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Mechanical stress generated by orthodontic forces on apical root cementum: a finite element model

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Structured Abstract
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Objectives – 1) To determine the mechanical stress generated at the root apex during different types of tooth movement using a finite element model of an ideal, human maxillary central incisor. 2) To determine the relationship of thickness of cementum and the magnitude of mechanical stress at the root apex.
Design – Computer simulation.
Setting and Sample Population – Not applicable, computer simulation.
Experimental Variables – Tooth and investing tissue layers (enamel, dentin, cementum, pulp, periodontal ligament, and alveolar bone).
Outcome Measure – Von Mises and maximum principal stresses.
Results – Increasing the apical thickness of cementum increases the amount of mechanical stress.
Conclusion – A finite element model incorporating all layers of a human maxillary central incisor has been developed. This model was used to determine the location and magnitude of mechanical stress generated for all regions of the tooth, PDL, and enclosed alveolar bone, when orthodontic forces are applied to the tooth. Mechanical stresses were found to increase at the root apex with increasing thickness of apical cementum.

Key words: cementum; finite element; mechanical stress; root resorption; three-dimension

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Introduction

The impact and significance of destructive, severe root resorption associated with orthodontic tooth movement certainly justifies the many clinical and laboratory reports published in the literature. True external apical root resorption presents a paradox; while known to be commonly occurring as an inflammatory reaction to tooth movement, severe resorption requiring clinical alteration of treatment, or in the worst scenario, loss of tooth, is fortunately rather rare. Although large clinical studies of root resorption have been conducted (1–6), data sources have been generally limited to two-dimensional periapical radiographs, panoramic films, and cephalometric films. Prospective, human studies are difficult to do because of the lack of a clear definition of the endpoint of the disease, while animal models are limited due to the problems in translating results to humans. Both studies are hampered by increased government intervention in ethical and privacy issues. Hence, as in similar areas of biomedical research lacking significant morbidity and mortality, knowledge of the biological process of external apical root resorption remains poorly understood.

Advances in engineering have allowed biologists to employ methods that do not require live organisms. These methods can be applied to the solution of biomechanical problems, with surprising clinical veracity. Finite element analysis is one of these methods that have been used successfully in medicine and dentistry. In the last several years, increasing speed and power, and decreasing cost per computational cycle have made the more sophisticated and better engineering programs available for wider applications. The model developed and analyzed in this and other recent papers would be extremely slow or painfully impractical on a personal computer (PC) 10 years ago.

Of particular interest to orthodontists in this field of engineering is the calculation of stresses developed on the tooth and surrounding tissues during orthodontic tooth movement. Although root resorption is often unavoidable, this side effect of tooth movement is normally reversible. But once the cemental layer is penetrated and dentin is exposed, the repair process is compromised.

The purpose of this study was to develop an improved tooth model in true three dimensions including not only all three layers of hard tissue, but the pulp and PDL as well. A series of ideal maxillary central incisor models were constructed with different apical cementum thicknesses. The model was then analyzed to determine areas of greater mechanical stress.

Finite element analysis

What is a finite element model (FEM)? If you have driven a car or ridden in an airplane then you have benefited from finite element analysis. They have always been somewhat of a mystery to the clinician, however, and their credibility in question due to the complexity and distance the model seems to represent from truth and reality in the oral cavity. Finite element models have their current origin and real use in mechanical engineering analysis and design. Finite element analysis is as indispensable to the engineer who designs an airplane frame, as a pair of archwires is to the orthodontist.

The 'elements' of finite elements are the building blocks of the physical model. There are a 'finite' number of them, as opposed to a theoretical model with complete continuity. The object of interest has to be broken up into a 'meshwork' that consists of a number of nodes on and in the object. These nodes or points are then connected to form a system of elements. For a two-dimensional example, if a brick wall is the meshwork, the bricks are the elements, and the four corners where the bricks meet each other are the 'nodes'. Knowing the mechanical properties of the object, such as modulus of elasticity and Poisson's ratio, one can determine how much distortion each part of the cube undergoes when any other part is moved by a force. Thus, you can apply a concentrated force at a certain part of the bumper and know what will happen at the other end.

