} = 3.10$
$E_y = 9.5$	$\nu_{xz} = 0.34$	$G_{xz} = 3.50$
$E_z = 9.5$	$\nu_{yz} = 0.27$	$G_{yz} = 3.10$

In this study, the base of the cortical bone cylinder was selected as a fixed support in all directions (x, y, and z) as a boundary condition, and two load cases: An axial load was considered in this study and applied as a nodal force of 100 N parallel to the long axis of the tooth divided equally into three contact points which are the mesial marginal ridge, the distal marginal ridge, and the palatal cusp tip. Each point consisted of 10 selected nodes, and a linear static analysis was performed. (Figure 4)

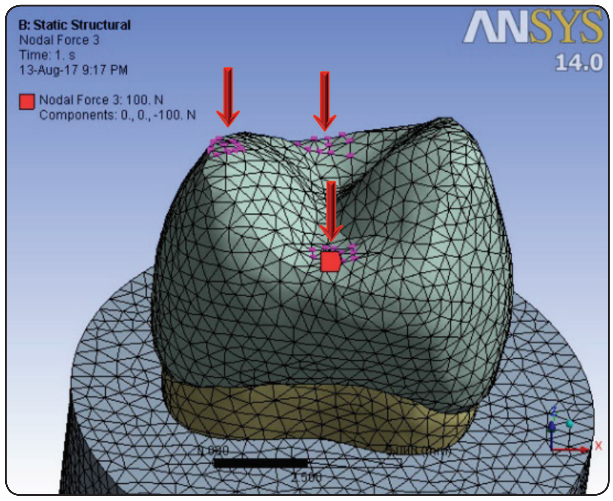

Fig. (4) Points of application of the axial load

RESULTS

Regardless to the restoration design, von Mises stress values ranged from 60 to 99 MPa approximately. Taking model (A) with the conventional crown as a control, model (B) showed a significant decrease in von Mises stress value compared to model (A), while model (C) showed a 10% increase in von Mises value compared to model (A). concerning maximum principle stresses, there were no significant differences between the three models in maximum tensile stress values (23 MPa approximately), while model (A) showed the minimum maximum compressive stress value (17 MPa approximately).

Regarding tooth structure, the maximum von Mises stresses in case of axial loading ranged from around 9 MPa to 14 MPa. Model (A) showed the minimum von Mises stress on tooth approximating 9 MPa, while model (C) showed the highest von Mises stress value which reached approximately 14MPa. Model (B) showed insignificant increase in von Mises value compared to model (A).

Concerning tooth and bone integrity, all induced stresses were within the physiological limits.

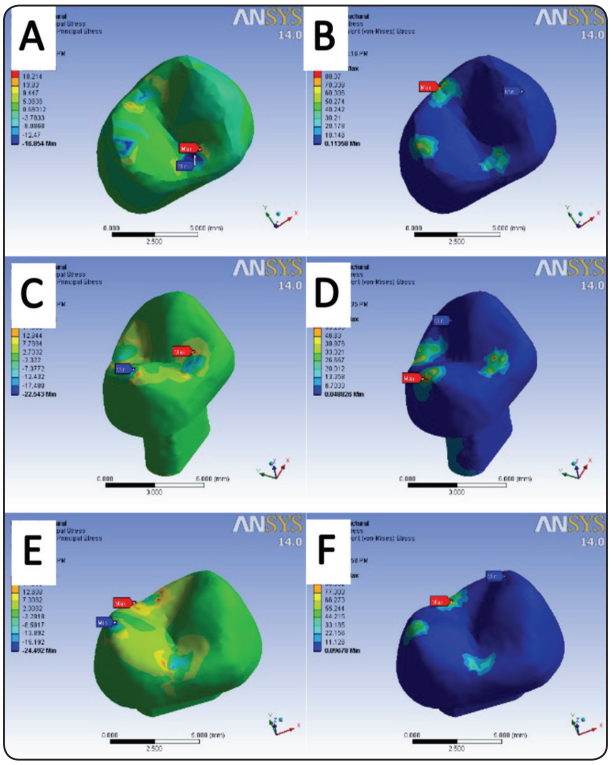

Fig. (5) Stress distribution in endocrown, A. Model (A) maximum principle stress; B. Model (A) von Mises stress; C. Model (B) maximum principle stress; D. Model (B) von Mises stress; E. Model (C) maximum principle stress; F. Model (C) von Mises stress

