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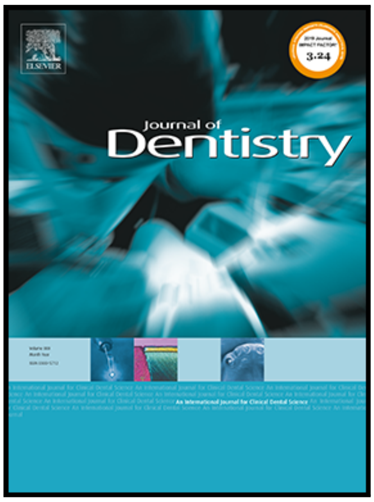

Finite element analysis of stress distribution in autotransplanted molars

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Biomechanical effects in autotransplantation teeth.

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ABSTRACT

Objective: The biomechanical response of an autotransplanted tooth and surrounding bone to occlusal loads is not well-known. The aim of the present study was to investigate the effect of root form and occlusal morphology on stress distribution in autotransplanted teeth and surrounding bone by using finite element analysis (FEA).

Methods: Seven FEA models representing different autotransplanted tooth situations were generated: (a) first molar, (b) third molar, (c) root canal-treated third molar, (d) root canal-treated, ankylosed, third molar, (e) crowned third molar, (f) crowned and root canal-treated third molar, (g) root canal-treated, ankylosed, and crowned third molar. Load (200 N) was applied on the occlusal surface, parallel to the long axis of the tooth. Maximum von Mises stress values on dentin and surrounding bone were calculated for each situation.

Results: Differences in stress distribution were observed among models. In ankylosed model, stress was primarily observed at the coronal region of the tooth. The stress was observed more at the coronal region of the tooth in crowned models compared with the non-crowned models. The stress distribution was homogeneous with root canal-treated and crowned autotransplanted tooth.

Conclusions: The occlusal morphology and root form of the autotransplanted tooth affected the stress in surrounding bone at the transfer site and the biomechanical response of the tooth. The stress was more homogeneous in crowned tooth and primarily observed at the coronal region, which may decrease the risk for root resorption.

Clinical Significance: Root configuration, occlusal form and root canal treatment induce significant changes on the stress distribution on teeth and bone, including characteristic stress concentration and increased stress values. Clinicians can consider crowning autotransplanted teeth for improved stress distribution within the tooth structure.

Key-Words

Autotransplantation, finite elemental analysis, ankylosis, periodontal ligament, biomimetic

1. Introduction

Autotransplantation refers to the transplantation of an erupted or unerupted tooth to another surgically prepared alveolar site to replace missing tooth [1]. This treatment has become an alternative to conventional prostheses and costly implant treatments [1]. Long term prognosis of autotransplantation is comparable to dental implants [2,3]. The survival rate of autogenously transferred teeth varies between 68% and 100% [4,5]. However, inflammatory and replacement root resorption, [2,6] ankylosis, [6,7] pulp necrosis, [8,9] and compromised periodontal recovery, [1,10] which may be observed in autotransplanted teeth jeopardize the clinical success of autotransplantation. Additionally, factors such as age, sex, tooth morphology and root development, alveolar bone volume and inflammation in the recipient area, and surgical technique determine the success of autotransplantation [11]. It was reported that the transfer of the teeth before the roots are completely formed is the most accurate method for improved pulp revascularization and vitality, decreased alveolar bone loss that may occur due to trauma [12]. However, it is also argued that complete root formation of transferred teeth and endodontic treatment are necessary to prevent the development of periodontal or pulp-related diseases [6,13]. The failure rates due to root resorption following the autotransplantation of teeth were reported to be low with complete root development [13]. Considering previous conflicting statements regarding the effect of root development, it is an important factor for the prognosis of autotransplanted teeth (ankylosis, pulp necrosis, and root resorption) [12].

Recent reports focused on the effects of biologic factors on the survival of autotransplanted teeth [2,6,9]. However, not only biological factors, but also biomechanical factors may affect the prognosis of autotransplanted teeth [14]. When the causes of PDL loss are analyzed, the need for crown restoration and the number and position of roots need to be taken into consideration.

