Mathematical models of teeth with alveolar bone resorption and biomechanical phenomena due to orthodontic forces

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In this paper, the assessment and comparison of the biomechanical reactions that occur in the fluid periodontal ligament during tooth movement have been emphasized. Using the finite element method we developed three-dimensional models of the central maxillary incisor and we simulated case studies with forces of progressively ascending intensities. We identified the stress distribution depending on the direction of the orthodontic force and the distribution of displacements, both by quantitative and qualitative methods. As the force and the degree of bone resorption increased, displacements and stress in the direction of force progressively increased, as parameters of orthodontic biomechanics.

1. Introduction

The quantitative and qualitative analysis of biomechanical reactions (stress and displacements) occurred during orthodontic tooth movements can be performed based on computer-aided simulation and implementation of the real processes and biological phenomena.

Biomechanics of orthodontic tooth movement can be analyzed by finite element method (FEM), a numerical analysis method that allows the precise identification of structural stress and displacement occurred under the action of factors or forces exerted on an object or human body, and with the application of these forces in different directions and with different intensities.

As a main component of the computer aided design and analysis, FEM is currently the most effective method of study and optimization of structures, for any shape and material of which they are made [1-3]. FEM is a numerical method for solving complex problems, and its use is justified in the study of solving analytical model that is possible only in some cases, but with a sufficient degree of approximation.

In orthodontics and implantology, FEM has the advantage of including the heterogeneity of dental and periodontal structures and the irregularity of dental contour in the dental design, representing an effective method for precise shaping of the tooth and periodontal system along with their complicated three-dimensional geometry [4-10].

Nowadays addressability of adult patients to orthodontic treatment for improving teeth alignment is very common. Among these patients there are cases with periodontal disease of variable severity and alveolar bone resorption, which react differently to the application of orthodontic forces compared with patients without bone resorption [11].

The aim of this study was to analyze and compare the biomechanical reactions (with the use of two parameters: stress and displacement) that occurred following the application of vertical orthodontic forces of variable intensities on a tooth with alveolar bone loss.

2. Experimental part

According to the geometry, dimensions and morphological data described in the textbooks [12], we have developed three-dimensional models for the upper central incisor (CI), simulating pathological conditions with periodontal implications. The used patterns corresponded to actual clinical situations associated with resorption of the alveolar bone of 0, 2, and 4 mm.

We considered the following three main criteria:

2.1. The geometry of tooth and periodontal structures

Definition and design of the CI model using the ALGOR analysis software was performed by editing and fabricating the tooth, periodontal space and surrounding alveolar bone (Fig. 1, Fig. 2). CI was chosen because it presents the most significant tooth movement and a high risk of root resorption compared to the other teeth.

The anatomical tilt of the longitudinal axis of 5° was taken into account and in the vertical plane of the tooth 11 horizontal planes were traced, corresponding to the areas

of interest (crown, root, cervical zone, point of action of the force):

- Five horizontal planes corresponding to the crown of CI, that included the tooth, marked as: plane +2, +4, +6, +8, and + 10.5.

- One horizontal plane of the cervical area, marked as plane "0" that included the tooth, periodontal ligament (PDL) and alveolar bone.

- Five horizontal planes at the root level, including the tooth, PDL and alveolar bone, marked as plane -2, -4, -6, -8, -10, and -13.

Maintaining the geometrical equivalence with the shape of CI of the general three-dimensional model that contains the tooth – PDL – alveolar bone complex, tetrahedral and hexahedral three-dimensional finite elements (FE) were used.

Boundary conditions imposed on all peripheral nodes in the alveolar bone were null movement conditions. Between the nodes of the composing elements of the whole tooth-PDL-alveolar bone complex connections were established with gap type contact elements. Loading of model was achieved through nodal forces of different amplitudes, depending on the phenomenon to be studied.
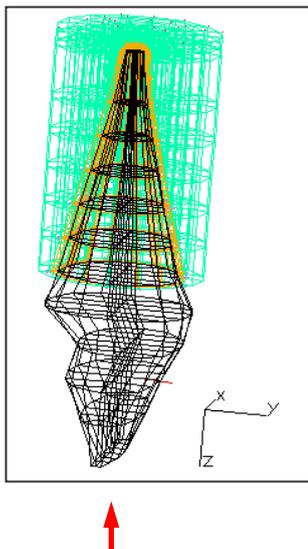

Fig. 1. Three-dimensional modeling of the upper central incisor in the ALGOR software (No of EF=976; No of nodes=1379); vertical force that induces orthodontic ingressive movement

2.2. Physical properties of the structures

All structures of the FEM model were considered elastic (validity of Hooke's law) and isotropic (with identical elastic characteristics in all directions) [13]. The values of the Poisson's ratio (ν) and of the Young's modulus (E) for different materials are shown in table 1 [14].

