Strain Analysis of a Human Tooth with Support Tissues Resorption

R. A. Moga, C. G. Chiorean

***Abstract*—The conservative and reconstructive dentistry took, in the last years, a rapid and progressive evolution, becoming a viable and reliable technique of oral rehabilitation. It aims to recuperate and conserve any remaining structure from the oral cavity. One of the major problems of the conservative and reconstructive dentistry is bone and periodontal ligament (PDL) resorption that 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 the distribution of the strain in the components of a human lower premolar tooth and its surrounding support tissues(bone and PDL), in case of their progressive reduction. Strain distribution indicated a rapid and massive increase of the strains values in PDL, closely related to the resorption process, leading to a logical conclusion that after a certain resorption degree the loss of the tooth is only a matter of time.**

***Index Terms*— biomechanics, finite element analysis, strain, tooth**

I. Introduction

The conservative and reconstructive dentistry took, in the last years, a rapid and progressive evolution, becoming a viable and reliable technique of oral rehabilitation. It aims to recuperate and conserve any remaining structure from the oral cavity, as much as possible, using a large arsenal of enriched by state of the art 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].

One of the major problems of the conservative and reconstructive dentistry is bone and periodontal ligament(PDL) resorption. It is widely known that tooth's surrounding support tissues resorption (eg., 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 not only the stress but also the strain distribution in the surrounding bones and PDL.

The strain distribution in a dental-periodontal unit having a reduced supporting tissues is difficult to assess without analyzing its biomechanical behavior using finite element analysis(FEA). Strain distribution completes the data provided by the von Mises stress analyses helping for a better understanding. Few and scarce information regarding FEA conducted over models having bone and PDL's resorption are currently available.

Most of the studies, analyze only the von Mises stress distribution in models with an almost complete support structure or idealized dimensions. In reality it is unlikely to find very often ideal dimensions and complete structures in nature. In the light of all these we believe that it is important to analyze structures and models close to the reality, as much as possible, for obtaining more accurate results. Understanding the behavior and knowing the areas of tensile and compressive stresses distribution, might improve the not only the theoretical knowledge but also the practical dental techniques.

An accurate bone and PDL architecture and their 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 common dentistry examinations, due to its indisputable qualities regarding not only the quality of the provided data but also the accessibility and minimal invasive procedure, extremely important for both the patients and clinicians.

Our aim in this study was to analyze the strain distribution (which is a description of deformation, used in engineering materials, showing the tensile and compressive stresses) 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 a occlusal force, simulating the mechanical efforts processes of the tooth.

II. Material and methods

A. Image processing and finite element model creation

We used in this study a dental CT, model PaX-

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Reve3D(Vatech America), FOV 5cmX5cm and voxel size 0.08mm.

The investigated area 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).

B. 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. For facilitating the FEA a better understanding the results in most current researches, axially applied static loads have been assumed instead of the more realistic dynamic-cyclic loads[3,4].

We considered that the base of the model had zero displacement, boundary condition being applied for restraining all forms of translational movements. A minimum ocllusal load of 10MPa in coronal-apical direction was applied on the top surface of the premolar's 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 enamel surface central in the occlusal face of the crown. We treated the other surfaces as free surfaces having 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 I
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]

III. Results

We analyzed in this study the strain level and its distribution, 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 10%. Strain scalar stress value, being considered to be a also proper tool for representing the state of deformations in engineering materials, it completes the data provided by the von Mises stress analyses, both necessary for a better understanding of tooth's biomechanical behavior. Despite the fact that strain analyses is important and completes the knowledge and understanding of the processes, it is not often used in biomechanical studies of tooth, bone, PDL[21], from far more preferred is von Mises stress analyze [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(compression stress state) to red(tensile stress state), Fig. 1. The maximum strain values in each of the models' components under occlusal loading are shown in Table II and Fig. 2-4.

