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Original Article

Evaluation of stress contours on a maxillary molar subjected to simulated tooth loads by finite element analysis technique

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Abstract Forces applied by dental occlusion generate stresses which are transmitted to the surrounding bone via the periodontal ligament causing a tissue response. The purpose of this study was to evaluate the response of a maxillary molar under secondary trauma from occlusion by observing the changes in its stress patterns. In order to visualize the exact pattern of stress distribution, three dimensional finite element analysis models were developed. A force of 3 N, moment of 27 Nmm and a counter rotation moment of 15 Nmm were applied to simulate orthodontic forces. Stresses produced at the periodontal ligament-tooth interface on a maxillary molar model with normal bone height subjected to an orthodontic force were compared with molar models showing bone loss and analyzed using finite element analysis technique. As the bone loss increased, it was observed that, the concentration of stresses at the apical one-third of the tooth also increased and there was high tendency for tooth displacement. The results suggest that an alteration in the magnitude of forces applied may be necessary in teeth with an increased crown to root ratio to maintain a healthy periodontium.

Keywords: Displacement, finite element analysis, increased crown to root ratio, maxillary molar, periodontal ligament-tooth interface, stress pattern, trauma from occlusion.

Introduction

Periodontal disease is marked with the loss of connective tissue attachment and alveolar bone. Institution of treatment often results in arrest of the disease process but with reduced periodontal support. Various experiments were conducted to determine the effect of traumatizing occlusal forces on teeth with reduced periodontal support. The results revealed that when the periodontium is healthy, it adapts to these altered forces, within certain limits, in spite of the reduced height of bone (Ericsson and Lindhe, 1977; Ericsson and Lindhe, 1982). Thus clinical changes were hypothesized based on experiments conducted on replicas and animal models (Ericsson *et al*., 1993) as the effects of trauma from occlusion were difficult to reproduce experimentally in human subjects. However, indirect assessment of the effects of external forces upon the periodontal tissues by histological and radiographic methods (Ramfjord and Ash, 1981) does not mimic the human stomatognathic system. Some studies have been conducted using photoelastic model systems to find out how stresses are distributed within the supporting structures of a tooth (Deines *et al*., 1993). Graphic representation of stress distribution is possible using photoelastic analysis; however, developing birefringent materials that match the physical properties of the tissues to be studied is difficult (Reinhardt *et al*., 1984). Finite element analysis technique has been reported to produce results similar to the photoelastic methods (Hood *et al*., 1975).

Finite element analysis, (FEA) is now being extensively used for the biomechanical analysis of orthopaedic, cardiovascular and dental structures (Reddy, 1993). This modelling technique lends itself to interpretation of clinical changes and helps the clinician establish information which cannot be done in vivo. Further, this technique is a non-invasive means of studying dento-skeletal structures and thus helps to investigate the soft tissue and skeletal responses to mechanical forces (Geramy, 2002; Geramy and Sharafoddin, 2003). It is a numerical method based on the principle of subdividing a structure into a number of finite elements which are interconnected with each other at the nodal points. The nodes are subjected to certain loading conditions resulting in behaviour of the model similar to that of the structure it represents.

The present study intended to evaluate the response of a maxillary molar with normal bone height subjected to orthodontic load application and compare it with teeth with loss of periodontal support, subjected to similar loads. Computerized modelling of the tooth was carried out for this purpose followed by use of finite element analysis technique to analyze the stress patterns produced at the periodontal ligament-tooth interface.

Materials and methods

The study was divided into three phases: 1) the first phase involved the construction of tooth geometry (modelling); 2) the second phase involved application of loads, and 3) the third phase involved computation of stress in all components of the assembly when subjected to forces. (Cobo *et al*., 1993).

In the modelling procedure, the computed tomography (CT) scanned images of a maxillary first molar were taken at a resolution of 1 mm. The two dimensional (2D) cut sections obtained by CT scan were digitized using the digitizer [CAD / LAL 12” x 12”(A-1212)] and the 2D coordinates so obtained were used to make a 2D Auto CAD cross-sectional view (Auto CAD version 14; Autodesk, Inc., California, USA). These were then imported to Autodesk Inventor version 5.5 (Autodesk Inventor Series) where the 2D graphics were converted to three dimensional graphics (3D) using ‘loft’ features explicitly available in the software. The solid 3D model thus generated was taken to ANSYS (Ansys Inc., USA) by file translation protocol (IGES format) and meshed with solid 45 finite elements in ANSYS version 8.1 (Fig. 1). Then the meshed 3D was subjected to finite element analysis (FEA), by applying proper constraints and loads.

