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Periodontal Ligament Stress Analysis During Periodontal Resorption

R.A. Moga, C.G. Chiorean

***Abstract*—Conservation of the PDL(periodontal ligament) height during the orthodontic treatment phase is an important aim during the treatment of periodontal disease. It was hypothesized that due to periodontal resorption,, the same amount of force determines an increase of maximum stress in the PDL, which might affect its dimensions. The objective was to quantify stress produced in the PDL at 10 different bone levels under transverse and vertical orthodontic loadings, for the special case of a two roots second mandibular premolar. The alveolar bone and PDL has been reduced in height by 10%, from 0% to 90%, and subjected to 6 constant loadings of 1-10 N/mm2. The von Mises stress values for the PDL were calculated. For 0% bone loss, a 1 N/mm2 intrusive load produced a maximum stress of 0.08 N/mm2. For 50% resorption the stress was 0.41N/mm2 while for the 90% level the stress was 2.96 N/mm2. For the 0-80% resorption the mesio-distal load produced the highest stress values. The stress gradually increased along with the PDL and bone height loss, but declined steadily from the cervical to the apical level. Approximately 5.7mm (30%) resorption is assumed to be the starting point for dramatic changes in stress level. Results lead to the conclusion that application of higher forces will determine higher stresses in the cervical level which might affect the height of the PDL during the orthodontic treatment phase, and could worsen the periodontal problems.**

***Index Terms*—Periodontal ligament biomechanics, finite element analysis, stress, bone loss, bone biology**

I. Introduction

One of the major problems in dentistry is considered to be the treatment of the periodontal disease [1]. The periodontal resorption determines a reduction of the periodontal capability to efficiently support current functional loadings and influence its biomechanical behavior under stress [1]. Conservation of the tooth-periodontal ligament(PDL)-alveolar bone complex at various levels of bone height, among other factors [2], is heavily dependent on knowing the PDL's stress distribution [3]-[5].

With adequate orthodontic-periodontal coordination, it is possible to reestablish a healthy and functional dentition [6]. Force systems in most orthodontic treatments are considered indeterminate and the magnitude of forces and moments are, in practice, largely unknown [7]-[9]. Hence, it is necessary to limit the orthodontic force to prevent any damage [9]. The physiological mechanism primarily responsible for tooth movement in response to force is the PDL. Short-term tooth movement is regarded as primarily governed by PDL deformation [8]-[9].

The PDL's resorption process was widely investigated in the last decades [10]-[19]. Published results showed a significant increase in stress concentration at the apex with bone loss [16] and that height reduction potentially causes mechanical damage to the PDL [20]. It was found that 2.5 mm of alveolar bone loss can be considered as a limit beyond which stress alterations were accelerated [17]. PDL's accurate modeling affects the deformation and thus strains magnitudes not only of the alveolar bone around the tooth subjected to load, but also those of the whole mandible [21]. A better understanding of the PDL's biomechanical behavior under physiological and traumatic loading conditions might enhance the understanding of PDL's biological reaction in health and disease [2]. Much still remains to be learned about its 3D responses to load and the factors that control them [22].

It was pointed out that when analyzing the bone resorption process it is important to simulate various levels of bone height in order to understand how axial loadings are absorbed by PDL. Previous studies used models having various levels of bone height [15]-[17], a PDL's thickness of 0.14-0.40 mm [15], [23], [24] and constantly loaded force varying from 0.3 N up to 1500 N(46 MPa) [2]-[26]. However, they neither closely investigate the linear periodontal resorption process nor used a highly accurate anatomical model. The boundary conditions and input data affect the accuracy of the results [3]-[4], [15], [27]-[32]. Therefore sensitivity analysis is needed for assess the robusticity of the results [27]. Previous studies did not mention anything regarding their sensitivity tests on their FEA models.

