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Stress Distribution Pattern in Roots of Incisors with Various Root Resorptions: A Finite Element Study

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Objectives Root resorption is a dangerous side effect in orthodontics, and maxillary incisors are at the highest risk for root resorption. It is important to understand optimal force considerations for patients with altered root lengths.The purpose of this study was to investigate the effects of root length on stress distribution on roots by means of three-dimensional finite element method (FEM).

Methods Three dimensional FEM models of maxillary central and lateral incisors were made. Then, root length of the incisors was changed in the increments of 1 mm from 0-4 mm. Applying 50 g (0.5 N) of force perpendicular to the tooth crown simulated uncontrolled tipping. Stresses and strains for each model were calculated and Pearson correlation coefficient was used to analysis the data.

Results There were significant correlations between root length of incisors and maximum stress in PDL. In the centrals with various root lengths, maximum stress was between 0.010884 and 0.056520 MPa, and in the laterals, it was between 0.027297 and 0.221040 MPa. By reducing root length of incisors, the maximum stress in buccal apical (r= 0.933,p<0.001 and 0.995, p<0.001 prospectively) and lingual crestal areas (r= 0.974 p=0.005 and 0.992, p=0.001 respectively) were reduced.

Conclusion Although in lateral incisors, stress at the lingual crestal area was more than buccal apical area, in central incisors with more than 2 mm resorption, the stress distribution of buccal apical was higher. Therefore, in maxillary central incisors with more root resorption, force control might be even more critical.

Keywords Finite element, Root resorption, Orthodontics

Introduction

Application of external forces to the teeth to produce orthodontic tooth movement carries some risks, one of which is irreversible root resorption.[1] Root resorption is a dangerous side effect in orthodontics which has to be avoided.[2] This is a biological response to an orthodontic force [3],and root resorption does not observed in only 20% of orthodontic treated maxillary incisors.[4] This process destroys the tooth root tissue and the affected patient could even loose the tooth because of the loss of its anchorage.[2] It is a biological and mechanical process which is strongly dependent on individual patient factors, but has not been fully studied. Furthermore, genetic factors, forces and moments, as well as their duration during application are co-factors.[2, 5]

In addition, tapered and short roots that result from alveolar bone loss or apical root resorption are prone to tipping.[6] Shaw et al.[7] determined the relationship between the thickness of cementum and magnitude of stress at root apex and concluded that the mechanical stress was increased at the root apex with the increased thickness of an apical cementum. Since many orthodontic patients have root resorption induced by orthodontic treatment, the influence of root length on the biomechanical behavior of a tooth is important. It has been shown that roots with a short apex enhance root resorption and patients at risk of severe apical root resorption can be identified according to the amount of resorption during the initial treatment stages.[3, 8, 9] If orthodontic force is concentrated in a particular region of the deviated root shape, root resorption may occur.[3, 10] Thus, it is of clinical significance to understand optimal force considerations for the patients with altered crown-to-root ratios.[6]

In order to evaluate the true relationship between root resorption and applied orthodontic forces, it is necessary to quantify the periodontal stress and strain generated by the orthodontic forces in teeth with different root lengths. Previous clinical studies [11-14] have not fully described these variables with tooth displacements because of difficulties in precisely quantifying the variations in root length and alveolar bone height for patients or subjects. In vivo measurement of stress is difficult at best; thus, development of an effective model for this system is a worthy goal.[1] One analytical approach to studying stress during tooth, one that allows for reasonable approximation of the biological tissues, is the finite element method (FEM).[3]

In orthodontics, FEM has been used successfully to model the application of forces to single-tooth systems. In FEM, the structure to be tested is divided into a finite number of elements which are connected to each other by nodes. Variables of interest are then approximated using mathematical functions.[1, 15] The ability of FEM to handle material in homogeneity and complex shapes makes the FEM the most suitable method for the analysis of stress in the periodontium.[16]

In this method, the initial tooth displacement has been used for evaluating optimal orthodontic force applications and subsequent tooth movements.[6, 17, 18] It must be stated that patterns of this initial displacement may be influenced by some variables such as tooth and root dimensions.[6]

The maxillary incisors undergo the most detailed tooth movement and are subjected to orthodontic force for a prolonged period. Since maxillary central and lateral incisors are at the highest risk for root resorption than all other teeth, they were chosen in this study.[19, 20]

To our knowledge there is no FEM based study which evaluated stress distribution in maxillary incisors with different root lengths. Thus, the purpose of this study was to investigate the effects of root length on stress distribution on roots by biomechanical concepts by means of three-dimensional finite element analysis.