To simulate a fibrous periodontal ligament, the collagen fibres running from the tooth to the surface of bone were represented by link elements. We adopted elastic link elements for the periodontal ligament to consider the physical mechanism of ligament motion. This is a more realistic representation of the periodontal ligament which has nonlinear stress-strain behaviour.

Table 1: Mechanical properties used for modelling tooth, periodontal ligament and alveolar bone

	Young’s modulus (N/mm^2)	***Poisson’s ratio***
Tooth	20,000	0.15
Periodontal ligament (PDL)	68	0.49
Alveolar bone	14,000	0.15

Finite element analysis technique allows the assignment of material properties representative of physical characteristics such as the Young’s modulus and Poisson’s ratio to all the tissues in the model, i.e., tooth, periodontal ligament and alveolar bone. Stresses following the application of loads can then be calculated at various points throughout the structure (Table 1) (Andersen *et al.*, 1991). In the present model, the outside surface of the alveolar bone was made fixed and all the nodal degrees of freedom set to zero. This boundary condition was set so that the base of the model does not move when subjected to force systems.

A force of 3 N was applied on the crown in a palatal direction. A counter tipping moment of 27 Nmm and a counter rotation moment of 15 Nmm were applied to simulate orthodontic forces (Fig. 1). Stresses were calculated and presented in colourful contour bands, where different colours represented different stress levels in the deformed state. A positive or negative value in the column of stress spectrum indicated tension or compression respectively. Bone levels were then reduced in height by 2 mm and 4 mm approximately to represent different stages of periodontitis (Cobo *et al.*, 1993; Geramy, 2000). A comparison of stresses following load application on each of these models was then made with the model with no bone loss.

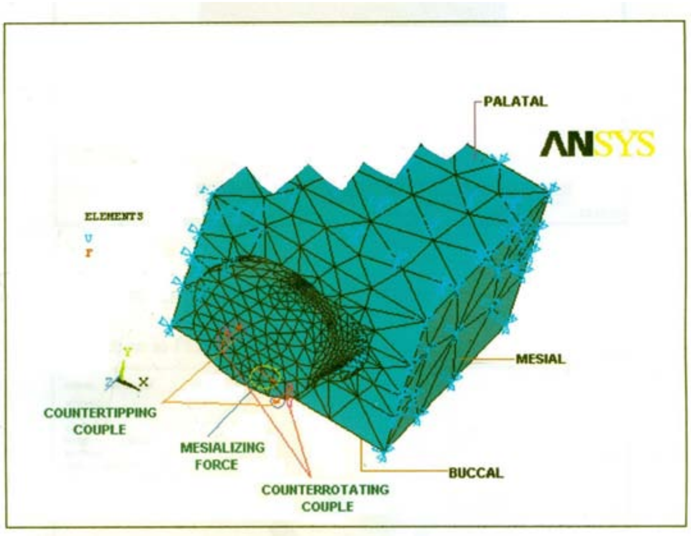

Fig. 1 Solid model of maxillary molar showing load vectors.

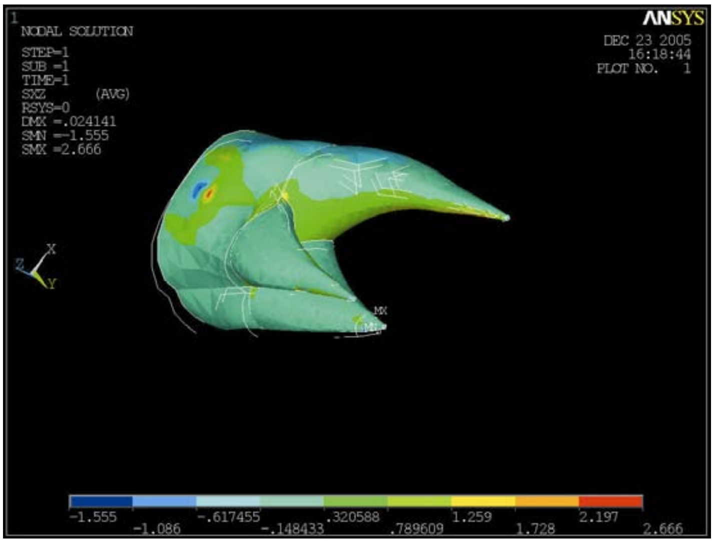

Fig. 2 Stress patterns on tooth with normal periodontal support.

