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Stress analysis of a human tooth with support tissues resorption

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Abstract

Conservative and reconstructive dentistry saw a constant evolution, becoming a reliable technique of oral rehabilitation aiming to maintain, as much as possible, the remaining teeth in the oral cavity. The resorption of tooth's surrounding support tissues (cortical-cancellous bone and PDL) reduces its capability to efficiently support current functional loadings, determining a failure in time. In this study 3D finite element analysis is used for studying the level and distribution of von Mises equivalent stress in the components of a human lower premolar tooth and its surrounding support tissues(bone and PDL), in case of their progressive reduction. Von Mises stress distribution indicated that a rapid and massive increase of stress values in all model's components, is closely related to the resorption process. Mechanical stress reaches highest values in bone. Additionally, a turning point in the biomechanical behavior of the support tissues can be observed at 70% resorption degree.

Rezumat

Stomatologia conservativa si minim invaziva a cunoscut o evolutie constanta, devenind o alternativa viabila de rabilitare orala avand ca scop mentinerea, cat mai mult posibil, a unitatilor dentare restante in cavitatea orala. Resorbtia tesuturilor de suport inconjuratoare ale unitatii dentare(os cortical, trabecular si ligament periodontal)reduc capacitatea de suport la incarcarilor functionale curente, determinand in timp esecul. In cadrul acestui studiu, analiza de element finit 3D este utilizata pentru studiul valorilor, nivelului si distributiei stresului von Mises in cazul componentelor tesuturile componente ale unui premolar mandibular si ale tesuturilor sale de suport (os si PDL), in cazul resorbtiei lor progresive. Distributia stresului von Mises a indicat faptul ca o crestere rapida si masiva a valorilor numerice ale stresului in toate elementele componente ale modelului este strans legata de procesul de resorbtie. Stresul mecanic atinge nivelul maxim in os. Aditional se poate observa un punct de cotitura in comportamentul biomecanic al tesuturilor de suport in jurul nivelului de 70% resorbtie a inaltimii tesuturilor de suport.

Keywords: biomechanics, finite element analysis, stress, tooth

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1. Introduction

In the last few years conservative and reconstructive dentistry saw a constant evolution, becoming a reliable technique of oral rehabilitation. Its aim is maintaining, as much as possible, the remaining teeth in the oral cavity, using a large arsenal of dental techniques and materials. Some clinical concepts regarding conservative and reconstructive dentistry are still controversial and are often based on profuse and inconclusive empirical literature needing further investigations [1].

Bone resorption along with the periodontal ligament(PDL) has been seen for a long time as a major problem of the conservative and reconstructive dentistry. It is well known that the resorption of the tooth's surrounding support tissues(cortical-cancellous bone and PDL) reduces its capability to efficiently support current functional loadings, determining a failure in time. The success of maintaining a tooth in place, among other factors, is heavily dependent on knowing the stress and strain distribution in the surrounding bones and PDL. The stress distribution in a tooth model having a reduced bone supporting tissues is difficult to assess without analyzing its biomechanical behavior using finite element analysis(FEA). Few and scarce information regarding FEA conducted over models having bone and PDL's resorption are currently available.

Most of the studies analyzes teeth and implant models having an almost complete support structure or an idealized bone and PDL structure and dimensions. In reality it is unlikely to find very often ideal dimensions in nature. So, it is important to analyze structures and models close to the reality for obtaining more accurate results.

Accurate bone architecture and PDL’s biomechanical behaviors under physiologic and traumatic loading conditions might enhance the understanding of biologic reactions in health and disease[6,7]. The accurate modeling of the PDL affects the deformation and thus strain magnitudes not only of the alveolar bone around the biting tooth, but that the whole mandible deforms differently under load[2]. The boundary conditions used in FEA might affect results' accuracy [3,4,5,8].

In the last years computerized tomography(CT) scan technology became almost an standard in examining tooth structures and its surroundings, due to its qualities regarding the minimum invasive techniques and procedures and the amount of detailed data provided.

The aim of this study is analyzing the level and the distribution of the von Mises equivalent stress(a scalar stress value used to predict failure in engineering materials) in the components of a human lower premolar tooth and its surrounding support tissues(bone and PDL), in case of their progressive reduction, under the action of the combined mechanical efforts simulating the processes of the tooth under occlusal load.