Previous studies used models of human upper incisives [11], [15]-[17], [19], upper [12] and lower [13], [14] canine and upper molars [18]. However, no one used the second lower premolar. The lower premolar, has a very complex geometry(e.g. the one used in this study has two root canals and two fused roots) but still similar with other lower and upper premolars. It's location on the mandible(a mobile bone) might influence the stress distribution in the periodontal tissues due oral kinematics [21].

Using a new model created based on the information provided by CT slices, being anatomical accurate and simulating a bone loss of 10%-90%, this protocol is

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expected to provide accurate new accurate information regarding the behavior of PDL under different loadings. This new data should complete the knowledge regarding the human teeth investigated during periodontal resorption. It should also fill the gaps regarding the way the stress distribution occurs in the PDL of a premolar during the gradual linear resorption process [22] and has potential clinical applicability.

II. MATERIAL AND METHODS

A. Model creation

A CBCT (PaX-Reve3D,Vatech America), FOV 5×5 cm and voxel size 0.08 mm, generating detailed 2D images was used in this study. The investigated area contained the second lower right premolar of a 34-year-old healthy male. More than 2200 2D slices(80 μm) were taken. 3D models of each components were generated, through image manual segmentation and then were assembled into a 3D complete model having the following dimensions 320×320×320 mm. Tooth's support surrounding tissues had a height of 19.2 mm, bone beneath had 6 mm, and the second lower right premolar had 26 mm of height, all measured on the CT slices.

Then this model was replicated, thus obtaining ten second human lower right premolar models having the same configuration except for the alveolar bone height and PDL. A homogenous horizontal reduction all around the tooth was assumed. The alveolar bone and PDL has been reduced in height by 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% simulating the progressive resorption. Each 10% height loss simulated a 1.92 mm (24 CT slices) of periodontal loss [26], [32].

AMIRA, version 5.4.0.(AMIRA, version 5.4.0, Visage Imaging Inc.), software was used for used for segmenting and generating the 3D models. The image segmentation process was done manually for each slice based on the different gray scale values and on Houndsfield units. A clear separation between 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 the similar properties of the dentin and cement. The PDL was attached to the intraalveolar surface and to the root. The PDL's thickness varied between 2-3 voxel (0.16-0.24 mm), depending on the anatomical topography and dimensions identified during the manual image segmentation process. The cortical bone layer had a minimum length and thickness of 2 mm, depending on the anatomy of the segmented region. The rest of the bone was filled with cancellous bone, according to the regions designated by the CT slices.

The 3D models were calculated and described using triangles in AMIRA. The surface models were strongly simplified but maintaining the shapes of the original surfaces. The meshes were obtained by filling the volumes restricted by the surfaces with tetrahedrons. The final mesh contained 14395 nodes and 73913 tetrahedrons

B. Finite element analysis

The FEA is a numerical form of analysis allowing stress and displacements to be identified. It is based on the discretization of continuum into a number of elements. The final mesh was exported and analyzed in ABAQUS, version 6.1.1.1sofware (ABAQUS, version 6.1.1, Dassault Systemes). Boundary conditions, material properties (elastic constants) and loading conditions were then assigned to each voxel, defining the way the model would deform under stress. The model structures were solved as a series of nodal displacements and the resulting von Mises stresses were calculated and displayed. Were investigated the overall stress value of the PDL, such as von Mises stress values in N/mm^2(MPa) at the cervical level and at the apical level under each of the 6 orthodontic loadings [26]. The von Mises stresses were preferred as they are usually used to define the yielding criteria for isotropic materials under different loading conditions and represents the overall stress intensity in contrast with individual stress components such as principal stresses. The FEA and results visualization were conducted in ABAQUS software using a color-coded projection onto the model geometry.

C. Material models and modeling assumptions

The components of the model, Fig. 1, were assumed to be homogeneous and isotropic, to possess linear elasticity, small deformations and displacements. However, the living tissues exhibit inhomogeneous, anisotropic and nonlinear behavior and normally they should be modeled as a elasto-plastic porous materials with a complex microstructure [3]. Such approach involves complex finite element models enhanced with advanced nonlinear constitutive equations experimentally calibrated, but such approach is scarce in the scientific literature. The main benefits of a FEA like the present one is the simplicity and yet the accuracy of the results. All the modeling decision from the present study (e.g. material properties and inclusion of the PDL) complied with the sensitivity test criteria presented in the literature. Elastic constants of all used materials are given in Table I.