Table 1. Physical properties of the dental and periodontal structures

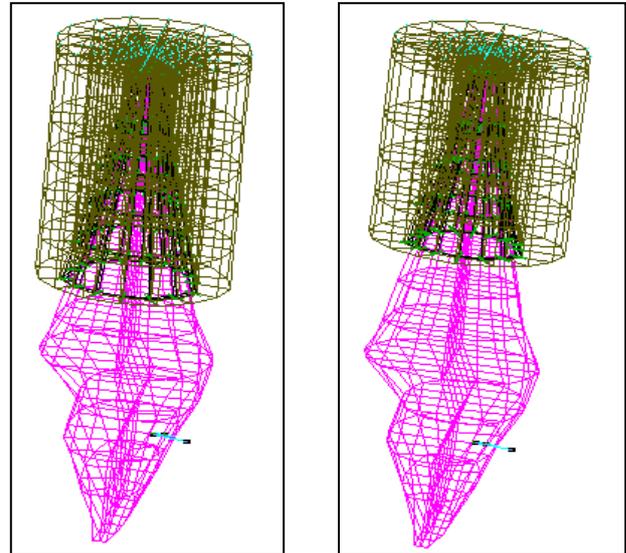| Material	E [N/mm^2]	ν
Tooth	$1.96 \cdot 10^4$	0.30
PDL	$6.66 \cdot 10^{-1}$	0.49
Bone	$1.37 \cdot 10^4$	0.30

Fig. 2. Three-dimensional models of the maxillary central incisor corresponding to actual clinical situations with bone resorption of 2 mm (No of FE=818; No of nodes = 1186), and of 4 mm, (No of FE = 674; N o of nodes=1010), respectively

2.3. Configuration of orthodontic forces

Vertical orthodontic forces were applied that produced ingressive tooth movement, with the application point in the node located in the middle portion of the CI surface.

3. Results

For a correct interpretation of the results regarding the loading of tooth with a vertical ingressive force, we performed simulations with progressively increasing forces of various intensities F=1N, F=3N, F=4N. The effects of forces were monitored using the values of stress and displacement of the periodontal ligament, on the palatal (P) and buccal (B) surface of each simulated dental model.

The values were also compared between the tooth with no bone resorption and the models with a resorption of 2 and 4 mm, respectively, in the condition of a vertical ingressive force of the same value. We considered that a bone resorption exceeding 4 mm would have been inconsistent with the real clinical situations.

The results considered significant for the interpretation of the biomechanical reactions in the orthodontic movement of the teeth and those that provided relevance to the studied phenomena were as follows:

1. Stress distribution in relation to the direction of the vertical ingressive force

2. Distribution of displacements in relation to the vertical force.

3.1. The analysis of stress distribution in relation to the vertical force indicated that the biomechanical phenomena occurred in the PDL become atypical as resorption increased, but they remained similar at the same degree of resorption in case of different values of vertical ingressive forces F=1N ÷ 4N.

In the case of tooth model with bone resorption of 2 mm the stress values were mostly positive and of stretching type and they became negative and of compressive type in the apical area. The following phenomena were noted:

• stress distribution in the PDL at the same degree of resorption was similar, but with elevated values as the ingressive vertical forces increased;

• regardless the value of ingressive forces the maximum values occurred at the level [-10] of the dental root (table 2, figure 3);

• stress values were almost similar both on the palatinal (P) and on the buccal (B) surface in all situations (with different degrees of resorption, and loadings with progressively increasing ingressive forces).

In the scenario of the tooth with bone resorption of -4 mm stress values were mostly negative and of compressive type, in the cervical area they became positive and of stretching type, with extremely low values, close to 0.

The following phenomena were noted:

• stress distribution was similar in the PDL with the same degree of resorption, but with elevated values as the ingressive vertical forces increased;

• regardless the value of ingressive forces the maximum values occurred at the level [-8] of the dental root (table 2, figure 4);

• stress values were similar both on the palatinal (P) and on the buccal (B) surfaces in all situations (with different degrees of resorption, and loadings with progressively increasing ingressive forces).