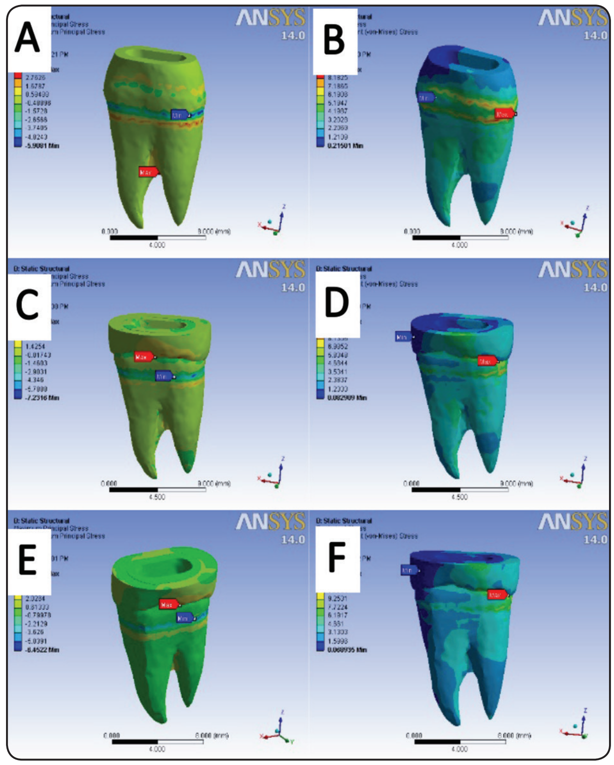

Fig. (6) Stress distribution in tooth structure. A. Model (A) maximum principle stress; B. Model (A) von Mises stress; C. Model (B) maximum principle stress; D. Model (B) von Mises stress; E. Model (C) maximum principle stress; F. Model (C) von Mises stress