Materials and Methods

There are 3 primary considerations in the development of the 3-dimensianal FEM tooth model: geometry of the teeth and periodontal structures, material properties, and loading configuration.

First, finite element model of an ideal central and lateral incisors with layer separating enamel, dentin, pulp and cementum including PDL, and an alveolar bone was prepared. The geometry of our 3-dimensional finite element model of maxillary incisors was created by designing the tooth according to the dimensions and morphology found in a standard dental anatomy textbook with ANSYS WORKBENCH R. 14 software.

Model A was constructed with the length of 23 mm and root length of 12 mm based on the data derived from wheeler᾽s dental anatomy, physiology, and occlusion.[21]

Each structure of the incisors was meshed using an auto-meshing routine in the finite element analysis program. The material properties for all the models were defined as linear and are shown Table 1.[22]

Table 1- Material parameters used in the finite element model.

Material	Young᾽s Modulus (N/mm^2)	Poisson᾽s Ratio
Enamel	20×10^3	0.3
Dentin	20×10^3	0.3
Periodontal ligament	66×10^{-2}	0.4
Bone	20×10^3	0.3
Bracket and Wire	210×10^3	0.3

Boundary conditions and solution: The element shape described in the model was a solid tetrahedral element, which is the best option to fit the curvature of the model objects. The FEM approximately consisted of 148915 elements and 270603 nodes. Fixed boundary conditions were chosen for all the nodes at the upper surface of the maxilla.

The PDL region was constructed from 1 to 3 element layer, depending on the geometry and curvature of the root. The mechanical properties of the FEM were considered to have linear elasticity and isometric properties of the same quality. Based on the other studies[23] the thickness of the PDL was considered to be 0.25 mm evenly.

In the next step, idealized brackets for load application were generated on the labial surfaces of the teeth. The 3D FEM of 0.016 × 0.022 inch standard edgewise brackets were made and attached to the crown such that the force applying point was equal to the center of the bracket slot.

Next step was to prepare 5 models with various root lengths. Root lengths of central and lateral incisors were changed in the increments of 1 mm from 0 to -4 mm.

Since one orthodontic movement that has been reported to increase the risk of root resorption is uncontrolled tipping, [1, 24] the loading configuration was designed to mimic this movement. Uncontrolled tipping was simulated by the application of a force acting in the buccal-lingual direction. (M/F=0)

Applying 50 g (0.5 N) of force perpendicular to the tooth crown simulated uncontrolled tipping. This lingually directed force was applied at a point on the labial surface of the crown (bracket position) 4 mm gingival to the incisal edge. No simulated wire and no additional moment was applied, as the aim of this study was to investigate only uncontrolled tipping movement. Finally, this force was applied on the mesh of the central and lateral incisor models with different root lengths. Stresses and strains for each model on the application of each root length were calculated in ANSYS WORKBENCH R. 14 software using linear structural analysis. The personal computer system used in this study was Intel, Core i7, RAM 8GB.

Interpretation of stress from FEM pictures: The stress generated in FEM pictures was represented by various colors, ranging from blue to red. Maximum stress areas were marked as (MX) and minimum stress areas marked as (MN). However, the values for maximum and minimum stress areas were different. The mean and standard deviation were used to describe the data. Also, Pearson correlation coefficient was used to investigate the relationship between data.

Results

Figures 1 through 4 show the changes in stress distribution on the buccal and lingual surfaces of PDL of central and lateral incisors with 4 levels of root resorption (1, 2, 3, and 4 mm resorption) in response to orthodontic force without counterbalancing moments. The stress distribution in the FEM model was represented by color coding, ranging from red to blue, with the areas of maximum stress being represented in red and blue showing areas of minimal stress. Tipping forces resulted in the greatest stress at the lingual of crest of lateral incisor (0.221040 MPa). The highest PDL stress was observed in lingual crestal areas of central and lateral incisors with standard root lengths (Table 2).