Young's modulus describes the tendency of a material to deform elastically under axial loading conditions, indicating its stiffness while Poisson's ratio is related to Young's modulus and shows how much a material expands when compressed, or contracts when stretched. Boundary conditions consist of prescription of displacements in several parts of the model. For restraining all forms of translational movements the base of the model was considered to have zero displacement, while all other parts were treated as free of boundary conditions. This manner of restraining prevents the models from any rigid body motion while the loadings are acting. Because of localized nature of the problem studied here, it must be emphasize that the lateral(mesial and distal) edges of the developed model have been chosen at some reasonable distance from the region of main interest(a volume of bone equivalent to the volume of the neighboring teeth roots) in order to obtain the solution without perturbation due to the dimensions of the mandible. Numerical studies performed for the model confirmed the localized nature of the phenomenon, and that there were almost no displacements at the mesial and distal edges. It has been assumed that the interfaces between all components were perfectly bonded interfaces all the components interact with each other.

Coronal-apical(intrusive) loads of 1 N/mm^2 and 10 N/mm^2, and 1 N/mm^2 and 3 N/mm^2 vestibular-palatinal(transversal) and mesio-distal(transversal) loads were applied, one at the time (in different loading sequences), at the enamel surface, centrally in the occlusal face of the crown, in order to estimate the loads' effect over the PDL. The other surfaces were treated as free surfaces with zero loads.

Table I. Elastic properties of materials used in the study

Material	Constitutive equation	Young's modulus, E (GPa)	Poisson ratio, υ	Refs.
Enamel	Isotropic, homogeneous and linear elastic	80	0.33	[22], [26]-[32]
Dentin	Isotropic, homogeneous and linear elastic	18.6	0.31	[22], [26]-[32]
Pulp	Isotropic, homogeneous and linear elastic	0.0021	0.45	[22], [26]-[32]
PDL	Isotropic, homogeneous and linear elastic	0.0689	0.45	[12],[22], [26]-[32]
Cortical bone	Isotropic, homogeneous and linear elastic	14.5	0.323	[1], [18], [26]-[32]
Cancellous bone	Isotropic, homogeneous and linear elastic	1.37	0.30	[1], [18], [22], [26]-[32]

III. Results

Coronal apical load. 0% bone loss. For the coronal apical 1 N/mm^2 directed force, the increased level of stress was located at the PDL's lingual cervical margin (Fig. 2A and Table II), decreasing to the apical region. The lowest stress value was approximately 0.04% of the cervical stress (Table III).

Alveolar bone loss. The highest stress values were found at the lingual cervical level (Fig. 3A, 4A and Table II), gradually increasing with the increase in bone resorption. The stress increased 5.1 times when resorption reached 50% of bone height and 36.6 times for the 90% bone loss (1 N/mm^2 load). For the 10 N/mm2 directed force, the stress level distribution maintains in the same locations, while the values increase by 10 times.

Vestibulo-lingual load. 0% bone loss. For the 1 N/mm2 and 3 N/mm^2 directed forces, the highest levels of stress were located at the PDL's vestibular and distal cervical level (Fig. 2B and Table II). Higher stress also appeared at the apical level. The highest apical stress was located on the vestibular and distal sides and was 17% of the cervical stress while the lowest apical stress was approximately 0.13% (Table III).

Alveolar bone loss. The highest stress values were found at the cervical level, on the vestibular and distal sides, shifting gradually versus the lingual and mesial sides (Fig. 3B, 4B and Table II) due to the resorption's direction and tooth load. The maximum stress gradually increased reaching 12.9 times for 50% bone resorption and 143 times for 90% bone loss.