2. Material and method

2.1. Image processing and finite element model creation

In this study we used a dental CT, model PaX-Reve3D(Vatech America), FOV 5cmX5cm and voxel size 0.08mm.

The area investigated concerned a healthy complete mandible section, containing the second lower right premolar of a 34 years old healthy male. More than 2200 2D slices were taken. The distance between two slices was 80µm, thus allowing the registration of highly accurate anatomical details. 3D models of each components: enamel, dentin, pulp chamber, periodontal ligament and surrounding bones(cortical and cancellous bone) were generated. All these models were assembled into 3D complete models in a further step.

The models contained an anatomical region of 320mmx320mmx320mm. Tooth's support surrounding tissues had a height of 19.2mm, the bone beneath had 6mm, while the tooth, the second lower right premolar, had 26mm of height. The models used in this study were divided into two major components. One was represented by the second right lower human premolar and which remained unchanged. The other component was the surrounding support tissues: cortical-cancellous bone and PDL, and was changed according to the presumed resorption progression. The models simulated a progressive resorption of the surrounding support tissues from 50% up to 90% of their entire volume(bone and PDL). Each progressive resorption step was considered to be of 24 slices(1.92mm).

For generating the 3D models was used AMIRA software, version 5.4.0 (Visage Imaging GmbH, Berlin, Germany). Image segmentation process was done manually for each slice, obtaining a better accuracy, based on the different gray scale values based on Houndsfield units. A clear separation among dentin and cement was impossible, so the entire cement layer, in the roots area, was considered to have the same properties as dentin. This simplification should be acceptable due to similar properties of the dentin and cement. PDL was attached to the intraalveolar surface and to the root having a thickness of minimum 1 voxel. According to specialized literature PDL's thickness is varying between 0.20mm-0.40mm[12]. PDL's thickness in our models varied between 1-3voxel(0.08mm-0.24mm), depending on the anatomical topography identified on CT's slices. Cortical bone layer segmented had a minimum of length of at least 2mm, depending on the anatomy of the region segmented on the CT's slices.

From the CT slices through the segmentation process surface models were obtained, calculated and described with triangles. For generating the volume models, the surface models needed to be strongly simplified but maintaining the shapes of the original surfaces. In the next step the volumes restricted by the surfaces were filled in with tetrahedrons and were obtained different mesh.

The models were calculated and described using triangles. Before generation, all surfaces were simplified using an internal function of AMIRA(edge collapse algorithm). The edges of the original surfaces were also successive reduced, thus obtaining a reduced number of triangles and row surfaces. The original surfaces form was maintained through reducing a certain error criteria, during AMIRA processes. After simplifying, the surfaces were optimized, obtaining a good quality triangles and then generating the models. The volumes were field with four nodes tetrahedrons, obtaining a final mesh. This mesh was than exported and analyzed in ABAQUS software, version 6.1.1. (Dassault Systemes Simulia Corp., Providence, Rhode Island, USA).

2.2. Boundary conditions

The tooth during its functionality in the oral cavity are subjected to different types of loadings, often difficult to be reproduced and measured. In most current researches, axially applied static loads have been assumed instead of the more realistic dynamic-cyclic loads[3,4].

The base of the model was considered to have zero displacement, boundary condition being applied for restraining all forms of translational movements. An minimum ocllusal load of 10MPa in coronal-apical direction was applied on the top surface of the crown in order to estimate the effect of the load over the models' components[3,4,13,14], Fig. 1. The vertical load was applied at the surface central in the occlusal face of the crown. The other surfaces are treated as free surfaces with zero loads.

The interface between all components are treated as perfectly bonded interface[3,4]. In reality, bone as material, is neither homogeneous nor isotropic, and should be modeled as a porous material with a complex microstructure[3,15]. For simplifying the FEA, it has been assumed to be isotropic, linear elastic and homogenous[2,3,9,16]. Based on these we considered that all the materials, in our models, to be homogenous, isotropic and linearly elastic[2,3,4.10]. The mechanical properties of the enamel, dentin, pulp, PDL, and cortical and cancellous bone, used in this study are given in Table I.