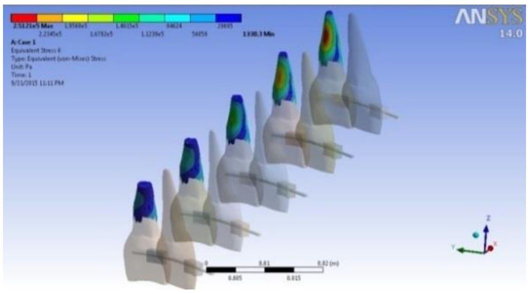

Figure 1- Stress distribution in the lingual surfaces of PLD of central incisors with 0, 1, 2, 3, and 4 mm resorption in response to orthodontic tipping force

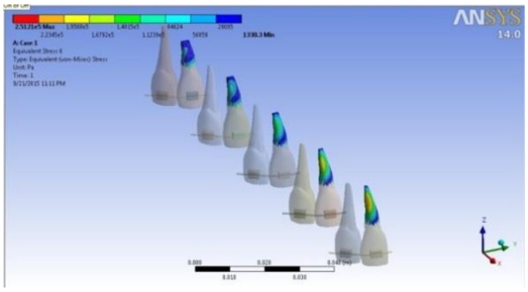

Figure 2: Stress distribution in the buccal surfaces of PLD of central incisors with 0, 1, 2, 3, and 4 mm resorption in response to orthodontic tipping force

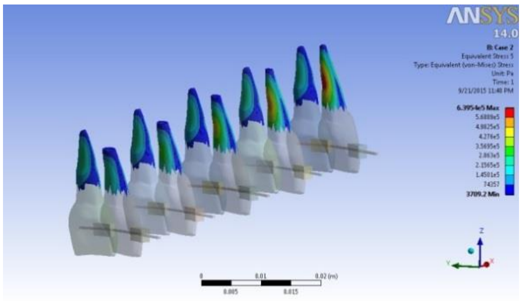

Figure 3: Stress distribution in the lingual surfaces of PLD of lateral incisors with 0, 1, 2, 3, and 4 mm resorption in response to orthodontic tipping force

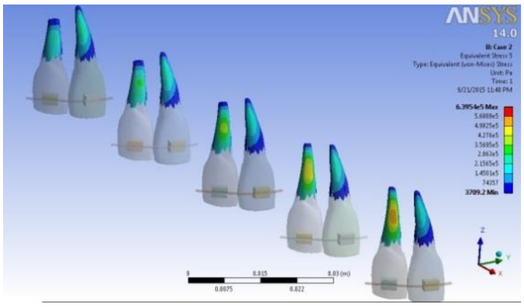

Figure 4: Stress distribution in the buccal surfaces of PLD of lateral incisors with 0, 1, 2, 3, and 4 mm resorption in response to orthodontic tipping force

Table 2- The mean of maximum stress distribution in central and lateral incisors with different root lengths in lingual crestal and also buccal apical areas.

	Mean of maximum stress in central incisor (MPa)	**Mean of maximum stress in lateral incisor (MPa)**
Ligual crestal area	0.031177±0.020573	0.177466±0.032640
Buccal apical area	0.016693±0.003956	0.034306±0.005790

In the centrals with various root lengths, maximum stress was between 0.010884 and 0.056520 MPa, and in the laterals, it was between 0.027297 and 0.221040 MPa.

Table 2 shows the mean of maximum stress distribution in different areas of central and lateral incisors with different root lengths.

In central incisors with normal root length and also -1 and -2 mm root lengths, the stress concentration of lingual crestal was higher than buccal apical areas. But with -3 and -4 mm root lengths, the stress distribution of buccal apical was higher than lingual crestal areas. All the models of lateral incisors had a tendency to concentrate stress at the lingual crestal area more than buccal apical area.

There were significant correlations between root length of incisors and maximum stress in PDL. Therefore, with reducing root length of central and lateral incisors, the maximum stress in buccal apical (r= 0.933, $p<0.001$ and 0.995, $p<0.001$ respectively) and lingual crestal areas (r= 0.974 p=0.005 and 0.992, p=0.001 respectively) were reduced significantly.