Biological applications have been successful where mechanical principles would be of the most interest; for example in modeling human joints (hip, knee, etc.) (7–9). In dentistry, models have been used to determine the stresses in dental implants (10, 11), and the failure rates of restorative materials (12–14). In orthodontics, finite element analysis has been used to show areas of maximum stress on materials [e.g. bracket/adhesive interface (15)]. Previous work of the type of simulation described in this study used finite elements to study stresses and strains on incisors, canines, and molars during tooth movement (16–21). Other studies have focused on investigating the stresses within the PDL induced by orthodontic forces (22–26). An interesting FEM model of the PDL incorporating time series data has also been reported (27).

Materials and methods

Creation of the three-dimensional (3D) model

Previous research has shown that maxillary incisors are the most resorbed teeth in the human dentition (4). An idealized maxillary central incisor was created to represent the broad ranges of dental morphology present in the human population based on dimensions obtained from a standard dental textbook on oral histology (28). The outermost layer of the maxillary central incisor was digitized and stored in stereolithography (STL) file format where the surface model is made up of thousands of small triangles. The current industry standard format for this kind of data is STL. The file was then imported into 3D Studio Max (Autodesk Corporation, Montreal, Quebec, Canada) for additional editing and construction of the internal anatomy. From the ideal central incisor data, layers separating the pulp, dentin and enamel were created to generate a set of landmarks which were converted to Cartesian coordinates. These landmarks or nodes were finally used to construct a 3D model using MSC Patran (MSC Software Corporation, Santa Ana, CA, USA) a leading finite element modeler.

Figure 1 shows a cross section of the model, and Fig. 2 shows an external three-dimensional view of the same; both generated by the computer program. The total number of nodes is 20 852 and the number of elements is 11 924.

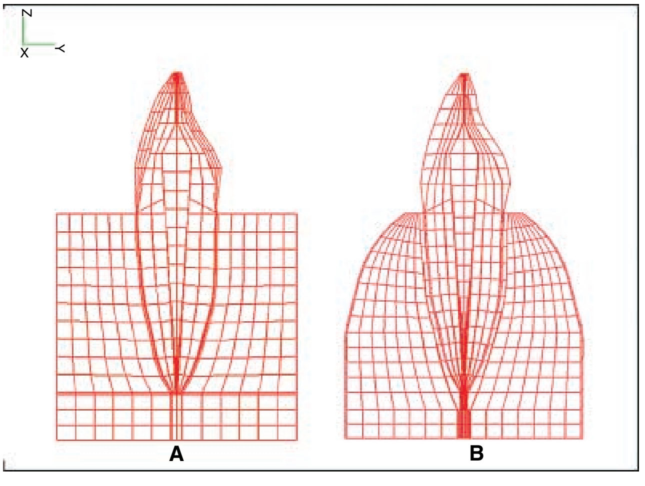

Fig. 1. Cross sections of finite element model of maxillary central incisor: (A) standard model, (B) modified apical cementum.