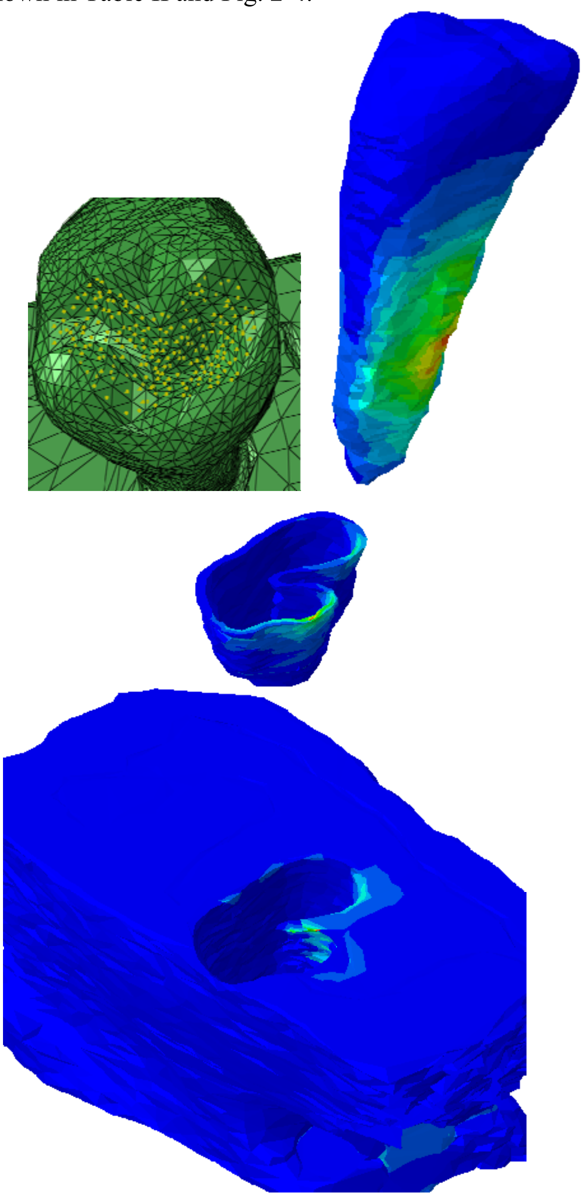

Fig. 1. presents the strain distribution within the all 3 model's components (tooth, PDL and bone) and the oclusal aplied load

A. Tooth (enamel, dentin, pulp)

Fig. 2. represents the strain 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 strain is concentrated on the mesial-lingual side of the premolar, due to spatial architecture of the model, and follows the resorption. There can be observe a gradual increase in strain values, which is normal, and explained by the gradual reduction of the bone and PDL. The maximum of compression is located at tooth's contact with the edge of the cortical bone and through PDL. This distribution is influenced by the model's structure similar with the real anatomical one.

B. Periodontal ligament(PDL)

Fig. 3. presents the strain distribution within the periodontal ligament having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%. This images show the presence of a maximum strain on the mesial and lingual side of the PDL, (a)-(b), and a progressive shift, (c) and (d), to the vestibular, mesial and distal side (e), due to its anatomy. The strain in PDL reaches greatest stress in the bottom, Fig. 3.(d), and (e), which in this situation, intuitively supports the occlusal load. It also can be noticed an rapid increase level of strain, which reaches the highest value at 80% resorption and maintaining almost the value at 90%, meaning that in this case the tensile stress in maximum and will drastically affect PDL integrity and biomechanical behavior.

C. Mandibular bone(cortical and cancellous bone)

Fig. 4. presents the strain 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 strain, (a), and only to the mesial and lingual side. The progression of the resorption process determines a gradual increase of strain's values. Practically the reduced cortical supporting bone, takes all the support of the occlusal load and determines the showed strain distribution. Model architecture, similar to the real thing, plays a crucial role in this behavior.