Table: 1 Elastic properties of materials used in the study

Material	Constitutive equation	Young's modulus E (GPa)	Poisson ratio, υ	Refs.
Enamel	Isotropic and linear elastic	80	0.33	[9,10,11]
Dentin	Isotropic and linear elastic	18.6	0.31	[1,9,10,11]
Pulp	Isotropic and linear elastic	0.0021	0.45	[9,10]
PDL	Isotropic and linear elastic	0.0689	0.45	[2,7,9,10,11]
Cortical bone	Isotropic and linear elastic	14.5	0.323	[3,4]
Cancellous bone	Isotropic and linear elastic	1.37	0.30	[2,3,4,5,9]

3. Results

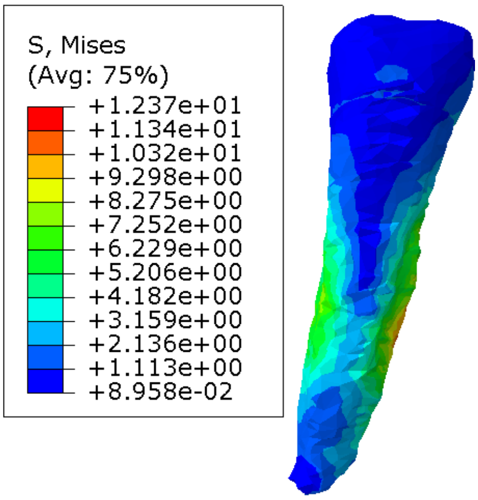
In this study was analyzed the level and the distribution of the von Mises equivalent stress in the components of a human lower premolar tooth and its surrounding support tissues(bone and PDL), in case of their progressive reduction from 50%, to 90%. Von Mises scalar stress value, being considered to be a proper tool for representing the state of stress in engineering materials for predicting their failure, is extensively used in recent biomechanical studies of tooth, bone, PDL and implants[1]-[11]. The variation of the overall stress state for each component of the models are presented under effect of the 10MPa loading. A qualitative and quantitative analysis was conducted based on ABAQUS's progressive visual color scale, ranging from dark blue(minimum- virtual no stress state) to red(maximum-potential failure state). The maximum stress values in each of the models' components under different loadings are shown in Table II and Fig. 1-3.

Table: 2 Maximum von Mises stresses variation (in MPa) of models' components under different load directions, during tooth's surrounding support tissues progressive resorption simulation

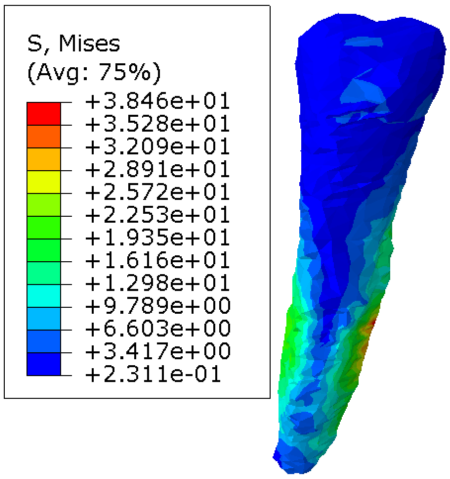
Tooth's surrounding support tissues resorption degree	Model components	Coronal apical load (MPa)
50%	Tooth-(enamel, dentin, pulp)	**12.37**
	PDL	**3.40**
	Bone(cortical and cancellous)	**33.73**
60%	Tooth-(enamel, dentin, pulp)	**38.46**
	PDL	**4.81**
	Bone(cortical and cancellous)	**31.99**
70%	Tooth-(enamel, dentin, pulp)	**79.57**
	PDL	**12.79**
	Bone(cortical and cancellous)	**42.22**
80%	Tooth-(enamel, dentin, pulp)	**81.06**
	PDL	**25.94**
	Bone(cortical and cancellous)	**78.63**
90%	Tooth-(enamel, dentin, pulp)	**94.11**
	PDL	**29.68**
	Bone(cortical and cancellous)	**185.9**

Fig. 1. represents the von Mises stresses distribution within the tooth having a surrounding support