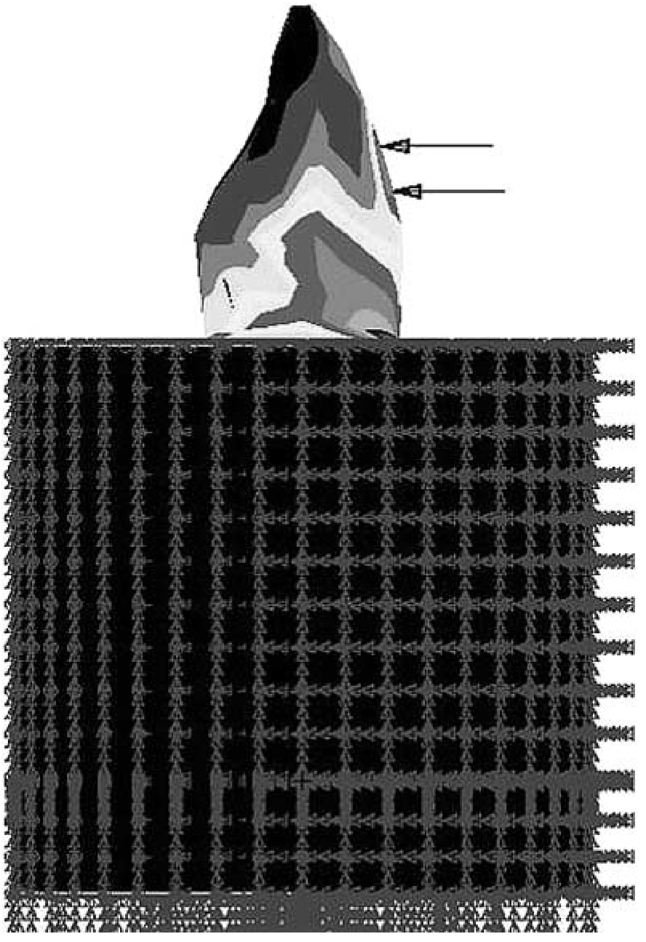

Fig. 2. Model of incisor in alveolar bone – external view. Arrows point to application of simulated orthodontic force.

Finite element analysis of the model

Boundary conditions were assigned to the nodes surrounding the outer most layer of the alveolar bone. These conditions are critical to indicate where the physical model starts and ends in space, and under what other types of mechanical restrictions the model will be subject to. Different load conditions were applied to the model to simulate basic types of orthodontic tooth movement. Forces acting on the tooth were placed on areas approximating the location of an orthodontic bracket as shown in Fig. 2 (torque or lingual tipping). The material properties, modulus of elasticity E (or Young's modulus) and Poisson's ratio v shown in Table 1, were determined in previous studies (29–32). As an example, when an archwire is in longitudinal strain it also changes its dimensions in the direction perpendicular to the applied stress. The dimensionless ratio between the strains along the two

***Table 1.* Material properties of the tooth components, PDL, and alveolar bone**

Layer	Young's modulus (N/mm^2)	Poisson's ratio
Enamel	84 100	0.33
Dentin	18 300	0.31
Pulp	2.03	0.45
Cementum	15 000	0.31
Periodontal ligament	0.5	0.00
Alveolar bone	340 000	0.26

perpendicular directions is called the Poisson ratio. The material properties for cementum were found to be between dentin and the periodontal ligament but closer in nature to dentin (33). Cementum has heretofore not been included in finite element models of the dentition.

Once the material properties were assigned to all the elements and the boundary and load conditions to the appropriate nodes, finite element analysis was performed using industry-standard commercial software called MSC Nastran (MSC Software Corporation). The final model incorporates all layers of the tooth: pulp, dentin, enamel, cementum, PDL, and alveolar bone.

A second model was created from the first one with a finer meshwork at the apex for the cementum in order to vary the thickness vertically at the apex. Fig. 1 shows two cross-sections from the model – note the meshwork, and elements that define the figure. The thickness of cementum on the root apex has been found to vary from 200 to 1000 μm (34) – these values were used to vary the thickness in the finite element model in increments of 200 μm.

Results

The results of the analyses are summarized in Tables 2 and 3 and Figures 3–9. The finite element analysis covers each layer of the tooth for all elements. Thus, a fairly large amount of information is generated for each type of force applied to the tooth. Because of the sheer volume of data, it is easier to convert this to a visual representation, with areas of higher stress coded with warmer colors.

Interpretation of the figures generated by the finite element program bears some explanation (Fig. 3 for example). First, the color coding is not uniform across figures. The program takes the range of numbers then spreads them out by magnitude across the color spectrum. Thus a red area in one figure might correspond to a stress of 0.9999 N/mm^2 whereas in another figure red might be 0.0111 N/mm^2 (the computer program does not allow the user to modify this). Second, the range of numbers is infinite. Von Mises and maximum principal stresses are commonly used measurements of stress for failure analysis in engineering (the magnitude of the stresses generated by orthodontic forces is very low; the same calculations work for stresses that can bend an airplane wing).