It is known that the PDL in a healthy tooth transmits occlusal forces from teeth to bone effectively [15]. Finite element analyses (FEAs) reported that ankylosed structures or implants did not act like natural teeth under occlusal forces [14]. Based on previous study [14,16] results within this context, considering that the autotransplanted teeth are exposed to long-term occlusal loads, creating an optimal biomechanical condition becomes crucial to increase the survival possibility of autotransplanted teeth. The long-term outcomes with autotransplanted teeth have been evaluated only biologically [2,3,12]. The aim of this study was to investigate the biomechanical effects of root form and occlusal morphology on the stress distribution in teeth and bone after autotransplantation by using FEA. The null hypothesis was that occlusal morphology and root form of third molar tooth would not affect the biomechanical response of the tooth and alveolar bone when autotransplanted to the first molar position.

2. Materials and methods

All models used in the presented study were generated by using previously published data [17]. The first molar, the third molar, and half a maxilla were initially modeled in their actual sizes without any layers (cortical bone, PDL, cement, etc.) by using a modeling software program (Sculptris v.1.02; Sculpteo Inc.Villejuif, France). The maxillary first molar was designed to have 3 roots, which were apart, while the maxillary third molar was designed with an irregular form and united roots. A sinus cavity was created within the maxilla. The designs obtained were transferred to the Space Claim module of the ANSYS software program (Ansyss Workbench v.14.5.1, Swanson analysis system, ANSYS, Canonsburg, PA), where all layers of teeth and bone were designed by using "shell", "unite", "intersect" commands and cutting tools. To create the pulp and the root canals for the first and third molars, 3-dimensional pulp and canal models of average sizes were designed. These designs were placed into the relevant teeth and space was created within the teeth by "extract" command [30]. The design of the enamel and cement tissue was performed using the negative shell command for both tooth structures. The enamel and cement tissue obtained was shaped and adapted to the main tooth model. After this adaptation, an area was created for the enamel and cementum tissue by subtracting from the main tooth model by using the extract command. Cement thickness was 50 µm on average. As a result, the area apart from the enamel, cementum, pulp chamber and root canals was accepted as the dentin layer. Thus, first and third molar tooth structures consisting of pulp, root canal, dentin, enamel and cement layers were obtained. By using the “shell” command, the periodontal ligament was formed to be 0.25 mm thick on the outside of the cementum. Canal filling material, base cement, and composite resin filling material were designed to be used in models with different characteristics to be created on the third molar tooth structure based on this tooth tissue. Besides, a modeling was performed in ankylosed teeth without PDL.

The zirconia crown structure was shaped to meet the standard tooth preparation depth; 0.5 mm reduction was done at the finish line, 1.2 mm in the middle of the axial walls of the tooth, and 2 mm on the occlusal surface. The adhesive resin cement space was also modeled.

To create tissue layers of the maxilla, a 3-dimensional model representing the sinus cavity was designed in accordance with the anatomical form. This sinus design was placed in an appropriate position and extracted from the main maxilla model. The cortical bone tissue was designed to have a thickness of 1.5 mm by applying the shell command towards the inner part of the maxillary model. With another shell command applied outward, 1 mm thick gingival tissue was created. After various adaptation applications, trabecular bone, cortical bone, and gingival tissue along with the sinus structure were in harmony with each other. (Fig. 1).

The designs obtained were duplicated and put together to form 7 different models; first molar (Model 1), third molar (Model 2), root canal-treated third molar (Model 3), root canal-treated and ankylosed third molar (Model 4), Crowned third molar (Model 5), crowned and root canal-treated third molar (Model 6), root canal-treated, ankylosed, and crowned third molar (Model 7).

"Subtract" and "intersect" commands were applied to ensure the compatibility between parts. All models were transferred to a software program (Mechanical APDL module; ANSYS). All parts were considered homogeneous, isotropic, and linearly elastic. The material properties of all parts were defined by using previously published data (Table 1). The interconnection type has been set to "bonded". "Patch conforming method" was preferred for meshing and quadratic tetrahedral elements were used. Due to the natural gnarled structure of the modeled parts, the desired values could not be reached in the convergence process. To provide the ideal distribution of stresses and to achieve more accurate results, "manual mesh refinement" was applied by increasing the number of elements and nodes. In this context, mesh improvement was achieved especially at regions where the stress outputs were intended to be obtained (Fig. 1). In different analyzes made with this process, the changes between stress values were found below 4%. This is how convergence was achieved. The number of elements and nodes, which belong to the parts of Model 1 and Model 6 are displayed in Table 2.