TABLE II

Maximum Strain (E) components at integration points variation (in Pa) of models' components under vertical load direction, during tooth's surrounding support tissues progressive resorption simulation

Tooth's surrounding support tissues resorption degree	Model components	Coronal aplical load (Pa)
50%	Tooth-(enamel, dentin, pulp)	**0.76**
	PDL	**40.88**
	Bone(cortical and cancellous)	**2.92**
60%	Tooth-(enamel, dentin, pulp)	**2.14**
	PDL	**115.1**
	Bone(cortical and cancellous)	**6.25**
70%	Tooth-(enamel, dentin, pulp)	**3.86**
	PDL	**190.7**
	Bone(cortical and cancellous)	**10.38**
80%	Tooth-(enamel, dentin, pulp)	**4.43**
	PDL	**435.7**
	Bone(cortical and cancellous)	**17.62**
90%	Tooth-(enamel, dentin, pulp)	**5.28**
	PDL	**431.1**
	Bone(cortical and cancellous)	**17.17**

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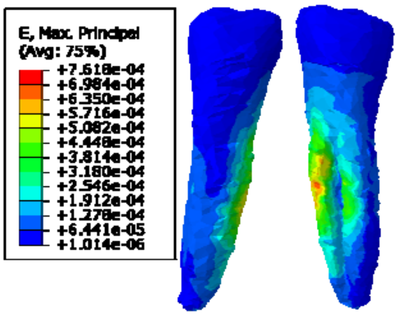
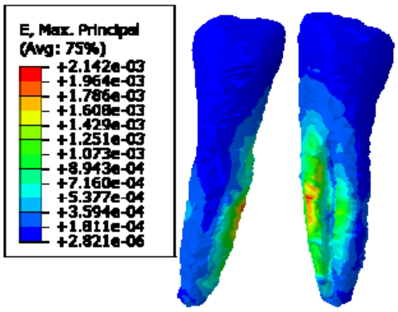
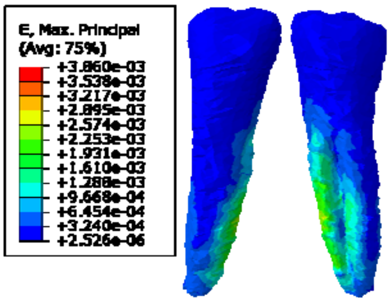


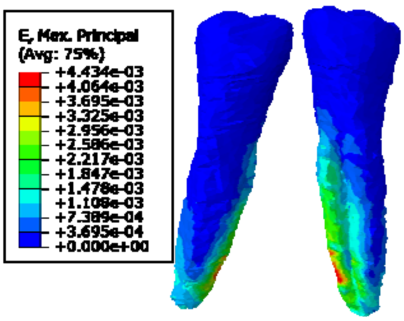
(a) resorption degree of 50%



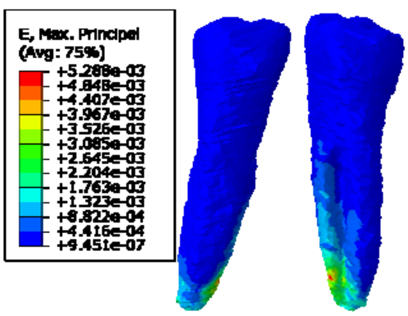
(b) resorption degree of 60%



(c) resorption degree of 70%

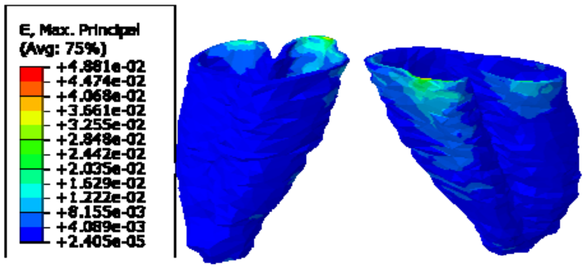


(d) resorption degree of 80%

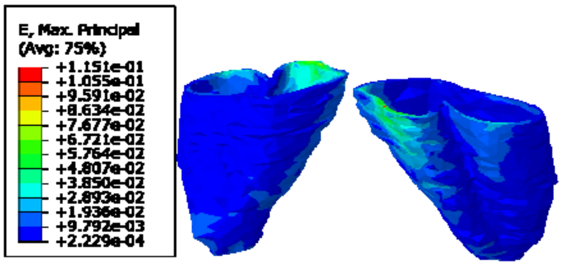


(e) resorption degree of 90%

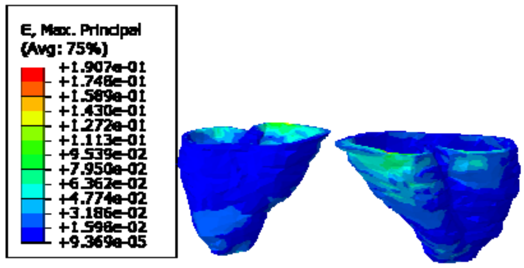
Fig. 2. Strain distribution within the tooth having a surrounding support tissues resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%.