Discussion

During orthodontic tooth movement, root resorption is the pathological phenomenon that is constantly occurring on the surface of the cementum. In order to correlate the root resorption and the force magnitude during various tooth movements, the stress distribution within the cementum should be considered rather than the stress within the PDL.[25] In this study, experimental orthodontic force was applied to central and lateral incisors with various root lengths and their stress distribution on the root was evaluated. In general, the stress in crestal and apical areas of root reduced by reducing root length when uncontrolled tipping force of 50 g was applied.

The cementum covering an apical third of a root has lower value of hardness and elastic modulus than cementum covering the middle and cervical third of the root and as some degree of apical external root resorption is a frequent and unavoidable complication of orthodontic treatment, during treatment planning, the patient or parent should be warned of this risk.[26-29] Also, Rex et al.[30] found that an apical cementum is less mineralized than the cementum of the cervical and middle thirds of the root; hence, an apical third is more susceptible to the root resorption. Moreover, Jimenez-Pellegrin and Arana-Chavez concluded that cementum repair occurs after resorption during rotation movement and a noncollagenous matrix protein osteopontin plays a role in both resorbing and repairing.[31]

Rudolph et al. reported that most of the forces from tipping was concentrated at the crest of the alveolar, not at the apex.[1] These results are in agreement with previous studies.[32, 33] Also in our study, the highest PDL stress was observed in lingual crestal areas of central and lateral incisors with standard root lengths. Tipping forces resulted in the greatest stress at the lingual of crest of lateral incisor (0.221040 MPa). In lateral incisors with different root resorptions, stress in the lingual crestal area was more than buccal apical area; but in central incisors with more than 2 mm resorption, the stress distribution of buccal apical was higher than lingual crestal areas. This might be attributed to the different crown-root ratio of standard central and lateral incisors. Jeon et al. concluded that increased crown-root ratio caused a significant increase in pressure and stress concentrations in the PDL.[16]

Kamble et al. found that in short root model, significant stress was concentrated at the neck of the root.[3] Although theoretically, we could not explain the reason for reduced stress at the root with reduced root length, clinically and as orthodontists, we should avoid jiggling or excessive force, especially in central incisors with greater resorption, since the root tip is more susceptible to the resorption rather than the cervical parts of the root.[25]

The key parameter indicating beginning root resorption is an increased value for hydrostatic pressure in the PDL[34] , which may cause a collapse of the capillaries and a dysfunction of blood supply.[2] The range of capillary blood pressure has been stated to be within the range of 15 mmHg (venous) to 35 mmHg (arterial) (equivalent to 0.0020-0.0047 MPa) in the standard literature.[35] In our study, in the centrals with various root lengths, maximum stress was between 0.010884 and 0.056520 MPa and, in the laterals, it was between 0.027297 and 0.221040 MPa.

Thongudomporn and Freer [9] have reported that the root with a short apex enhanced root resorption, which supported the finding of the study by Kample et al.[3] In their research, the biomechanical burden on the root apex was likely to decrease during tipping in blunt-shaped roots compared with angular-shaped roots.[3] In our study, root length was reduced in straight increments of 1 mm. Therefore, root shapes became angular at the corners in resorbed samples.

Also, some radiographic studies [9, 36] have reported that blunt-shaped roots frequently show root resorption when compared with normal roots. Shaw et al.[7] concluded that the mechanical stress was found to increase at the root apex with an increase in the thickness of an apical cementum; therefore, close attention must be paid to deviated root shape.[3]

Maxillary incisors were chosen because an apical root resorption occurs mainly in the maxillary anterior teeth.[19, 20] The maxillary incisors most commonly show EARR after orthodontic treatment and are used to determine root resorption during experimental studies.[37] It has been shown that when there is no root resorption of the maxillary or mandibular incisors, resorption of other teeth is improbable.[38]

What are the clinical implications of this study? In clinical cases, the bracket slot, arch wire, the resin-tooth, and resin-bracket interface could also influence the distribution of stress within the periodontal tissues when orthodontic forces are applied.[25, 39] All these factors should be included in future studies of FEM to simulate the nearest possible clinical condition and elucidate the stress pattern during orthodontic tooth movement.[25] In our study, simulations did not take these into account, the results may represent the theoretical best-case scenario that cannot be achieved clinically. Although the link between external forces and apical root resorption is far from clear-cut,[1] in a patient whose incisors show previous root resorption, the forces must be applied with caution.