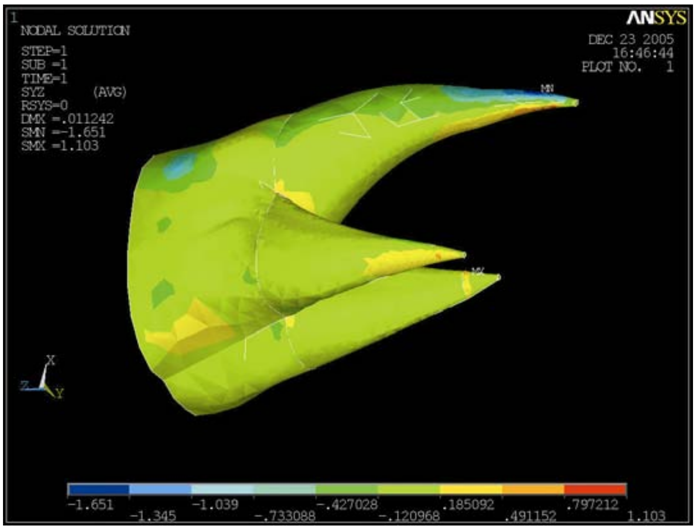

Fig. 3 Stress patterns on tooth with 2 mm bone loss.

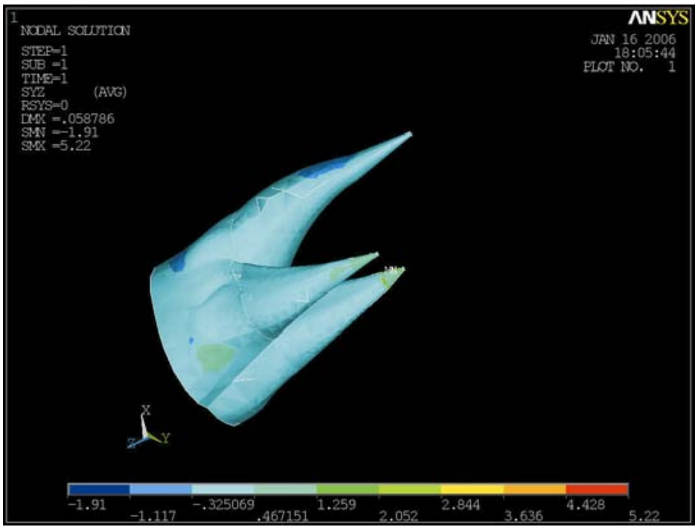

Fig. 4 Stress patterns on tooth with 4 mm bone loss.

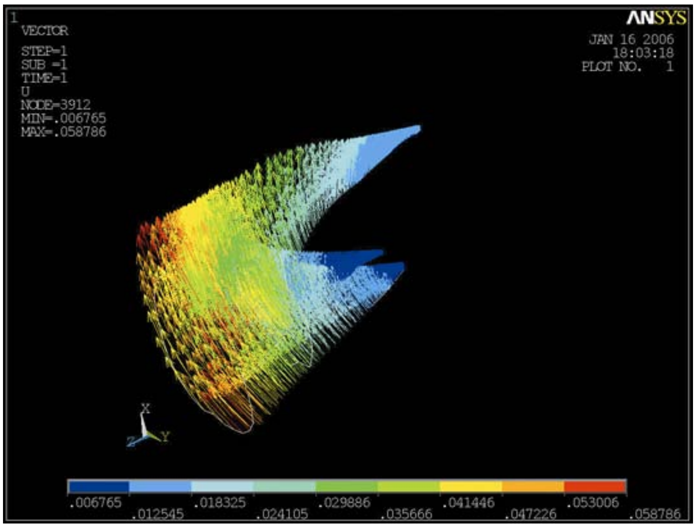

Fig. 5 Displacement Vector plot - tooth with 4 mm bone loss.

Results

Application of load on the models of teeth with normal bone support and those of the models with 2 mm and 4 mm bone loss were adopted for comparison of response of periodontal tissues to occlusal loads. The models with loss of periodontal support would represent teeth with occlusal trauma.

Normal periodontal support

Application of a palatally directed load produced compressive stress (about 0.59 N/mm^2) on the outer surface of the palatal root extending cervico-apically from the alveolar crest. Heavy compressive stresses were also seen on the disto-palatal line angles of the crown near the alveolar crest. Tensile stresses were seen scattered on the distal surface and on the inner surface of the palatal root as well as in the furcation (0.32 N/mm^2). The displacement was generally in a palatal direction with maximum displacement at the crown portion (0.024 mm) (Fig. 2).