At the junction of maxillary bone and other bones, the models were fixed rigidly to ensure that they would not move in x, y, and z directions. A 200 N force was applied parallel to the long axis of the tooth on a common node located on the occlusal facets in all models [31,32]. The direction and the magnitude of the load were same on all models.

Stress outputs were obtained by using 2 different ways. In the first case, Equivalent Von Mises stresses were obtained in all models and the stress distributions were analyzed by cross sectioning the mesiodistal midpoint of the tooth. In the second case, maximum Equivalent Von Mises stresses observed on cortical and trabecular bone were recorded as MPa. The data were evaluated through tables and visuals.

3. Results

When the stress distributions in the section views were examined, differences were observed among the models (Fig. 2). It was observed that while the stress spread more around the pulp in Model 3, the stress spread more along the crown in Model 6 (Fig. 2). When Figure 2 is examined, the stress distribution on the dentin can be observed with the orange color indicator in all models. Here, the stress was more homogeneously distributed with crown restoration, especially when crowned Model 5, Model 6, and Model 7 were compared with the other models without crowning (Model 3 and Model 4). The stress distribution in the root canal-treated transplanted tooth (Model 3) was higher along the dentin and root compared with the root canal-treated ankylosed transplanted tooth (Model 4). When Model 1 and Model 2 were evaluated, root configurations also showed differences for stress distribution on dentin. In Model 1, it was found that the stress was homogeneously distributed along the dentin, along the root (Fig 2) and root bifurcation points (Fig. 3), while in Model 2, stress was higher on the coronal dentin (Fig 2) and root tips (Fig 3). Stress in first molar progressed more towards the apical region into the root. It was observed that the maximum stresses were seen in cortical bone in Model 4 (4 Mpa), Model 7 (3.4 Mpa), Model 6 (3.3 Mpa) and Model 1 (2.2 Mpa)(Table 3). In other models, maximum stresses were seen in trabecular bone. The higher stresses in trabecular bone were observed in teeth in normal periodontal range, except for Model 1. In ankylosed teeth, higher stresses were observed in the cortical bone.

The first molar with PDL had a homogeneous stress distribution at the bifurcation site, however, with autotransplanted third molar with PDL, stress was more prominent at the apex of the root (Fig. 3, Models 1 and 2). The stress in ankylosed teeth was mostly observed in coronal areas, not at the apex of the roots (Models 4 and 7) (Figs. 3 Models 4 and 7). In Models 3 and 6, the stress was concentrated more at the apex of non-crowned tooth. However, the stress concentrated more at the coronal region in crowned model.

4. Discussion

Autotransplantation has a psychological advantage as it brings the patient's natural tooth back to function, and more radical or costly treatments such as implants or fixed partial dentures may be eliminated [4,33]. One of the success criteria for a restoration is the material's biomechanical response to occlusal forces along with its abutment, implant, and surrounding alveolar bone. For this purpose, multi-directional force analysis studies have been conducted and interesting results have been reported [34,35]. Autotransplanting an erupted or impacted third molar to the first molar region, where chewing forces are high, is a commonly performed surgical procedure [36]. However, there is no research in the literature regarding the biomechanical response of the autotransplanted teeth and surrounding bone to the chewing forces. Thus, the presented study investigated the biomechanical response of autotransplanted tooth and surrounding tissues with 7 different models. When the maximum stress values were evaluated, there were differences among the models, therefore, the null hypothesis was rejected.

Simulation-based medicine and the development of complex computer models of biological structures is becoming ubiquitous for advancing biomedical engineering and clinical research. Finite element analysis (FEA) has been widely used in the last few decades to understand and predict biomechanical phenomena [37]. The present study was to aim to investigate the biomechanical effects of a autotransplanted teeth and surrounding bone by using FEA.