The results show maximum stresses occur at the alveolar crest during orthodontic tipping and torquing forces. The highest stress on the root occurs during intrusion. Table 2 summarizes the stresses by type of force applied to the model (extrusion/intrusion, torque, tipping, and rotation) and tooth layer (pulp, dentin, cementum, periodontal ligament, alveolar bone). Note that the greatest stresses for all types of movements are the greatest on the cementum, the lowest in the periodontal ligament or alveolar bone. All types of tooth

***Table 2.* Mechanical stresses produced at different layers by different orthodontic forces**

Forces	Pulp	Dentin	Cementum	Periodontal ligament	Alveolar bone	Average	Entire root apex
Stress at apex (N/mm^2)							
Extrusive/intrusive	0.005426	0.009064	0.011146	0.002034	0.001664	0.006918	0.00995
Tipping (labial-lingual)	0.004881	0.010547	0.011277	0.001007	0.000605	0.006928	0.009169
Tipping (mesial-distal)	0.00328	0.0085	0.008732	0.000894	0.00054	0.005352	0.008733
Rotation	0.000368	0.000356	0.001071	0.000027	0.000015	0.000456	0.000844

Table 3. **Variable cementum thickness and mechanical stress at the root apex**

Apex cementum thickness (μm)	Stress at apex (N/mm^2)
1000	0.00625
800	0.00152
600	0.00122
400	0.00115
200	0.00088

movements produced very similar stresses at the apex except for rotational movements which were considerably lower (0.0008 N/mm^2 vs. 0.0099–0.0087 N/mm^2).

The effect of applying a lingually directed force on the labial surface of the crown of the incisor on the dentin is shown in Fig. 3, cementum in Fig. 4, alveolar bone in Fig. 5, and pulp in Fig. 6 (similar images were generated for enamel and other perspectives but are omitted for brevity). Note that the forces on the cementum (root surface) are much higher than comparable regions of the dentin (the stresses computed for the enamel were also higher than those in the dentin in the crown). All structures reflect the common area of maximum stress at the alveolar crest, including stress computed in the pulp. Stresses on the contralateral side of the tooth, however, were relatively high at the apical portion of the pulp. Figure 6 shows the periodontal ligament under the assumptions of uniform thickness

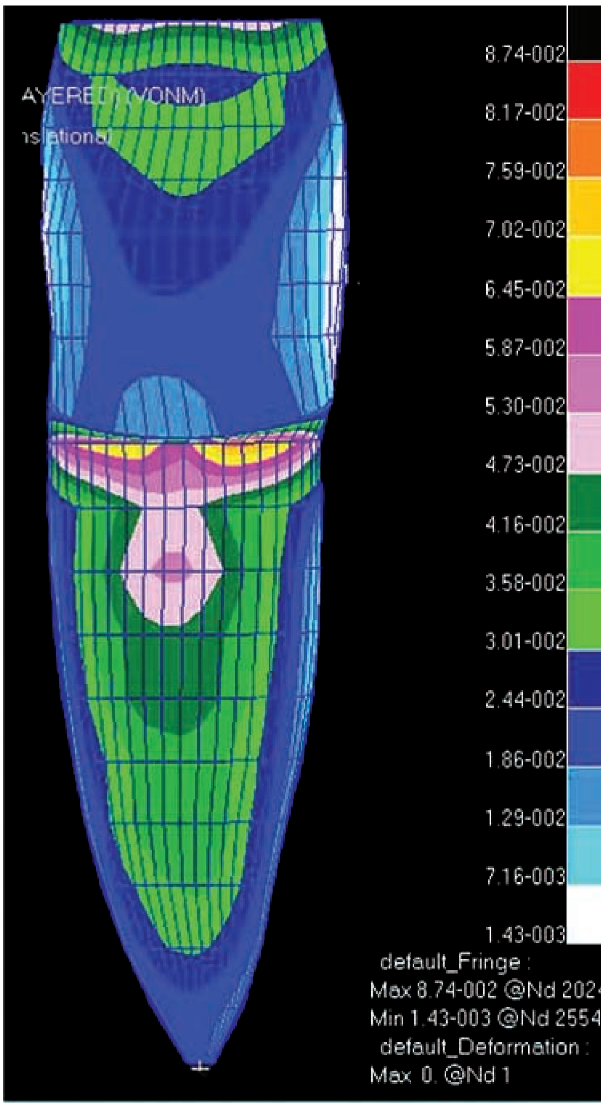

Fig. 3. Mechanical stress on dentin only – lingual tipping – facial view.