2 mm bone loss

Compressive stresses were seen on the crown portion near the alveolar crest and cervical 2/3rd of the root surface ranging from -0.427 N/mm^2 whereas, the inner surfaces of the palatal root, furcation, the cervical aspect of the buccal surface and the apical 1/3rd of distobuccal root showed tensile stresses of about 0.185 N/mm^2. At the apical third of the palatal root, there was maximum compression of -1.65 N/mm^2. The displacement is about 0.011 mm in the palatal direction (Fig. 3).

4 mm bone loss

Tensile stresses here were on the distobuccal surface and tips of buccal roots (2.84 N/mm^2). High compressive stresses (-1.12 N/mm^2) were observed on the apical 1/3rd of the palatal root and on the distopalatal line angles (Fig. 4). Considerable displacement was evident palatally (0.058 mm) (Fig. 5).

Discussion

In the present study, a solid homogeneous model of the tooth with different levels of bone loss was developed and analyzed.

In case of the tooth with normal periodontal support, the direction of force application had a significant effect on the distribution of stresses. An evenly distributed stress state was developed along the palatal and buccal surfaces. Small concentrations of stresses were evident at the apexes of the roots. The interradicular area, which is the centre of axis of rotation of a molar, showed tensile stresses suggestive of remodelling.

There was uniform displacement well within the periodontal ligament space towards the palatal direction. Displacement tendency decreased gradually towards the apex. The root surface configuration, curvatures and divergence may have been responsible for withstanding and dissipation of intrusive forces. These results correlate with histopathologic observations, wherein, the tooth would move toward the side of compression and away from the side of tension (Carranza, 1996). These findings confirm that bodily movement results in a uniform stress distribution in the periodontium.

In situations with 2 mm and 4 mm bone loss, the stresses seemed to be progressively concentrated at the apical 1/3 of the tooth. These findings corroborate with those of Geramy and Faghihi (2004) who observed that with more alveolar bone loss, there was increased stress in the periodontal ligament. Deflections increased with decreasing level of periodontal support. This was apparent due to a shift of the tooth’s centre of rotation towards the apex with greater bone loss. With this apical shift, there is acceleration of tipping tendency due to an increased component of lateral forces.

Consequently, teeth with increased crown to root ratio pose a major challenge for tooth movement (Proffit and Fields, 2000). In patients with periodontitis, increased demands are placed on the clinician for careful application of the force systems used in tooth movement, especially when using removable appliances (Boyd *et al*., 1989). Excessive orthodontic force with advanced periodontal bone loss may traumatize the periodontium and increase chances of apical root resorption (Beck and Harris, 1994). There is also a high chance of tissue damage caused by greater amounts of tooth displacement.

Despite the best efforts to model the structure accurately, the model may have limitations as only static loads are applied in this study. Intermittent dynamic loads, as encountered in clinical situations could be used for further investigations. Accuracy of the computer model and the results interpreted will depend on the overall size and proportion of the tooth as well as the assigned mechanical properties of bone, tooth and periodontal ligament (Andersen *et al*., 1991).

Conclusions

To assess the effects of secondary trauma from occlusion, forces applied on a tooth with healthy periodontium were compared with that of teeth with reduced periodontal support. It was observed that as the bone loss increased, 1) the stress concentration also increased at the apical 1/3 of tooth, 2) the tooth displacement also increased, suggesting a shift in the centre of axis of rotation of the tooth apically, and 3) the increased crown to root ratio would lead to a tipping tendency. The results indicate that in cases with reduced periodontal support, increased amount of stress is inevitable in spite of application of a constant amount of force. This would necessitate an alteration in magnitude of forces applied during orthodontic treatment in order to sustain existing periodontal support in a healthy condition for the duration of force application.

Clinical implications

Forces which are normally considered harmless, such as orthodontic forces may be traumatic in a compromised system. Similarly, the presence of occlusal prematurities, abnormal contact relationships or even the effects of parafunctional forces may precipitate concentration of stresses in specific areas. Elimination of such prematurities or abnormal forces with the creation of balanced cusp to fossa relationships would allow for establishment of vertically directed forces and a more desirable stress distribution pattern, causing a favourable tissue response. Hence a modification in the applied force system is desirable to reduce the harmful effect of lateral forces and simulate the response of a tooth with a healthy periodontium. This was aptly demonstrated using this simple finite element model. Interpretation and correlation of the resultant periodontal changes such as widening of the periodontal ligament space width and location and patterns of bone loss seen radiographically may also be possible with the help of finite element analysis. Further research may utilize this technique as an aid in enhanced understanding and diagnosis of occlusion and joint related problems.

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