Mesio-distal load. 0% bone loss. For the 1 N/mm^2 and 3 N/mm^2 directed forces, the highest stress was located at the PDL's vestibular, distal and lingual cervical level (Fig. 2C and Table II). Higher stress level also appeared in the vestibular and distal apical region. The highest apical stress value was 26% of the cervical stress while the lowest was 0.25% (Table III).

Alveolar bone loss. The highest stress values were found at the cervical level, on the vestibular, distal and lingual sides (Fig. 3C, 4C and Table II), gradually shifting versus the lingual and mesial sides according the resorption level due to the resorption's direction and tooth load. The maximum stress gradually increased reaching 13 times for the 50% bone loss and 129 times for 90% level. A decrease in stress value was manifest at 90% level (Table III), explained by the local conditions due to massive bone height loss.

During the resorption process (0-80%) the mesio-distal load (1 N/mm2 load) produced the highest von Mises stress values. At 90% bone loss the vestibulo-lingual load (1 N/mm^2 load) determined the highest stress in the PDL (Fig. 5a). For the 10 N/mm^2 load, a gradual increase of the stress values appeared (Fig. 5b), with the highest values at 80% and 90% bone loss. For the 3 N/mm^2 loads, a gradual increase of the mesio-distal load appeared(0-80% bone loss) while for the 90% bone loss the vestibulo-lingual one produced the maximum equivalent stress value.

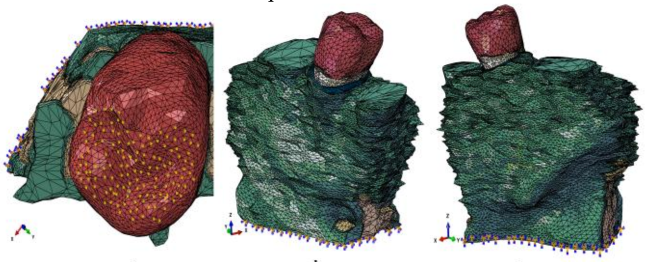

Fig. 1(a, b, c) The FE Mesh used in Abaqus for 0% resorption level with boundary conditions: a- the occlusal face of the crown were the loads were applied; b-vestibular view; c-lingual view

IV. Discussions

The tooth-PDL-alveolar bone complex is subjected to high occlusal forces during mastication but their effect on the PDL with different levels of resorption needs further studies [1], [17]. Furthermore, the stress values that produce biological changes in dental structures are not entirely known and understood[3]-[5]. Based on this fact the presents study tried to assess the PDL loss and its consequences.

The stress in the living PDL is difficult to be measured experimentally so in this case the FEA is the proper method to investigate the von Mises equivalent stress.

The FEA is an accurate method to study and describe the biomechanical behavior of different living structures but relays directly on the input data [15]. Therefore, the results are directly influenced by the work precision. The models used in this study were highly anatomical accurate, having 14395 nodes and 73913 tetrahedrons (created through image manual segmentation) while some of the previous studies [2]-[19] used models having 726 - 37884 nodes(created after Ash's dental dental anatomy).

Furthermore, the discrepancies within the accepted values of the physical properties of the 3D models can produce results alteration [15]. Therefore for a proper comparison all the boundary conditions used in this study were provided by previous studies.

It was pointed out that when analyzing periodontal resorption it is important to simulate various levels of bone height [1]. However, little information regarding the stress distribution during complete linear periodontal resorption of 0-90% is available, being hypothesized that a reduction in alveolar support causes an increase in maximum stress in the periodontal structures.

For a robust FEA's results sensitivity testes are advisable [27]. Despite all these, previous studies failed to mention anything about their sensitivity testes. This study complied with the sensitivity tests criteria regarding the modeling decisions [27] and conducted a geometric morphometric analysis for confirming the deformation results.

Horizontal bone loss is the more common type of alveolar bone resorption [6]. Previous studies used models having various levels of bone height ranging from 25% to 75% bone height resorption [15]-[17], however, none described a periodontal resorption of 0% up to 90%.