Table 2. Stress distribution

Resorption level	Force value	Maximum values of the stress	
		Palatinal side (P)	Buccal side (B)
-2 mm	F=1N F=3N F=4N	0,0169690 N/mm² 0,0509077 N/mm² 0,0678769 N/mm²	0,0203903 N/mm² 0,0611709 N/mm² 0,0815612 N/mm²
-4 mm	F=1N F=3N F=4N	-0,0222168 N/mm² -0,0666503 N/mm² -0,0888670 N/mm²	-0,0222495 N/mm² -0,0674856 N/mm² -0,0899810 N/mm²

Comparing the biomechanical behavior of the tooth with bone resorption with that of the dental model with no resorption the following biomechanical phenomena were noted (figure 5):

- In the case of tooth with no resorption all the stress values in the PDL were negative and of compressive type, reaching the maximum value on both surfaces of the apex: palatinal (P) and buccal (B);

- The maximum loading and maximum stress on the tooth with no resorption was at the level [−13] (the apex of the dental root), with extremely high values in comparison with the other measured values (-0.439965 N/mm²); as the degree of bone resorption increased, the maximum stress in PDL has transferred to the level [−10] (resorption of −2 mm) and to level [−8] (resorption of −4 mm);

- In the tooth with bone resorption the behavior of PDL has completely changed: a loading of mostly stretching type could be noted (positive stress) in the case of resorption of −2 mm and a compressive loading (negative stress) with the dental model with bone resorption of −4 mm;

- We consider that the change of the PDL behavior in the case of tooth with bone resorption in comparison with the simulated model with no resorption was due to the homogeneous structure, but also with strongly elastic characteristics of the PDL tissue: as the bone resorption occurred and increased, the mobility of the rigid tooth increased in the periodontal space; in the dental model with no resorption the stability of the tooth was ensured, with a maximum embedment length in the bone tissue.

3.2. **Tracking the distribution of displacements in relation to the vertical force** that occur in the PDL we noted a similar distribution to that of the tooth with a bone resorption of both −2 mm and −4 mm, with descending values from the cervical area (level 0) to the apex of the root (level -13) (Fig. 6, Fig. 7).
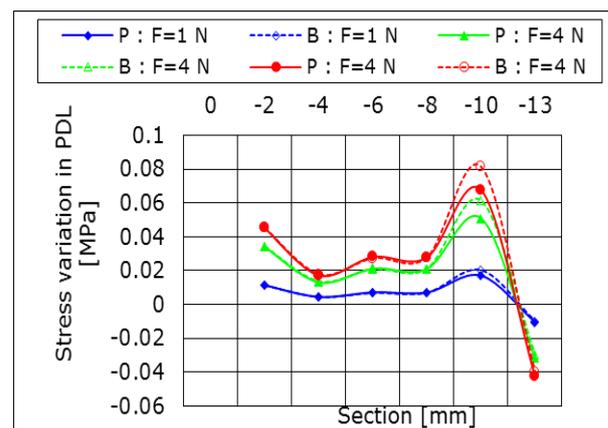

Fig. 3. Comparison: the variation of stress at different levels of force; resorption of -2 mm
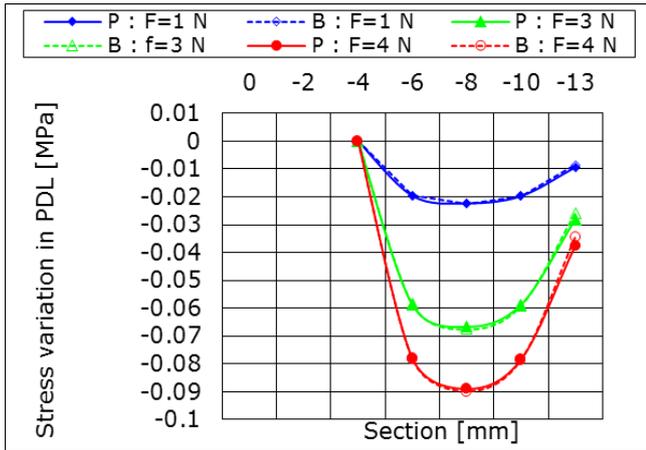
Fig. 4. Comparison: the variation of stress at different levels of force; resorption of -4 mm
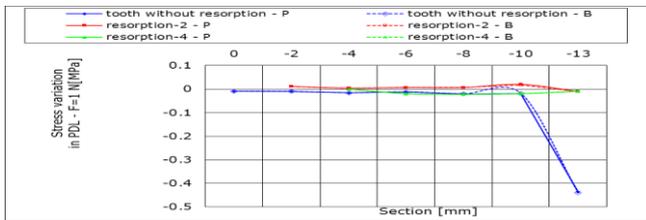

Fig. 5. The variation of stress; F=1 N; Comparison: resorption of 0 mm, -2 mm, -4 mm