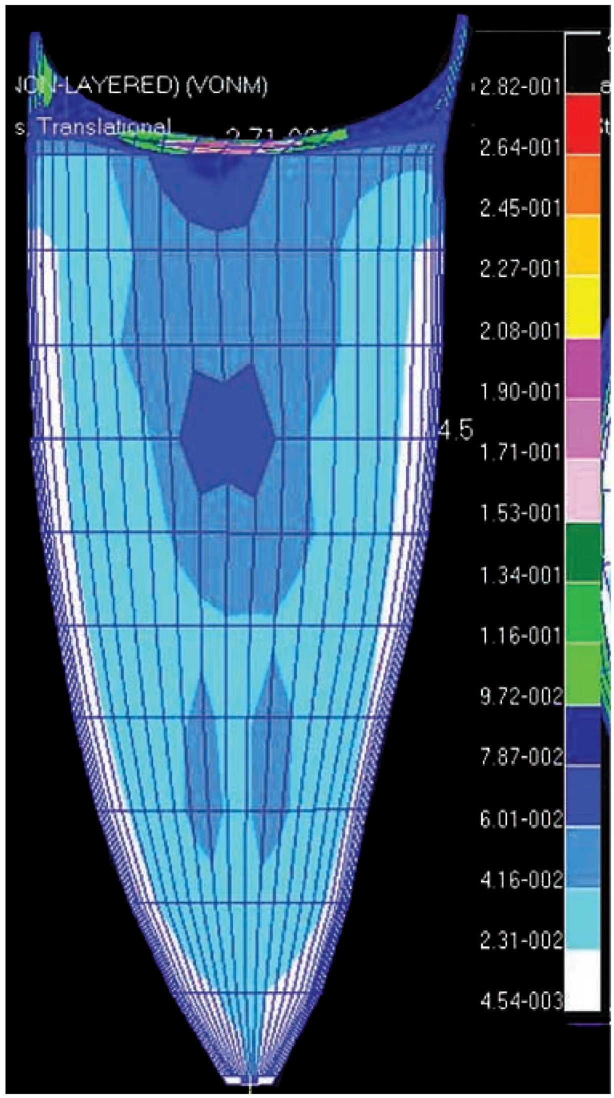

Fig. 4. Mechanical stress on cementum only – lingual tipping – facial view.

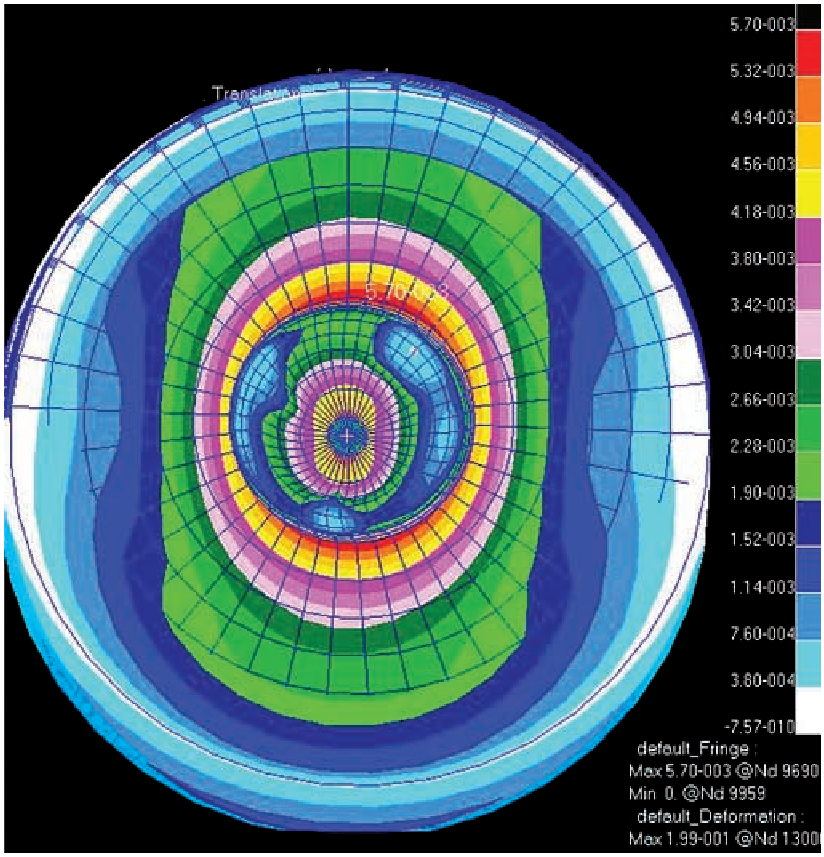

Fig. 5. Mechanical stress on alveolar bone only – lingual tipping pulp – apical view.

and composition. The PDL exhibits the same stress pattern observed in the other structures but the magnitude is less than that observed on the cementum.