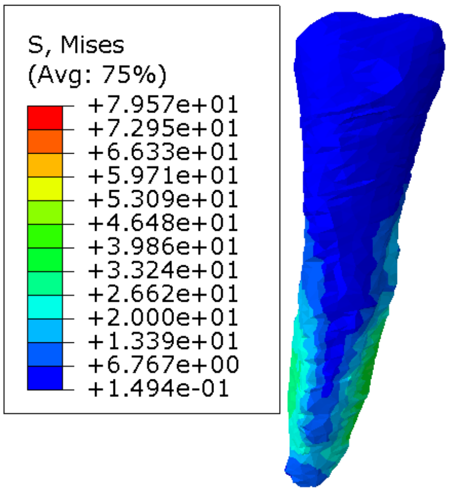
tissues resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%. In the images can be observed that the maximum von Mises stresses were concentrated on the both sides of the tooth, respectively the mesial and distal side, were the support tissues are located and follows their resorption. This distribution is influenced by the model's structure similar with the real anatomical ones.



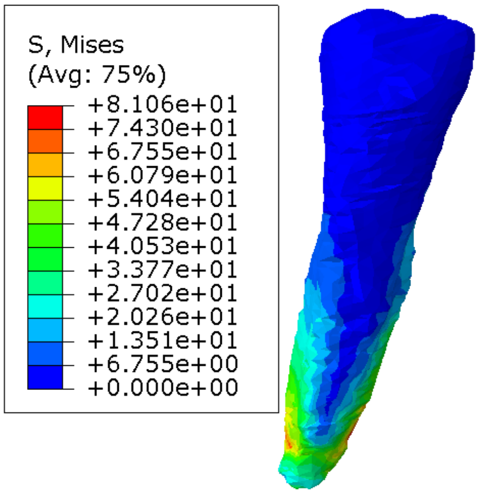
(a) vestibular side



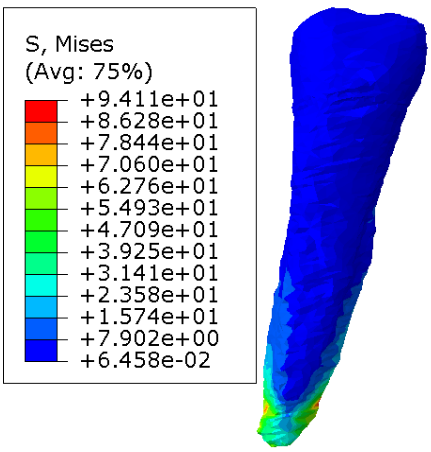
(b) vestibular side



(c) vestibular side



(d) vestibular side



(e) vestibular side

Fig. 1. presents the von Mises stresses distribution within the tooth having a surrounding support tissues resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%.

Fig. 2. presents the von Mises stresses distribution within the periodontal ligament having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%. In this images it is observed the presence of a maximum von Mises stresses on the lingual side of the PDL, (a)-(b), and a progressive shift, (c) and (d), to the mesial and distal side (e), due to its anatomy. The mechanical stress in PDL reaches greatest stress in the bottom, Fig. 2.(e), which in this situation, intuitively supports the occlusal load. Fig. 3. presents the von Mises stresses distribution within the mandibular bone having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%. The bone is little affected by the stresses, (a), and only to the vestibular and lingual side. The progression of the resorption process determines a rise of the von Mises stresses, (b), and a gradual shift to mesial and distal sides (e). Practically the reduced supporting bone, Fig. 3.(e) takes the support of the occlusal load and determines the showed stress distribution. Model architecture, similar to the real thing, plays a crucial role in this behavior.