Experimental techniques have their limitations in measuring internal stress levels of the PDL.[25] Strain gauge techniques may be useful in measuring tooth displacement; however, they cannot be directly placed in the PDL without causing tissue damage.[40] It is relevant noting that any comparison of laboratory results with clinical outcomes should be interpreted with caution, since the photoelastic method does not faithfully reproduce the role played by the periodontal ligament.[41] The FEM is a noninvasive, accurate method that permits the simulation of various amounts of root resorption and also analytically applies various force systems at any point and in any direction.[3, 25] FEM has many advantages over other methods, which are highlighted by the ability to include heterogeneity of tooth material and irregularity of the tooth contour in the model design.[1] The accuracy of computer models however depends on assigned constitutive properties and the results are based on the nature of modeling systems. For this reason, the procedure of modeling is of paramount importance.[25] The limitations of any model include approximations in the material behaviors and shapes of the tissues. It must be stated that cementum-dentin junction (CDJ) and cementum significantly influence the stress distribution within the tooth supporting structure. However, most of the reported FE analysis did not take CDJ and cementum into account, which possibly resulted in overestimated stress values in the PDL and alveolar bone. Similar to previous works, the PDL was treated as linear-elastic and isotropic, even though the PDL exhibited anisotropy and non-linear viscoelastic behavior because of tissue fluid. The material properties of the periodontal ligament, the morphology of the root, and the alveolar bone are patient specific. Therefore, the M/F values generally advocated to obtain orthodontic tooth movement should be used only as guidelines. To be effective and accurate, the force system selected for a specific tooth movement must be monitored and the outcome compared with the predicted tooth movement.[6, 42-45] There are no reliable and adequate data that pertain to anisotropic and non-linear properties of the PDL.[16] For all the calculations, this is an idealization of the realistic behavior of the tooth-supporting structures [46] and linearity assumptions about force distribution are problematic.[1] However, in combined experimental and numerical studies, this assumption has been proved to be valid for orthodontic loading and is sufficient to describe initial tooth displacements.[47-49] There are insufficient data available regarding the material properties of PDL since it is not considered as an engineering material. Further studies should explain the exact material nature of PDL in young and adult individuals.[25]

In the present study, initial stress and strains were calculated using the FEM. After orthodontic force was applied, histological changes can alter the physical properties of the tissues and, therefore, Young᾽s modulus and Poisson᾽s ratio.[32] During force application, the physical properties, vascular, cellular, and extracellular components of the cementum and periodontal ligament are altered.[27,50-52] For these reasons, the secondary response could be different from the initial response of the PDL. To overcome these limitations, it is necessary to develop a more accurate modeling technique and a time-dependent 3D FEM analysis. The future improvements in software and updated versions could help in the refinement of meshing process and creating a more accurate 3D FEM model.[25]

This study had some limitations as calculations were made using a mathematical model. The results were based on the fact that the thickness of the PDL was uniformly 0.25 mm. However, the PDL had an hourglass shape and its thickness was different according to age, position, and individual variations.[23] Also, the errors associated with the bony tissues, deformation of the bracket, forces of circum-oral muscles, and bite forces were not considered in our study.

Conclusion

Although it must be stated that theoretical numerical models have restrictions with respect to their representation of living biological structures, clinically, this stress distribution can be taken to mean that, with reducing root length of maxillary incisors, the maximum stress in buccal apical and also lingual crestal areas are reduced significantly.

Although in lateral incisors with different root resorptions, stress in the lingual crestal area was more than buccal apical area, in central incisors with more than 2 mm resorption, the stress distribution of buccal apical was higher than lingual crestal areas. Therefore in maxillary central incisors with more root resorption, force control might be even more critical.

Conflict of Interests

None Declared ■

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