For simplifying the FEA, all the interfaces were considered perfectly bonded interfaces [3], [4]. This assumption does not necessarily simulate clinical situations and is considered to be an inherent limitation of this process. However, the goal of this study was a qualitative analysis and these assumptions do not alter the accuracy of the results.

Previous studies [15] shown PDL stress values of 0.0012-0.132 N/mm^2 at the cervical margin for forces of 1 N applied to the center of the tooth and mesio-distally, while the stress values at the apex were 0.002-0.05 N/mm^2. In this study the results of the structural response of the system have been obtained in terms of the von Mises cervical stress for the 1 N/mm^2 load force (Table II) and were similar to those provided by previous studies [4], [13], [15]-[17] for the same value of the force. For the 3 and 10 N/mm^2 load forces the obtained results are higher than those previous cited. The results for the apical stress for the 3-10 N/mm^2 loads up to 70% bone height loss were much below the value [14] of 0.05 N/mm^2, while the apical stress results for the 1 N/mm2 loads are in agreement with Cobo's [14]. The apical stress value [14] at 8 mm of bone height loss was of 0.364 N/mm^2. The maximum apical stress level (Table III), for similar bone height loss conditions, was of 0.023 N/mm^2 for the 1 N/mm^2 load and 0.238 N/mm^2 for the 10N/mm^2 load at 40% height reduction. This behavior and the numerical results were within the limits stated both by Geramy [14], [17] and Cobo [14]. The difference occur because of differently applied load directions and the 3D model design, in agreement with Poiate, et al.[23]. This study found the highest stress values at the cervical level which are in agreement with Wilson et al.[29] and Wiejun et al. [30] but differ from those reported by Geramy [15].

Alveolar bone height loss causes an increase in the PDL's von Mises stress values at all levels [10]-[15]. This study is in agreement with this and provides an accurate description of the phenomenon. A certain predictability regarding the rise of stress values and their tendency to increase can be noted confirming the tendency shown in previous studies [15], [17].

A previous study stated 19% bone loss as a limit beyond which the stress increase accelerates [27]. The obtained results are in agreement with all this. Each layer of periodontal resorption(almost 2mm) determined an increase of the stress values which is in agreement with previous studies [15], [17]. This FEA's results showed a gradual increase in stress values (0-20% bone loss) and a massive increase after 30% bone loss which is in agreement with Shang's results [1]. It also shown that 5.7 mm of alveolar bone loss (30%) is assumed to be the starting point for dramatic changes in stress level which contradicts Geramy's [17] results.

The model used is the second lower right premolar, with two root canals, while most of the studies used single-rooted and single canal teeth [1], [15], [17] and this aspect might also influence the biomechanical behavior.

The novelty in this approach consists in: the high anatomical accuracy of the 3D models, the gradual periodontal resorption that simulated a complete process (0-90%), the FEA conducted according to sensitivity tests criteria, totally new numerical stress values for the 70-90% resorption levels and new values for 0-70% resorption levels.

This qualitative analysis explains why after a long period of slow resorption process of the tooth surrounding support tissues, showing no warning signs, as soon as a certain resorption degree is passed, the tooth is rapidly lost. In the open literature there is no data regarding the maximum tolerable stress for living tissues [17], however, the stress increase during periodontal resorption is so high that it can be considered to be out of the range of tolerable stress, similar with Geramy's conclusions [17]. Further studies are needed for finding the maximum tolerable stress and allowing a more accurate discussion regarding this study's results.