PDL is a protective component surrounding the root of the tooth, enabling a homogeneous transmission of occlusal forces to the surrounding bone by allowing the tooth to have micro movements [2,9,10]. The PDL also acts as a tooth-protecting stress breaker against excessive forces [14]. Supporting this statement, in Model 1, where a first molar tooth with PDL was present, stress was more intense in multiple directions in coronal dentin and root bifurcation areas. In Models 2, 3, 5, and 6, where an autotransplanted third molar with PDL was present, the stress was more intense on the coronal region, and especially towards the apical root as the root configuration was different from the first molar. In ankylosed teeth (Models 4 and 7), stress concentrated more on the coronal region. These results are important in terms of possible prevention of root-related complications such as root resorption or fracture. It has been reported that marginal bone loss at the cervical region of implants and screw loosening were due to the stress concentration at the cervical region of implants, which can be considered almost ankylosed [38,39].

As displayed in Table 3, s max values found to increase in ankylosed teeth at cortical and alveolar bone compared with an autotransplanted third molar with PDL (Model 2; cortical bone: 1.1 MPa, trabecular bone 1.6 MPa; Model 4; cortical bone: 4 MPa, trabecular bone 2.8 MPa). For teeth with PDL, stress distribution along the border between the cortical and alveolar bone contributes to this result. Additionally, previous studies reported that mechanical resistance to root fractures was lower in ankylosed teeth [14,16]. Jang et al reported an increase in s max values for the dentin of ankylosed teeth, which may also increase the root fracture risk with ankylosed teeth compared with teeth with a PDL. It should be noted that even though their methodology was similar to that in the present study, they loaded central incisor teeth in their model and the load they used was not vertical but with a 135 degree [14].

As seen in ankylosed models, it may not be appropriate to directly relate a possible root complication with 200 N chewing force because the stress concentrated more at the cervical region, and the maximum stress value in dentin was lower than the intact human dentin's tensile strength (104 MPa), which was previously reported [40,41]. It should be noted that the dentin's strength value was measured analyzing tensile stresses [40], and the fact that compressive stresses were evaluated in the present study should be taken into account when interpreting this outcome. Oblique compressive stresses were investigated in Roperto et al's study [41], and the methodology they used was similar to the methodology used in the present study. However, the lack of stress-breaking properties with the absence of PDL in ankylosed teeth reveals the risk of fractures that may occur at the cervical region. In this situation, root canal treatment alone would possibly not be sufficient to protect the ankylosed teeth. When the stress distribution in Models 7 and 4 was analyzed, it was observed that the stress concentrated more at the crown region because the autotransplanted tooth was crowned and root canal treated (Fig. 2). Similarly, in Model 3 and Model 6, the stress was distributed within the crown more homogeneously and there was no severe stress accumulation on the dentin as the tooth with PDL was crowned [15]. Similarly, with the help of proprioception, the cervical fractures are prevented and the roots are protected also with ankylosed teeth. These results are derived from the basics of the science of biomimetics [42]. Biomimetic science aims at reclaiming the lost tooth tissue in the natural tooth structure by using materials with appropriate elastic modulus to mimic the tissues, and with the correct occlusal form (biodome, bio rim) [42-44]. Studies have reported that the crown form (varying number and shape of cusps) and root configuration affect fracture resistance [42,46,47]. Under vertical loading, more stress was transferred by abrasion, especially at the mesial root, while under oblique loading, the stress caused by abrasion was reduced. The stress is mainly distributed on the buccal surface and mesial root with vertical loading, or on the lingual surface and distal root with oblique loading. The maximum von Mises with oblique loading was significantly higher than with vertical loading [45]. With excessive occlusal curvature, less bite force would be required for a crack that would occur following bending, and that the longitudinal course of the cracks would be low due to the shortness of the cusps [47]. Tooth preparations are recommended to be done in line with the anatomy of the tooth. This would allow increased restorative material resistance and cement space [47]. Moreover, the resistance of both the enamel and the dentine can be increased against forces by forming the cusps and fossae (biodome) in restorations. Superstructure/restoration resistance helps preserving the esthetics, function, and soft tissues. Resistance is provided for cusps prepared with biodome using a bio rim design, which also protects the gingiva [42,43]. The fact that the anatomical shape of the tooth can be prepared in a design similar to the natural tooth with CAD-CAM technology allows the abovementioned concepts to be replicated. These concepts were also observed to influence stress distribution [42]. Considering the findings of present study, when figures 2, 6, and 7 are examined, it can be interpreted that the stress in third molar was more homogeneously distributed in the crown, and that possible fracture or root resorption at the cervical region may be prevented after autotransplantation. In addition, researchers have stated that tubercular movements present in restored molar teeth after occlusal loading would lead to formation of fractures due to stress in wide restorations [48]. In Model 3, stress was more concentrated in the dentin area with tubercular movements, whereas in Model 6, stress was restricted by crowning and tubercular movements were observed mostly on crowns (Fig. 2). With this, fracture risk may be minimized by crowning the third molar tooth autotransplanted to the first molar location, after the root canal treatment. [48]. Additionally, the stress distribution in the restorative material varied for restorative materials presenting a different elastic modulus [47]. In Models 5 and 6, varying stress distribution in dentin may have sourced from the fact that the materials applied together with root canal treatment had different elastic moduli (Fig. 2). Even though the max stress values in cortical and alveolar bone in the present study were not at a level that would cause bone deformation and fracture (with PDL and ankylosed), some researchers have stated that compression forces could increase the osteoclastic activity and may cause bone resorption [14].