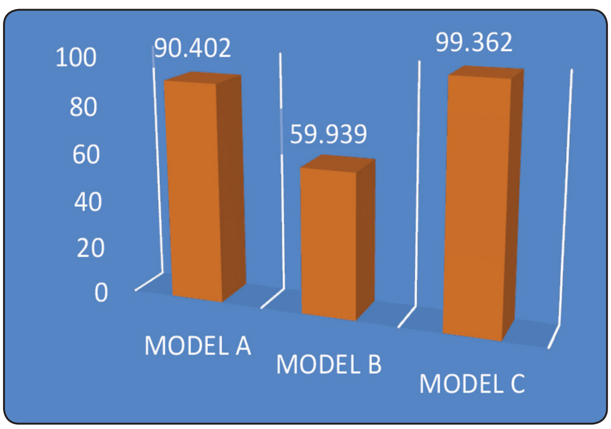

Fig. (7) Column chart showing von Mises stress on restoration in MPa

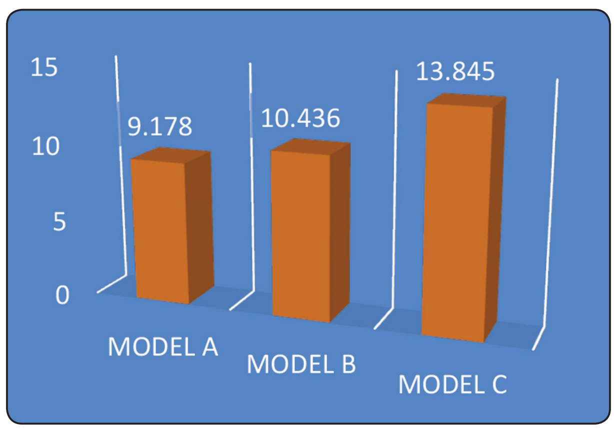

Fig. (8) Column chart showing the von Mises stress on tooth structure in MPa

DISCUSSION

A constant problem in reconstructive dentistry is the restoration of endodontically treated teeth. The restorative option performed with the conventional crown, the composite core, and the glass fiber post attempts to mimic the resilience of dentin and the biomechanical behavior and esthetics of enamel.[30,31] On the other hand, ceramic endocrown is a total crown that extends within the pulp chamber as a one-piece "monoblock" without an intra-radicular post.[18] The high bond strength of glass ceramics to the dental structure and the smaller number of bond interfaces probably make the dentin, enamel and ceramic group more resistant when compared with the dentin, enamel, post, resin, and ceramic group.[5]

Although endocrowns have been proven to be a successful alternative to conventional crowns, the clinical performance of endocrown-restored premolars is inferior to that of molars restored with endocrowns.[25,32] This may be explained by the fact that the surface available for adhesive bonding was larger on molars than on premolars, and the ratio between crown base and crown height might cause higher leverage for premolar than for molar endocrowns.[25]

Nevertheless, because of the absence of information about the biomechanical behavior of endocrowns and the expectation that this type of restoration would behave similarly or superiorly to conventional crowns (because of the potential to be retained in the pulp chamber by micro-mechanical retention given by the adhesive system and resin cement), the aim of our study was to evaluate the effect of endocrown pulpal extention on the stress distribution in endodontically treated maxillary premolars using finite element method.

FEA was chosen because it is a suitable method for determining strains and stresses in a loaded structure. FEA was first used in dentistry at the 1970s[33], in which, the first molars with full gold crown preparations were analyzed with 2D FEA method. After 3D FEA models were developed in 1980s[34], FEA method has been used frequently and widely in structural, thermal or other kinds of analysis in dental restorations such as inlays, crowns, implants, and fixed partial dentures[35,36]. The wide application of FEA is due to its efficiency, cost saving, and continuously improving accuracy. Expensive and time-consuming in vitro and in vivo experiments[37] can be avoided by means of FEA. Therefore, FEA method plays a more and more important role in the development of material and structure of dental restorations.[38,39]

Gaoqi Wang et al[40] conducted a study to verify the finite element analysis model of a three-unit fixed bridge with in vitro electronic strain gauge and analyze clinical situation with the verified model. It was found that FEA has displayed strains close to those measured in vitro, and the FEA model was considered as validated.

The FEA starts with the construction of an accurate FE model, which is the key to the analysis process. Acquisition of a realistic geometry of the object to be studied is very important for model construction. The conventional image acquisition methods used the standard anatomical data in the literatures,[41,42] a digitized version of a plaster model,[41] or the cross-sectional histological images of the object.[43] In some pioneering modeling techniques, manual extraction of inner and outer contours from computed tomography (CT) data of teeth was required, which may introduce serious errors.[44] In some other previous techniques, sequential software was used to transform images from one kind of software to another, which may lose some of the original data.[45] For the above two reasons, previous ways of modeling were not patient-specific, were time-consuming and required a lot of efforts from users. As a result, a relatively simple model was created so that the accuracy of subsequent analysis was directly affected. Clinical researchers were usually unwilling to choose intensive methods either.

The use of high resolution cone-beam CT was in accordance with the studies of **M. Rodrigues et al**[46] and **K. Lee et al**[47] who used cone-beam CT in their FEA.