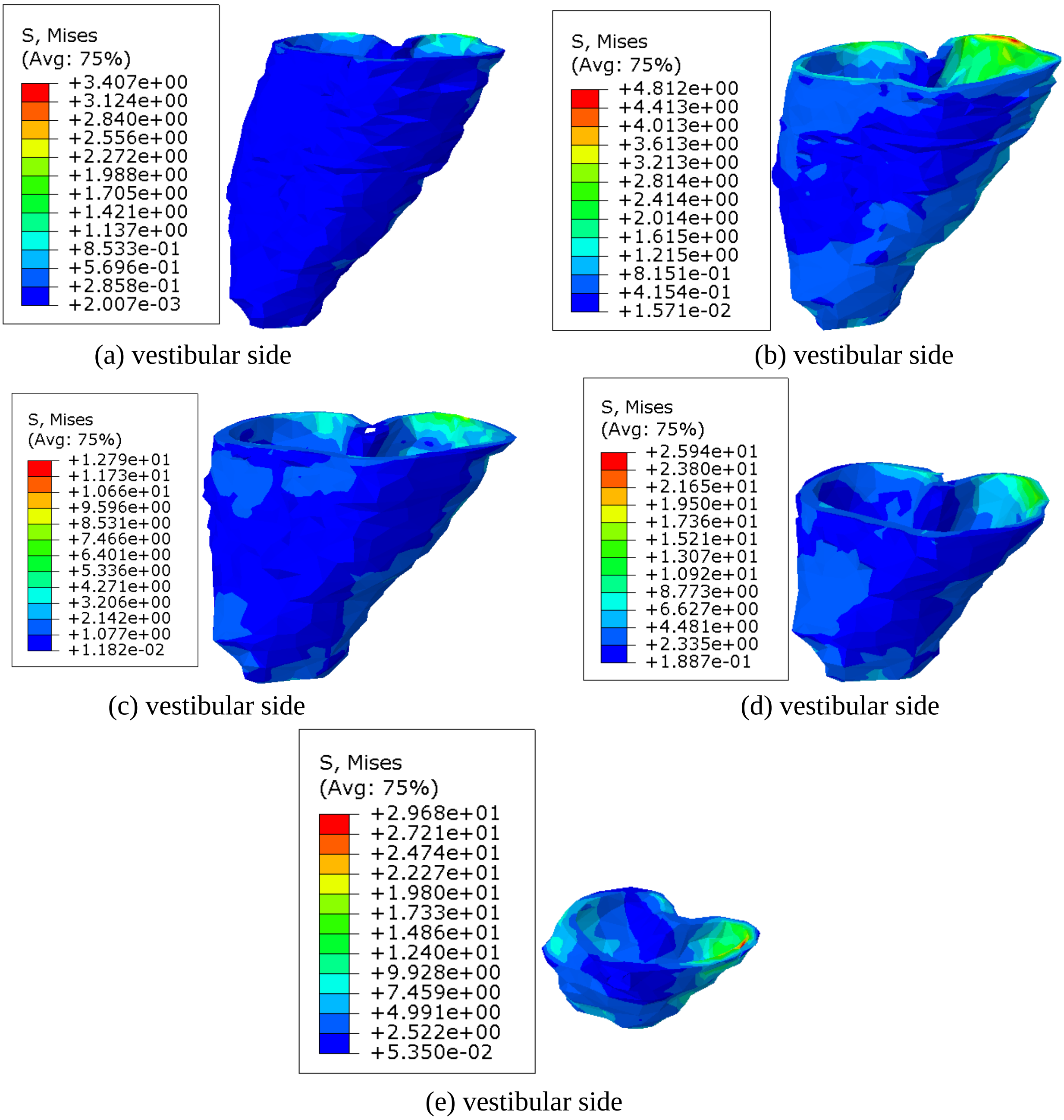
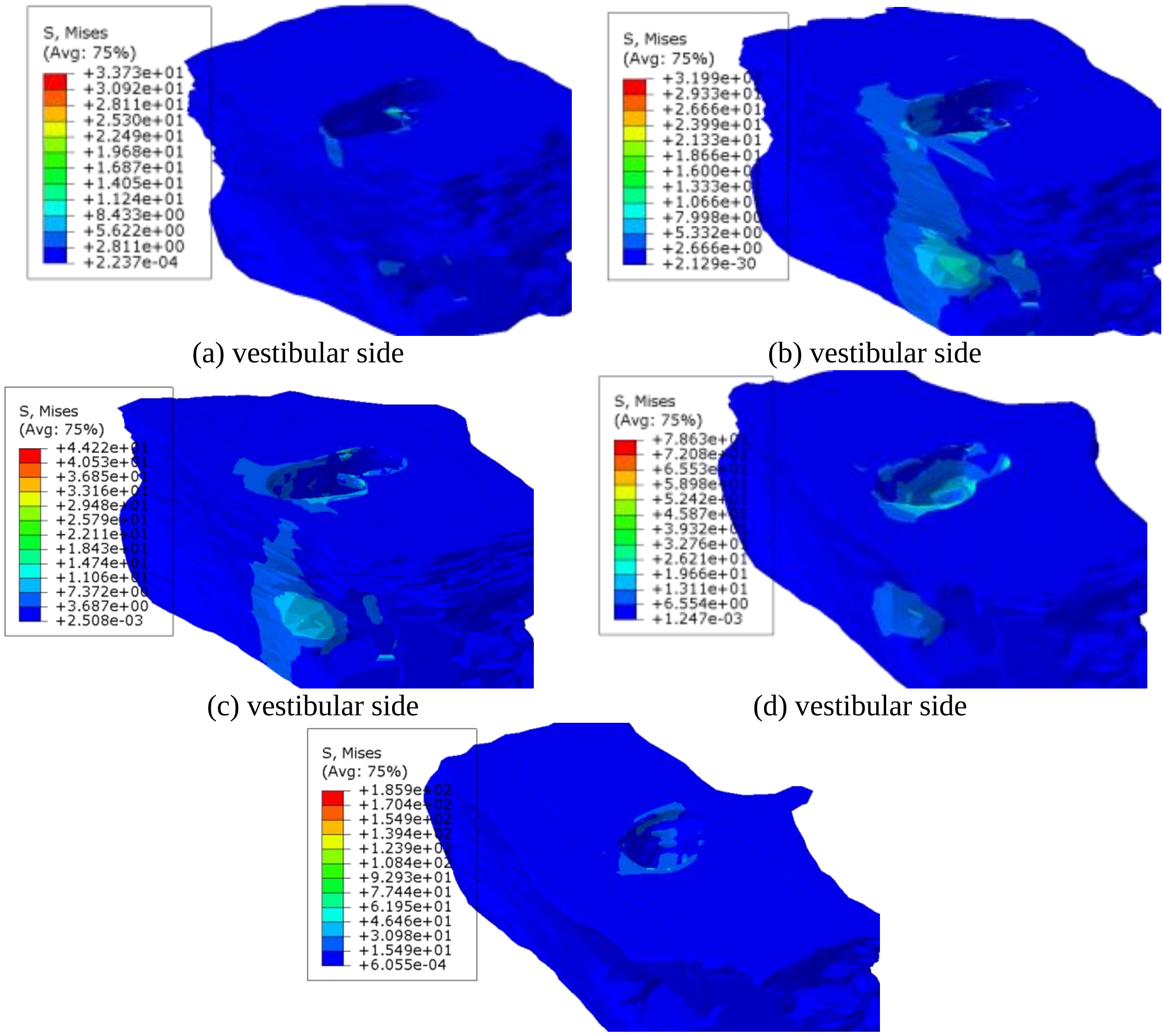