Figure 7 shows the stress on the root from an apical perspective. The distribution of this type of stress is fairly even from the apex up the root surface. The stress in the apical area is low (0.0009–0.0019 N/mm^2). Figure 8 show the distribution from an extrusive force. Here the range around the apex is 0.0005–0.0011 N/mm^2. The difference is quite small.

Table 3 shows the results of varying the apical thickness of the cemental layer only. Increasing stresses were found to correspond to increasing thickness. The range was a high of 0.0062 N/mm^2 for a thickness of 1000 μm to a low of 0.0009 N/mm^2 for 200 μm. This is a very narrow range of values but a trend is clearly evident.

Discussion

Previous three-dimensional finite element models only rendered the outer layers of the tooth and omitted the internal structures and cementum. This new model of a human maxillary central incisor computed mechanical stresses from orthodontic forces applied to the tooth are in the enamel, dentin, cementum, pulp, periodontal ligament, and alveolar bone.

The initial results showed that maximum stresses are produced on the outside layers in areas that are in agreement with previous studies. For example, it has been shown that during tipping movements, the greatest stresses occur at the alveolar crest and not at the apex. Rotational forces in general produce the least stresses at all points on the root surface, although the smooth contours of this ideal root form are not found in nature. The stresses computed for the dentin and pulp reflected the stresses found in the cementum and enamel for the same forces.

Clinically, intrusive forces have been traditional suspects in severe cases of root resorption although there is some disagreement in the literature (2, 5, 6, 35, 36). The finite element model shows that stresses at the root apex are higher and distributed differently during intrusion compared with other movements, including extrusion. Histological studies have associated

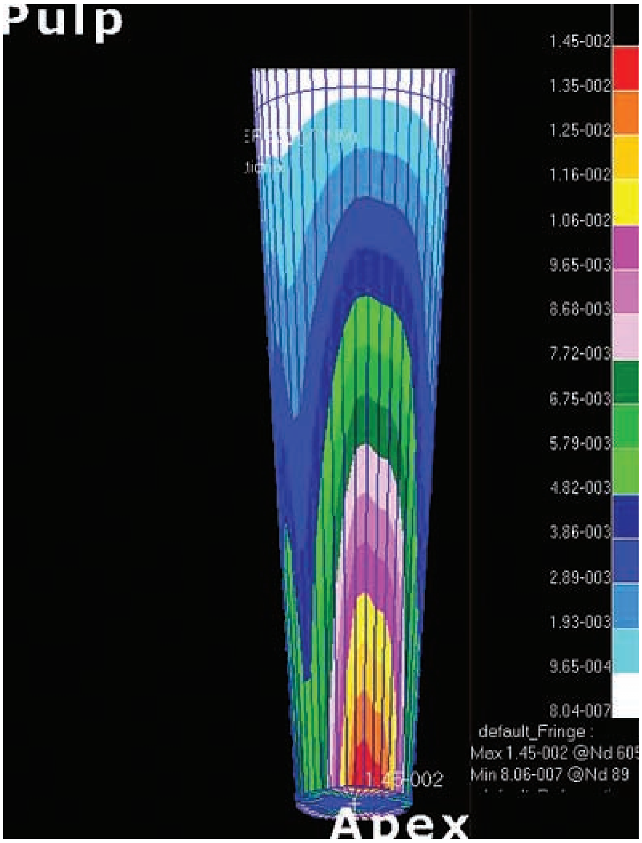

Fig. 6. Mechanical stress on the pulp only – lingual tipping – facial view.