Elastic and anisotropic structures are modelled and analyzed by using different methods. Anisotropic and nonlinear FEA resolutions require highly specialized computer systems and due to the fact that their mathematical resolutions are complex, researchers have been using isotropic designs for anisotropic structures like bone and PDL [49-51]. In addition, mathematical models of anisotropic designs are in experimental stages, and to the authors knowledge, there is no consensus on their optimal application method. Because of the mentioned reasons and to enable comparisons with previous studies, the models were designed isotropic and homogenous.

In the present study, the occlusal load was applied on the same location on all models on x, y, z planes, and its direction and magnitude were standardized. The occlusal load was applied on a node rather than on the surface to prevent the potential effect of differences in surface topographies on the magnitude and direction of the load [52]. The load was applied on a common node to standardize the load application across groups tested in the present study. The fact that only vertical load was used is a limitation of the present study and the design was limited to vertical load application because the interpretation of the results would not be possible only in one study considering the previous studies results.

Considering the findings of the present study, the prognosis of autotransplanted tooth against occlusal forces could be improved with root canal treatment and crown application. Also, the occlusal morphology and PDL are significant variables in stress distribution in dentin and cortical bone. The stress concentration at the cervical region of ankylosed teeth can be prevented with a crown.

When the stress values found in the present study are considered, their magnitudes were not high. Nevertheless, comparisons amongst models were still possible and shed a light on potential differences that may be seen intraorally, particularly when higher occlusal loads are considered in patients with parafunctional habits.

Although the ability to standardize parameters and simulate only the required cases is an advantage with FEA, complex intraoral conditions cannot be completely replicated. For instance thermal changes and their effects are not applicable in FEA studies A limitation of the present study was that while qualitative and quantitative evaluations can be carried out with static loading, the situations that could lead to clinical fatigue could not be tested. There is a need for clinical studies to further evaluate the models utilized in the present study, along with long-term follow-ups. FEA studies are done with numerical models and no numerical model can be fully verified. This limitation also applies to the present study [53]. Therefore, the findings from the model in the present study can not be completely related to the clinical situation. This should be considered when interpreting the results [54,55].

5. Conclusions

Within the limitations of this study, the following conclusions can be drawn:

1. The occlusal morphology and the presence of PDL influenced stress distribution in dentin and cortical bone.

2. The stress concentration at the cervical region in ankylosed teeth and possible fractures may be prevented with the new occlusal surface by crowning.

3. Root canal treatment alone was not sufficient preventing increased stresses on autotransplanted teeth; crowning can also be considered along with root canal treatment.