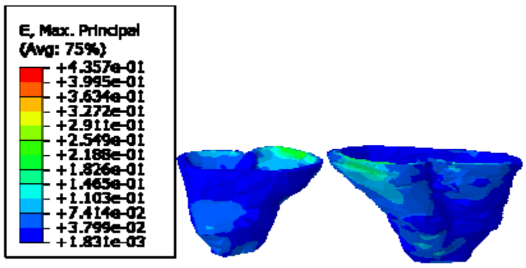
(a)) resorption degree of 50%



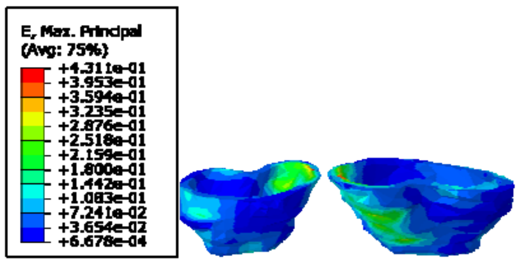
(b)) resorption degree of 60%



(c)) resorption degree of 70%



(d)) resorption degree of 80%



(e)) resorption degree of 90%

Fig. 3. Strain distribution within the peridontal ligament having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%.

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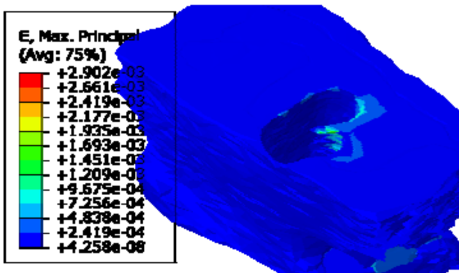
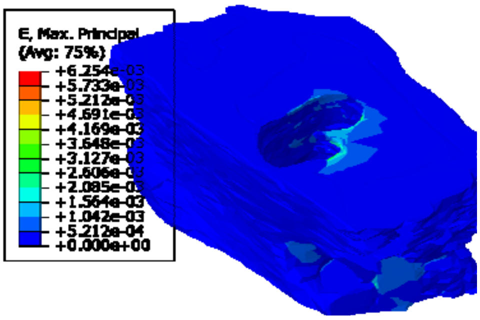
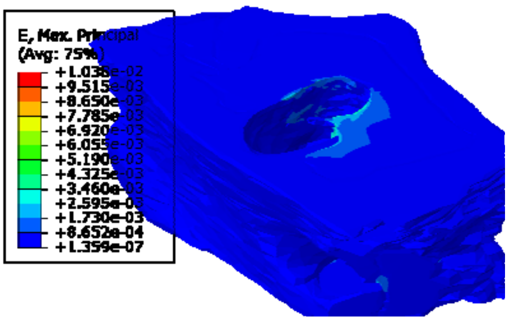


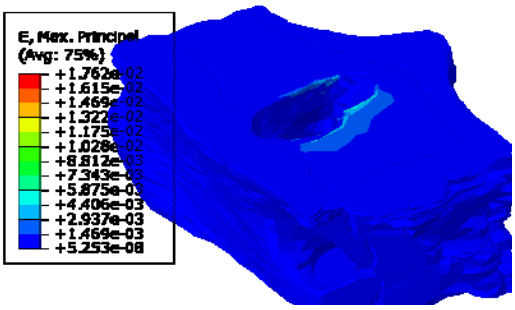
(a)) resorption degree of 50%



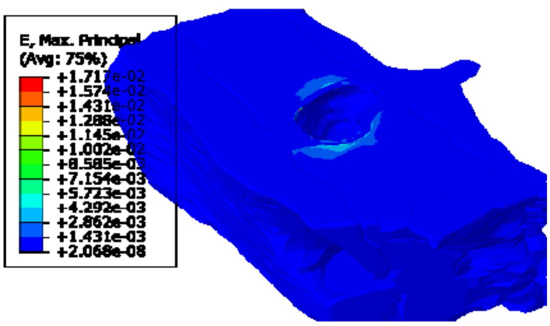
(b)) resorption degree of 60%



(c)) resorption degree of 70%



(d)) resorption degree of 80%



(e)) resorption degree of 90%

Fig. 4. Strain distribution within the mandibular bonep having a resorption degree of (a) 50%, (b) 60%, (c) 70%, (d) 80%, (e) 90%.