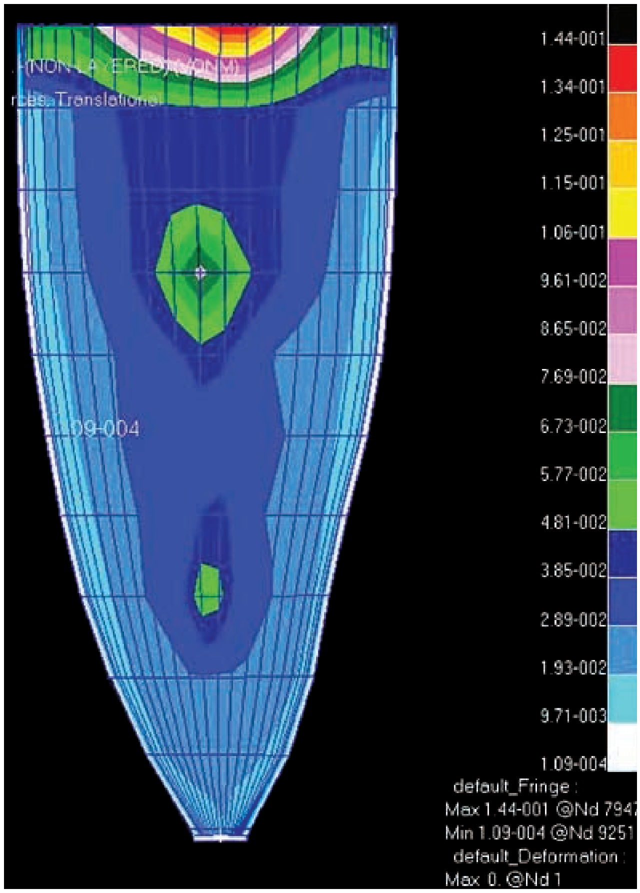

Fig. 7. Mechanical stress on periodontal ligament only – lingual tipping – facial view.

intrusive forces with increased early resorptive cellular acitivity (37, 38).

The second part of this research demonstrated the effect of increasing the thickness of cementum at the root apex. As each increment was added, the amount of mechanical stress increased. This would suggest also that a longer root incurs more mechanical stress at

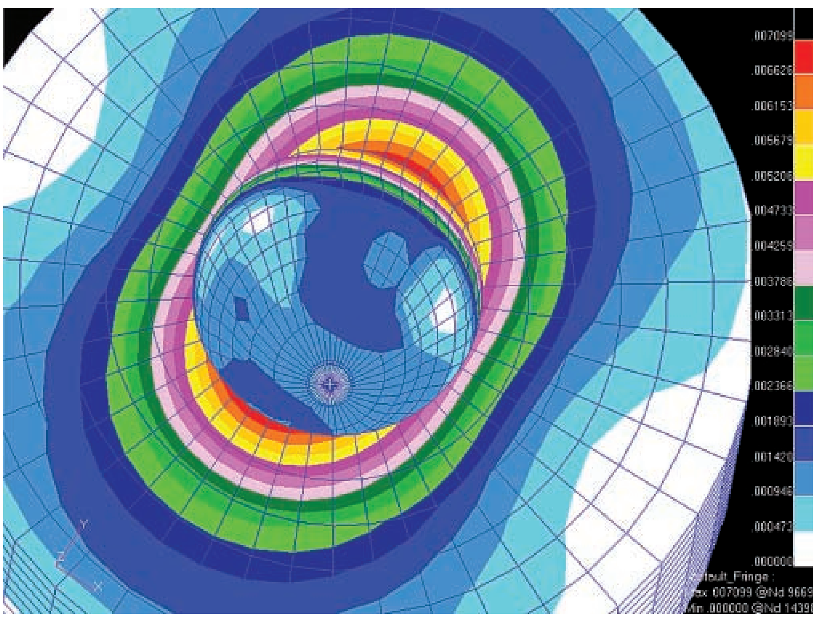

Fig. 8. Mechanical stress at root apex from intrusion – apical view.