Credit author statement

Authors: Ömer Kırmalı: Conceptualization, Writing - Original Draft, Formal analysis, Nurullah Türker: Methodology, Resources, Supervision, Türker Akar: Investigation, Supervision, Burak Yılmaz: Writing - review & editing

CONFLICT OF INTEREST STATAMENT

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ÖMER KIRMALI, 07.06.2021

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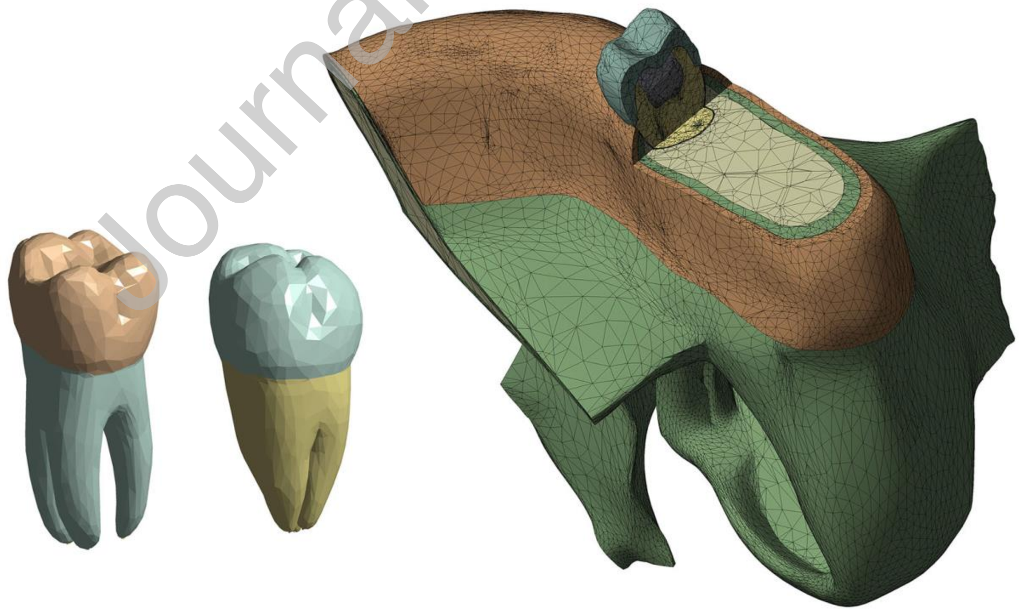

Fig. 1. Tooth models and sectioned model of meshed geometry.