V. CONCLUSIONS

It was observed that during the linear periodontal resorption simulation the von Mises stress gradually increased along with the PDL and bone height loss, but declined steadily from the cervical to the apical level, thus validating the research hypothesis. Each 2 mm layer of PDL protects from stress the PDL beneath. After 30% periodontal resorption the stress significantly increase. Approximately 5.7 mm of periodontal loss (30%) is assumed to be the starting point for dramatic changes in stress level. The maximum stress values were found when the periodontal loss reached 90%. The vestibulo-lingual loadings produced the highest von Misses stress values for the 90% bone loss. The results show that due to periodontal resorption the same amount of force determines an increase of maximum stress in the PDL cervical level, which ultimately might affect its height and could worsen the periodontal problems. All these should be taken into consideration by the orthodontist when applies the orthodontic forces at patients having periodontitis. This analysis provides an integrated approach to the solutions of biological and biomedical problems.

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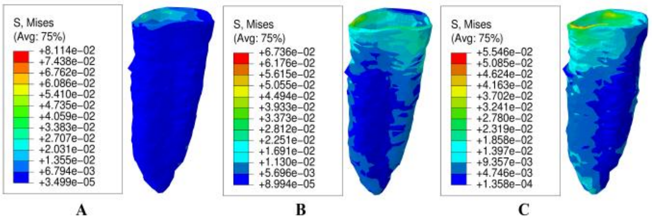


Fig. 2(A, B, C) Von Mises stress distribution for 1N/mm^2 for 0% resorption level: A-Coronal apical load; B-Vestibulo-lingual load; C-Mesio-distal load

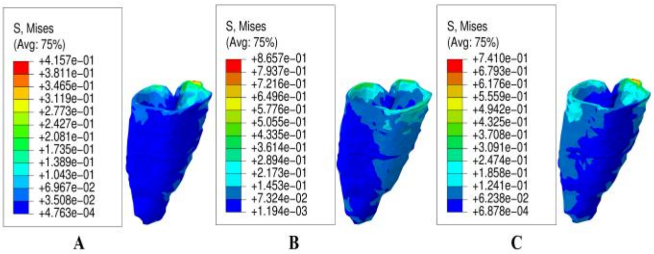


Fig. 3(A, B, C) Von Mises stress distribution for 1N/mm^2 for 50% resorption level: A-Coronal apical load; B-Vestibulo-lingual load; C-Mesio-distal load

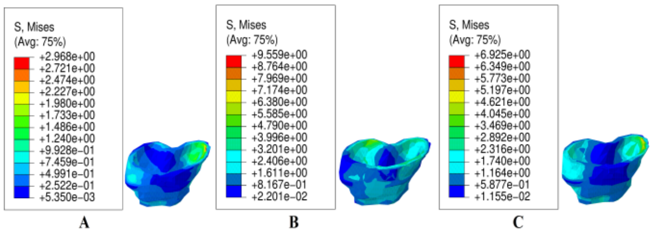
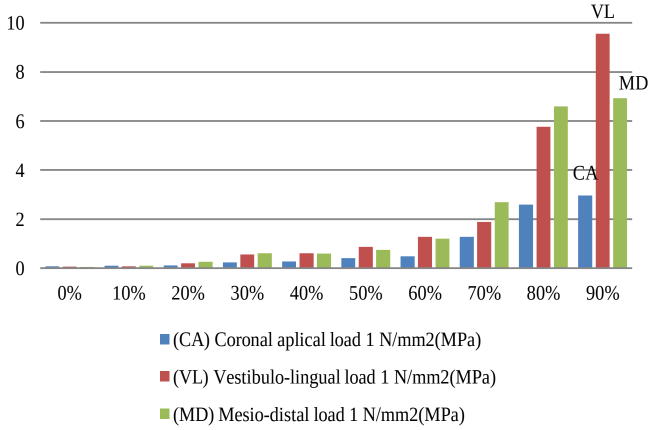


Fig. 4(A, B, C) Von Mises stress distribution for 1N/mm^2 for 90% resorption level.: A-Coronal apical load; B-Vestibulo-lingual load; C-Mesio-distal load