Fig. 2. presents the von Mises stresses distribution within the peridontal ligament having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%.



(a) vestibular side (b) vestibular side

(c) vestibular side (d) vestibular side

(e) vestibular side

Fig. 3. presents the von Mises stresses distribution within the mandibular bone having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%.

4. Discussions

The aim of this study was to investigate the stress distribution in bone, periodontal ligament and tooth, during tooth's support tissues resorption process. We considered the entire model to be made of homogenous, isotropic and linearly elastic materials and to be subjected to a 10MPa static load. All these material properties and boundary conditions have been reported to provide a good and clear indication of the actual situation observed in clinical studies [3]-[5], [17]-[19], therefore we considered them perfectly suited for this study.

Our hypothesis regarding the progression of the support tissues resorption from 50% to 90% height, is considered to be accurate for describing the entire process despite the fact that the literature provide few data regarding this subject.

The model we used, being created by manual segmentation from a dental CT slices, is extremely detailed and accurate being considered almost similar to the natural thing. It respects not only the anatomical position of different material layers but also the height, length, growth, inclination and angle of different anatomical components. This aspect gives high accuracy to the data provided by the FEM analysis.

Table II and Fig. 2 shows that in case of the tooth subjected to a vertical load of 10MPa the maximum von Mises stresses were concentrated on the mesial and distal sides of the tooth, were the support tissues are located and follows their resorption.

Qualitative and quantitative analysis based on ABAQUS's progressive visual color scale, ranging from dark blue to red showed that the zones were the stresses increases have the tendency to move toward the apex of the tooth following PDL and bone's resorption. Their location on the mesial and distal sides of the tooth can be explain by the tridimensional position of the tooth relative to the bone and PDL, which is not vertical but has a certain degree of inclination in all the 3 spatial plans, similar to the anatomical reality.