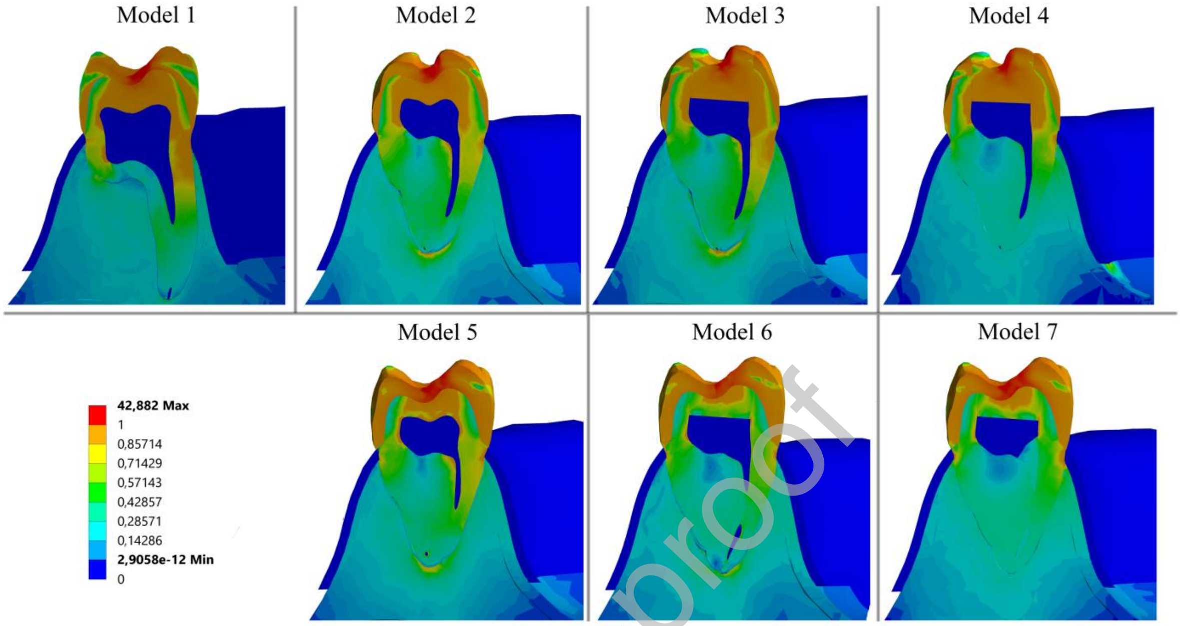

Fig. 2. Cross-sectional view of stress distributions in all models.

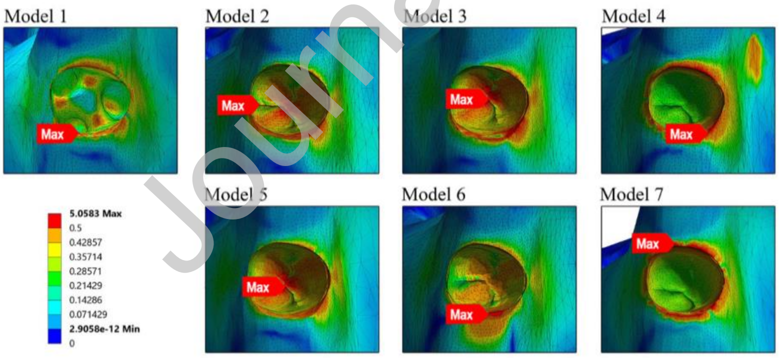

Fig. 3. Coronal and apical view of stress distribution in cortical and trabecular bone

Table 1. Properties of materials used in present study.

	Young's Modulus (GPa)	Poisson's Ratio	

Gingiva	0.003	0.45 [18]	
Cortical Bone	13.7	0.3 [19]	
Trabecular Bone	1.37	0.3 [19]	
Enamel	80	2 [20]	
Dentine	18.6	0.31 [21]	
Cementum	18.6	0.31 [22]	
Pulp	0.00207	0.45 [23]	
Periodontal Ligament	0.0689	0.45 [24]	
Monolithic Zirconia	205	0.23 [25]	
Resin Cement	9.1	0.3 [26]	
Composite Resin	12	0.33 [27]	
Glas Ionomer Cement	7.56	0.35 [28]	
Gutta Percha	0.00069	0.45 [29]	

Table 2. Number of elements and nodes in Model 1 and Model 6.

	First Molar (Model 1)		**Third Molar (Model 6)**	
	Elements	**Nodes**	**Elements**	**Nodes**
Gingiva	14853	28763	46353	84790
Cortical Bone	48872	89833	119698	215775
Trabecular Bone	20692	36492	13054	23752
Enamel	3715	6716	701	1613
Dentine	9283	15994	18007	30023
Cementum	10668	20622	3248	6703
Pulp	8110	14768	-	-
Periodontal Ligament	6343	12607	3629	7285
Monolithic Zirconia	-	-	1969	3589

Resin Cement	-	-	3928	8065
Composite Resine	-	-	1358	2484
Glas Ionomer Cement	-	-	4106	7257
Gutta Percha	-	-	6221	11737

Table 3. Maximum stress values observed on cortical and trabecular bone (MPa, Equivalent Von Mises Stress)

	Cortical Bone	**Trabecular Bone**
Model 1	2.2	1.0
Model 2	1.1	1.6
Model 3	1.2	1.4
Model 4	4.0	2.8
Model 5	0.9	1.5
Model 6	3.3	5.1
Model 7	3.4	2.5

Model 1: First molar tooth model; Model 2: Third molar tooth model; Model 3: Root canal-treated third molar tooth model. Model 4: Channel treated, ankylosed, third molar tooth model. Model 5: Crowned third molar tooth model. Model 6: Third molar tooth, channel treated, with crown restoration. Model 7: Channel treated, ankylosed, crowned third molar tooth model.