IV. DISCUSSION

The aim of this study was to investigate the strain distribution in bone, periodontal ligament and tooth, during tooth's support tissues resorption process.

The entire model was considered to be made of homogenous, isotropic and linearly elastic materials and to be subjected to a vertical 10MPa static load. 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]-[21], therefore we consider them perfectly suited for this study.

Literature provide few available data regarding the resorption process. Despite all these, based on our practically and theoretical experience we considered that our hypothesis regarding the progression of the support tissues resorption from 50% to 90% height, to be accurate for describing the entire process.

We created an extremely detailed and accurate 3D model, based on the dental CT's slices on which we conducted manual segmentation. Therefore we consider our model to be 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 increase its accuracy for providing detailed data for the FEM analysis.

Table II and Fig. 2 shows that in our case, for the tooth subjected to a vertical occlusal load of 10MPa, the maximum strain is concentrated on the mesial-lingual side due to geometric configuration and following the 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 tensile stress increases have the tendency to move toward the apex of the tooth following PDL and bone's resorption. Their location can be explain by the tridimensional position of the premolar relative to the support tissues, which is similar to the anatomical reality, being not vertical but with a certain degree of inclination in all the 3 spatial plans. This helps the clinician interpreting and understand biomechanical behavior. Table II shows a gradual increase of strain's values and a certain predictability. This fact confirms the empirical knowledge regarding tooth biomechanical behavior.

Fig. 3.(c) and the values presented in Table II shows that the 70% resorption degree marks an increase of almost 4.5 times of the maximum strain values in the PDL, while the 80% resorption, Fig. 3.(d), 10.6 times. This confirms the empirical knowledge, that a massive reduction of the support tissues will eventually lead to a rapid loss of the tooth. The strain position in the PDL, showed in Fig. 3, are placed on the PDL's mesial and lingual side, having the tendency to shift to mesial and distal side due to the tridimensional position of the premolar relative to the support tissues and the loading direction.

Fig. 4(d) and Table II shows that there is almost a gadual increase in strains values when the resorption attains the bone. 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). The fact is showed in Fig.4 (a), (b), (c), (d) and (e).

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All these suggest that the most affected component of the model is the PDL, being the weak spot in the entire model, thus confirming the empirical knowledge that if there is a reduction of the supporting tissues the tooth will soon be lost.

Finite element analysis(FEA), despite the fact that is an accurate method to study and describe the behavior of different structures under different loads, has certain limits, one of these being the fact that it depends on the 3D model architecture. A close to the anatomical reality architecture will provide good chances to obtain accurate data [22].

Literature shows that FEA is employed intensively in the last years for predict the biomechanical behavior of various designs of dental structures [3]-[5].

Through a finite element analysis can be obtained a detailed comprehension of biomechanical behavior of each model's component, improving both theoretical and practical knowledge related to the tooth conservation in the oral cavity. By understanding FEM's limits and advantages and how to interpret the results the clinician is able to improve both its skills and knowledge and apply these results in daily clinical situations.

The limits of these types of studies derives from the FEA's 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 and strain distribution and their intensity is important for a better a understanding of the resorption process that may lead to loss of the tooth.

An important aspect the clinician must 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, highlighting the need of in vivo clinical experimentation for validating FEA results.

V. Conclusion

As an overall conclusion, the following assumptions are reached for. It is clearly visible that PDL is most affected by the resorption process, and after a certain resorption degree the loss of the tooth is only a matter of time. This 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. Strain 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. These aspects confirms the empirical knowledge related to tooth's biomechanical behavior. Further studies are envisaged considering anisotropy and nonlinear constitutive equations to model more closely the real behavior of the human tooth with support tissues resorption. acknowledgment

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