Knowing this fact is extremely important for the clinical practice for better understanding the tooth biomechanical behavior. Following the values provided by the Table II there can be seen a certain predictability regarding the rise of the values and the tendency to increase the stresses. When the resorption attains to 70% of tooth's surrounding support tissues, Fig. 1(c), there can be observed a sudden increase of almost 100% of the stresses values. This moment can be consider a turning point regarding tooth's biomechanical behavior and most certainly affects tooth's prognosis for maintaining in oral cavity. From this point its progression it is not so spectacular Fig. 1(d) and (e). This fact confirms the empirical knowledge regarding tooth biomechanical behavior.

Fig. 2.(c) and the values presented in Table II shows that the 70% resorption degree marks an increase of almost 260% of the stresses values in the PDL. This mathematical progression rate is maintained for the next two levels of resorption, Fig. 2.(d) and (e). These increasing stress values confirms the existence of a turning point at 70% of the resorption degree, thus confirming the empirical knowledge. The position of the von Mises stresses in the PDL, showed in Fig. 2, are placed on the PDL's lingual side and when the resorption level advances, have the tendency to shift to the mesial and distal side. This behavior is determined by the tridimensional position of the tooth and PDL relative to the bone and the loading direction.

Fig. 3(d) and Table II shows that there is almost 170% increase in stress values when the resorption attains to 80% of the bone. Fig. 3(c) confirms the existence of that turning point at 70% resorption degree. Cortical bone takes most of the stresses determined by the oclusal loading, due to its elastic modulus (E = 14.5GPa) which is ten times the elastic modulus of the cancellous bone (E = 1.37GPa). This fact is showed in Fig.3 (a), (b), (c), (d) and (e).

The finite element analysis(FEA) is an accurate method to study and describe the behavior of different structures under different loads, but one of its limit is given by the correctitude level of the analyzed 3D model. More the model is precise and close to the anatomical structures, more the provided data is accurate. The FEA was employed intensively to predict the biomechanical behavior of various designs of dental structures and the effect of the clinical factors on their success [3]-[5].

By using FEA a detailed comprehension of biomechanical behavior of each model's component can be achieved. These data could improve not only the theoretical knowledge but also the techniques and procedures applied in conserving the tooth in the oral cavity. By understanding how the FEA works and by being able to read and understand its results the clinician is able to improve its skills and knowledge and apply these results in daily clinical situations.

The limits of these types of studies derives from the FEA own inherent limitations. It is important to know that the stress values that produces biological changes in dental structures,(eg., resorption process), are not entirely know and understood. The values provided by the FEA studies are not necessarily identical to the actual values [3]-[5], depending on a lot of FEM variables.

For a better conservation of teeth, PDL and bone, in order to respect and follow the conservative and reconstructive dentistry principles, recent studies have focused on describing their biomechanical behavior [3]-[5], [8]-[11]. It is widely known and accepted that increased stress around the tooth can lead bone and PDL resorption [4,12]. Therefore, determining the stress distribution and intensity is important for a better a understanding of the resorption process that may lead to loss of the tooth.

Another aspect important to be aware of, is the fact that FEA is based on mathematical principles and processes, while the living biological tissues do not react in the same way. This aspect highlights that FEA should not be considered the only way to understand the tooth biomechanical behavior, and clinical experimentation is needed for validating the FEA results, no matter how difficult this is.

5. Conclusions

After this FEA study, as an overall conclusion, the following assumptions are reached for. It is visible that the mechanical stress distribution is depending on the type of load and the tooth's 3D spatial position relative to PDL and bone and closely follows the resorption process. There is seen a rapid and massive increase of the stress values in all the model's components, closely related to the resorption process. These aspect confirms the empirical knowledge related to tooth's biomechanical behavior.

The mechanical stress reaches the highest values in the bone, knowing that the cortical bone takes most of these stresses. Additionally, a turning point in the biomechanical behavior of the support tissues can be observed at 70% resorption degree. These might explain why after a long period of slow tooth's surrounding support tissues resorption process showing no warning signs, soon as a certain resorption degree is passed, the tooth is rapidly lost.

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