Regarding stress distribution in the restoration, model (B) showed the best biomechanical behavior with an average von Mises value of 60 MPa. Comparing with Model (A) with the fiber post & conventional crown, the results could be attributed to the overall increased ceramic bulk in the encocrown model (B) compared to the classical crown through the endocrown intra-coronal extension together with the vertical stop obtained by the circumferential butt joint , moreover the reducing the interfaces in the restorative system and the endocrown vertical intra-pulpal extension allowed better stress distribution along the axial direction of applied forces. This finding was in agreement with the studies conducted by **Chang et al**[5] and **Lin et al**[48] who proved that endocrowns showed a higher fracture resistance and less failure probability than conventional crowns. Furthermore, better stress distribution in model (B) compared to model (C) with the 3 mm extension cavity might be due to the increased the pulpal extension of the endocrown of model (B) allowing more surface area for better stress distribution of the axially oriented forces.[49] However, this result didn't coincide with the study carried by **El-Damanhoury et al**[50] who concluded that intra-radicular extension of the endocrown preparation negatively affected both the marginal adaptation and the internal fit of the final restoration which could be related to the restoration deformation as subjected to applied forces.. This variation could be attributed to the use of polymer-infiltrated ceramic (Vita Enamic) as an endocrown material in their study with different mechanical properties than Celtra Duo used in our study , and could also be attributed to the use of resin teeth models which does not precisely simulate the biomechanical behavior of endodontically treated natural teeth .

Concerning stresses in the tooth structure, model (C) showed the worst biomechanical behavior with the highest von Mises stress value (approximately 14 MPa) compared to models (A) and (B). This could be explained by the fact that model (C) with 3mm ceramic extension and 2mm composite seal increased the number of interfacing surfaces in the pulp chamber compared to models (A) and (B) with only one intra-pulpal material (Fiber post or ceramic respectively) which might have yielded more stresses within the tooth structure in model (C).

Better stress distribution of model (B) in tooth structure compared to model (C) is going well with a study by **Laden et al**[51] who stated that increasing the intra-pulpal extension improved the protection of the tooth structure and reduced failure probability in maxillary premolars.

On the other hand, model (A) showed the least stresses on tooth structure having the elastic modulus of fiber post with a very close value to that of dentin which resulted into Monobloc effect and ideal stress distribution in tooth structure[14,18]. Although Celtra Duo as a zirconia reinforced lithium silicate is slightly stiffer than fiber post with expected more stress concentration in tooth structure ,[52,53] however model (B) showed stress distribution in tooth structure that was nearly similar to model (A) owing to the fact that both models have more intra-pulpal material extension than model (c) and this goes consistently with **Rocca et al**[54] who concluded that endocrowns with endo-core extensions displayed outcomes in terms of fatigue resistance equivalent to fiber post & classical adhesive crowns, additionally the innovative ultra-fine microstructure of the celtra duo is supposed to have a considerable role thanks to the zirconia inclusion which allowed finer crystal size and higher glass content with a net high flexural strength and shock absorbing capacity dissipating more stresses along the tooth structure.

All the resultant stress values on restoration and tooth structure were within the physiological limits regardless to the model design.[55,56]

Within the limitations of this finite element study, the following conclusions & recommendations were drawn:

CONCLUSION

1. Model (B) with the 5 mm pulpal extension showed the stress distribution in tooth structure within the normal physiologic limits.
2. The endocrown pulpal extension influenced the stress distribution in endodontically treated maxillary premolars, where model (B) showed the best stress distribution in the restoration.

3. Minimizing intra-pulpal interfaces led to a better stress distribution in tooth structure.
4. Zirconia reinforced lithium silicate is considered a successful endocrown material regarding stress distribution among the endocrown and the tooth structure.

RECOMMENDATIONS

1. Endocrown with 5 mm pulpal extension is recommended as restorative option for endodontically treated maxillary premolars.
2. Zirconia reinforced lithium silicate is a material of choice for endocrown restorations.
3. Further ongoing finite element analysis with different load cases together with in -vitro studies are highly needed to validate the clinical acceptance of endocrowns as a restorative option for maxillary premolars.

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