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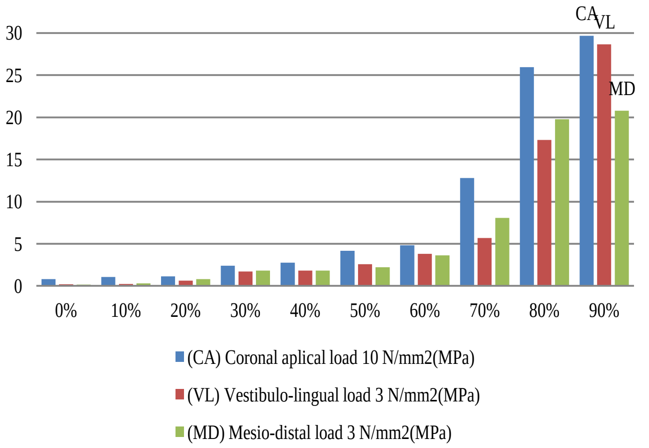

b

Fig. 5(a,b): a-Maximum von Mises stresses at the cervical level for 1 N/mm^2(MPa) loading forces for the 10 levels of bone height loss; b-Maximum von Mises stresses at the cervical level for 3-10 N/mm^2(MPa) loading forces for the 10 levels of bone height loss

Table II. PDL's von Mises stress values in N/mm^2(MPa) at the cervical level, under the 6 loadings, during bone height resorption simulation

alveolar bone reduced in height %	alveolar bone and PDL height mm	A. Coronal apical load 1 N/mm^2 (MPa)	10 N/mm^2 (MPa)	B. Vestibular-Lingual load 1 N/mm^2 (MPa)	3 N/mm^2 (MPa)	C. Mesial-Distal load 1 N/mm^2 (MPa)	3 N/mm^2 (MPa)
0%	19.2	0.08	0.81	0.06	0.20	0.05	0.16
10%	17.28	0.10	1.07	0.07	0.23	0.10	0.30
20%	15.36	0.11	1.14	0.20	0.61	0.26	0.80
30%	13.44	0.24	2.41	0.56	1.71	0.60	1.81
40%	11.52	0.27	2.77	0.60	1.81	0.60	1.81
50%	9.6	0.41	4.15	0.86	2.59	0.74	2.22
60%	7.68	0.48	4.81	1.27	3.82	1.20	3.61
70%	5.76	1.27	12.79	1.89	5.67	2.69	8.06
80%	3.84	2.59	25.94	5.77	17.32	6.58	19.77
90%	1.92	2.96	29.68	9.55	28.68	6.92	20.78

Table III. PDL's von Mises stress values in N/mm^2(MPa) at the apical level, under the 6 loadings, during bone height resorption simulation

alveolar bone reduced in height %	alveolar bone and PDL height mm	A. Coronal apical load 1 N/mm^2(MPa)	10 N/mm^2(MPa)	B. Vestibulo-lingual load 1 N/mm^2(MPa)	3 N/mm^2(MPa)	C. Mesio-distal load 1 N/mm^2(MPa)	3 N/mm^2(MPa)
0%	19.2	3.5E-05	35E-05	8.9E-05	26E-05	13.5E-05	40E-05
10%	17.28	7.4E-05	74E-05	12.5 E-05	37E-05	16.9E-05	50E-05
20%	15.36	22.2E-05	222E-05	35.5E-05	106E-05	33.5E-05	100E-05
30%	13.44	37.5E-05	375E-05	39.7E-05	119E-05	51.1E-05	153E-05
40%	11.52	84.1E-05	841E-05	165.8E-05	497E-05	109.3E-05	327E-05
50%	9.6	47.6E-05	476E-05	119.4E-05	358E-05	68.7E-05	206E-05
60%	7.68	157.1E-05	1571E-05	191.8E-05	575E-05	299.2E-05	897E-05
70%	5.76	118.2E-05	1182E-05	706.8E-05	2120E-05	230.5E-05	2098E-05
80%	3.84	1887E-05	18870E-05	4082E-05	12250E-05	3560E-05	10680E-05
90%	1.92	535E-05	5350E-05	2201E-05	6600 E-05	1155E-05	3460E-05

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