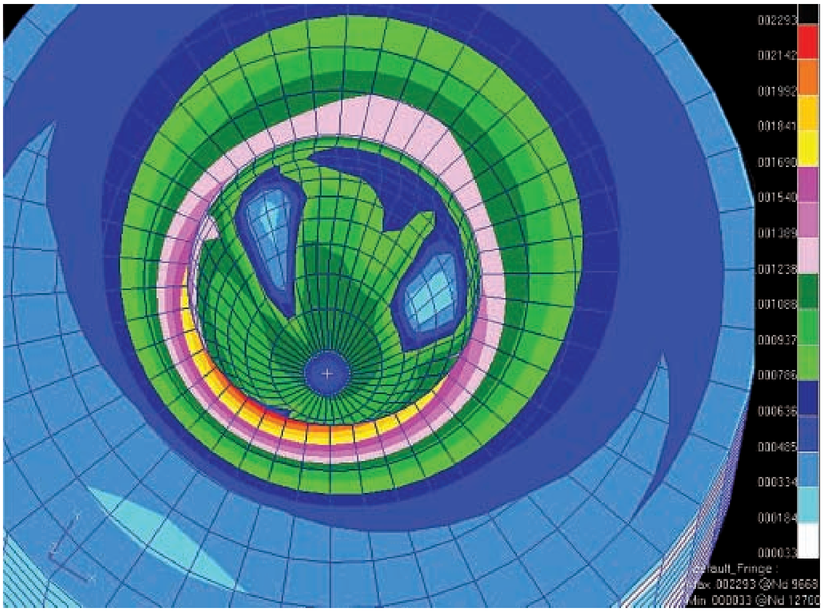

Fig. 9. Mechanical stress at root apex from extrusion – apical view.

apex than a shorter one of the same size. Clinically, longer teeth have been found to have more root resorption (4). It has also been reported that the thickness of cementum increases in a linear relationship with age, and the steepness (slope) of the line varies within the dental arch (39); however, the studies on age as a factor in orthodontically induced external root resorption are inconclusive. Regardless, the simple extension of the root by a small amount adds a measurable stress component to the root.

It is commonly accepted that some type of irreversible damage must occur to the cemental layer before true root resorption occurs. For this to be seen radiographically of course the damage must be considerable. This new model of the root allows a much more detailed depiction of the apical area. Photomicrographs found in most endodontic textbooks amply show the tremendous variation in topography of the apex. It is not unreasonable to suppose, then that an otherwise undetectable deformed apex might be the key to severe resorption.

Limitations of this study involve the approximation of the material behavior and geometries of the tooth model. The three-dimensional model created in this experiment is an idealized model of the maxillary central incisor, different variation of root shapes, and density of materials. The stress–strain relationship was assumed to be linear, elastic, and isotropic. Anisotropic and viscoelastic behavior of the periodontal ligaments was excluded from this model. Recent work seems to suggest that this assumption in particular is weak (40). Lastly, no differentiation was made between cellular and acellular cementum.

Finite element analysis, while useful, is in its infancy as a clinical research tool for the orthodontist. What remains is to connect known, applied forces more closely to the actual process of force that produces not simply physical deformation, but the initiation of a cascade of events leading to bone remodeling and tooth displacement as an indirect response to the external force. Unlike the lifeless objects rendered by design engineers, the tooth has physiological parameters that mediate the effect of the forces upon the tissues (41–46). Recent work has attempted to model this connection between the forces measured in *in vivo* with forces calculated in a finite-element model of the same tooth (25). The more complicated relationships between the cementum, periodontal ligament, and lamina dura bear further scrutiny. Newer imaging methods will eventually encourage the development of models that have the required degree of detail of the root surface anatomy and topography necessary to find the actual areas where resorption starts to take place.

Summary

We have reported a novel three-dimensional model incorporating all layers of an ideal maxillary central incisor (pulp, dentin, enamel, cementum, periodontal ligament, and alveolar bone). This model was used to represent the different types of mechanical stress on different thicknesses of apical cementum when orthodontic forces are applied to the tooth. Although the amount of stress found on the root surfaces was the same as in previous studies, the computed stresses for enamel, dentin, pulp, and cementum were different. Increasing the thickness of apical cementum increased the amount of mechanical stress at the apex.

We conclude that a three-dimensional model of a human maxillary central incisor subject to simulated orthodontic forces using finite element analysis is a useful approach in the study of where maximum stresses occur, particularly at the root apex. This model is but a next step in the progression of increasingly sophisticated, and more importantly, biologically meaningful analyses *in vitro* using computational methods and technological improvements.

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