Table 3. Distribution of displacements

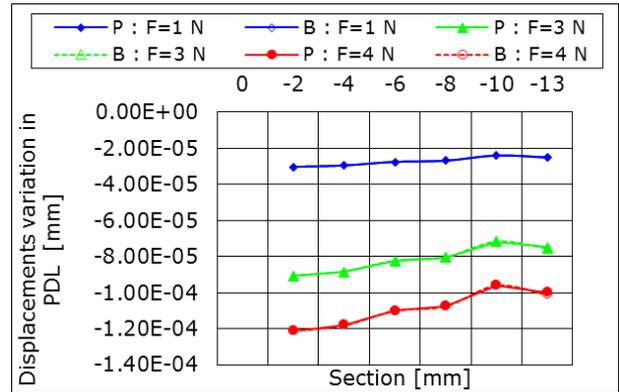| Resorption level	Force value	Maximum values of the displacements at the cervical level	
		Palatinal side (P)	Vestibular side (V)
-2 mm	F=1N F=3N F=4N	-3.025.10^{-5} mm -9.076.10^{-5} mm -1.21.10^{-4} mm	-3.026.10^{-5} mm - 9.077.10^{-5} mm -1.21.10^{-4} mm
-4 mm	F=1N F=3N F=4N	-3.062.10^{-5} mm -9.185.10^{-5} mm -1.225.10^{-4} mm	-3.062.10^{-5} mm -9.187.10^{-5} mm -1.225.10^{-4} mm

Fig. 6. Comparison: the variation of displacements at different levels of force; resorption of -2 mm
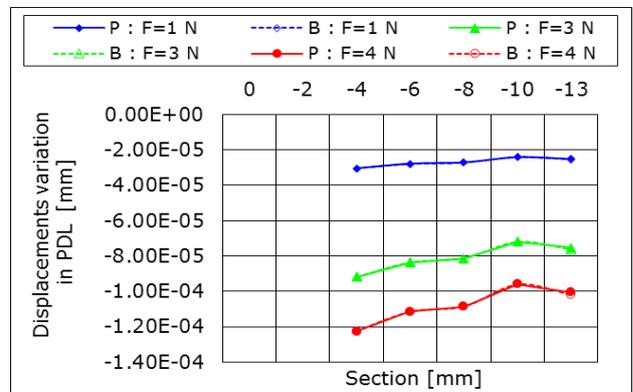

Fig. 7. Comparison: the variation of displacements at different levels of force; resorption of -4 mm
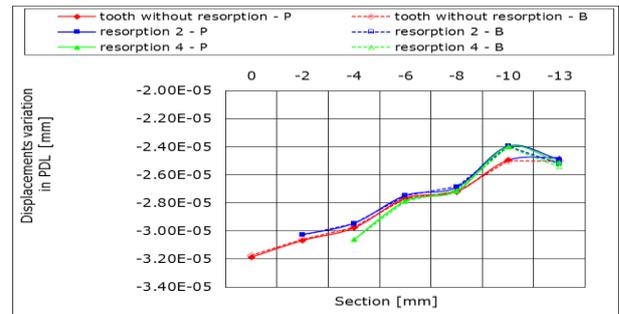

Fig. 8. The variation of displacements; F=1 N; Comparison: resorption 0 mm, -2 mm, -4 mm

4. Discussion

The maximum values of displacements were evident in the cervical area (table 3), regardless of the degree of resorption and the value of the applied force. In the simulated situations (different degrees of resorption and different values of the ingressive vertical forces), the displacements were negative with a stretching effect on the PDL.

The values of displacements on the two surfaces of the tooth, palatinal (P) and buccal (V) were similar (table 3), increasing progressively as the force and degree of resorption increased.

The distribution of displacements in the PDL was similar in the case of tooth with no resorption, noting that the same value of force generated much lower displacements as compared to those registered in the dental model with bone resorption (Figure 8).

Although an annually bone resorption of 0.017 mm of can be considered quite normal [15], increased resorption can be detected in the adult patients referred for orthodontic treatment. Melsen suggested the application of mild intrusive forces in the treatment of adult patients with reduced resorption [16]. On the other hand, there are authors who believe that there is also an increased risk of root resorption in adult patients when orthodontic forces with high intensity are applied. With the use of FEM we proved that the resorption of alveolar bone lowered the resistance center of the tooth and also modified the stress distribution [17-19].

5. Conclusions

The results obtained with the design and simulation with the finite element method revealed the distribution of stress and displacements during orthodontic tooth movement. In the PDL, o homogenous structure that also presents pronounced elastic characteristics, there were significant biomechanical reactions to the increase of ingressive forces and bone resorption.

The stress in the direction of force increased gradually with the resorption of the alveolar bone, both in the cervical and apical area. The values of displacements gradually increased as the applied force and the bone resorption amplified.

Acknowledgements

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