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Stress distribution in maxillary first molar periodontium using straight pull headgear with vertical and horizontal tubes: A finite element analysis

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ABSTRACT

Background: One of the most effective ways for distal movement of molars to treat Class II malocclusion is using extraoral force through a headgear device. The purpose of this study was the comparison of stress distribution in maxillary first molar periodontium using straight pull headgear in vertical and horizontal tubes through finite element method.

Materials and Methods: Based on the real geometry model, a basic model of the first molar and maxillary bone was obtained using three-dimensional imaging of the skull. After the geometric modeling of periodontium components through CATIA software and the definition of mechanical properties and element classification, a force of 150 g for each headgear was defined in ABAQUS software. Consequently, Von Mises and Principal stresses were evaluated. The statistical analysis was performed using T-paired and Wilcoxon nonparametric tests.

Results: Extension of areas with Von Mises and Principal stresses utilizing straight pull headgear with a vertical tube was not different from that of using a horizontal tube, but the numerical value of the Von Mises stress in the vertical tube was significantly reduced ($P < 0/05$). On the other hand, the difference of the principal stress between both tubes was not significant ($P > 0/05$).

Conclusion: Based on the results, when force applied to the straight pull headgear with a vertical tube, Von Mises stress was reduced significantly in comparison with the horizontal tube. Therefore, to correct the mesiolingual movement of the maxillary first molar, vertical headgear tube is recommended.

Key Words: Finite element analysis, extraoral traction appliance, maxilla, molar, Dental stress analyses

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INTRODUCTION

The second half of the twentieth century has seen the rise in popularity in the application of nonextraction treatment within the orthodontic community. In the treatment of Class II molar relationship and in the finding of a solution for tooth size-arch length, discrepancy in the maxillary arch limiting the distal movement of the maxillary first molars is a common goal.[1] Some of the common ways for distalizing tooth include extraoral traction with cervical,

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occipital, or high-pull headgear and also some intraoral appliance such as Herbst,[1] Twin Force Bite Corrector,[2] Jasper Jumper,[3] transpalatal arch, coil springs, repelling magnets, K-loop, pendulum, Jones Jig,[4] and temporary anchorage device.[5-7]

To date, the common device utilized to distaly is move the maxillary first molar has been the headgear. It has an advantage (simplicity) and a major disadvantage (full patient compliance is needed). To tip or bodily move molars distally, extraoral force through a facebow to the molars is a relatively simple method. The force is directed specifically to the teeth which need to be moved, and the reactive reciprocal forces are not distributed on the other teeth that are in the correct positions.[8] Various types of molar distal movement are possible through the controlling the force vector. In this regards, the combination of appropriate outer bow length and its angulation to the occlusal plan should be considered.[9] Since in most cases, the mesial movement of maxillary molars as the result of premature loss of second deciduous molars leads to mesially in rotation of molars to the lingual zone, thus the application of an appliance which corrects this rotation along the distal movement of the teeth is preferred.

To correct this rotation, orthodontists conventionally use a combination of horizontal headgear tube and mesial out offset in the headgear inner bow. However, clinically engaging this modified inner bow is difficult and even more impossible due to the degree of molar rotation. Clinicians often try to stepwise correction of such a condition, using transpalatal arch or removable appliance before the headgear. It seems that the vertical headgear tube which redirects the planar insertion of inner bow from occlusal will overcome such a problem. Although we have not found any article describing the application of vertical headgear tube, we think investigating on the effect of vertical headgear tube by means of a finite element method (FEM) will comprehensively answer this idea, which ease of insertion helps reduce the destroying force on the rotated molar.

Since the advent of headgear treatment, various studies have been conducted to clarify morphological, biomechanical, cephalometric, and histologic changes on craniofacial complex and teeth following the utilization of various headgear types.[10,11] While as to date, very few studies have investigated biomechanical changes in maxillary molars after the application of straight pull headgear (combination headgear) under similar biological circumstances in different biophysical human structures. The application of heavy forces to maxillary dentition during a person's treatment with a headgear induces high concentration of stress on periodontal tissue.

Orthodontic tooth movement has been widely thought to occur due to a compression and a tension within the surrounding tissues generated by orthodontic appliances. This was traditionally documented as the classic "pressure-tension" theory.[12]

There have been numerous studies in orthodontics on the tissue reaction of periodontal ligament (PDL) during tooth movement. Most of them examined the tissue reaction in the pressure zone of PDL morphologically and histochemically.[13] Consequently, the tissue reaction has been identified as a process of inflammation with a degeneration of the compressed PDL and a remarkable osteoclastic bone resorption.[13] The force which moves a tooth more rapidly with less injuries to the supportive tissues, less discomfort, and pain to the patient, and also less root resorption is preferable.[14]

Engineering has become quite established in the field of orthodontics. Using a model solution, finite element analysis (FEA) is a computational procedure to calculate the stress in an element. As a result, the determination of stress resulting from external force and pressure is possible. By this method, the evaluation of mechanical aspects of biomaterials and human tissues that can be hardly measured *in vivo* is feasible. This numerical form of analysis allows identification of stress and displacement.[15] With FEA, forces and stresses can be calculated. It is necessary to build a virtual model through using an image processing and digital reconstruction software.[16,17]

The aim of this study was to compare the distribution of stress in maxillary first molars using straight pull headgear on a vertical and horizontal tube using FEM.

MATERIALS AND METHODS

The procedure utilized in this study for the application of the finite element mesh can be summarized as follows:

Modeling

The first step in FEA is modeling so that the quality of this step determines the accuracy of the analysis. A primary model of the maxillary first molar and bone was developed Three-dimensional (3D) geometry of the whole above-mentioned system was scanned and digitized using ATOS II (Triple Scan) scanning technology (GOM mbH, Braunschweig, Germany) and ATOS Viewer (Version v6.3.0) software (GOM, Germany). The resultant dense point cloud was transferred to 3D imaging scanner (3Shape Trios® 3Shape Dental Systems Copenhagen, Denmark) from a well-shaped dry skull. Consequently, by transferring the data to CATIA V5 R20 the software (Dassault System, Suresnes Cedex, France), a complete construction model of the PDLs, lamina dura, enamel, cortical, and spongy bone was created in shape environment of software. Based on the exact dimension of the band and tube, which were measured with a digital caliper (Digital Caliper Model No. 550-115, MTC tools, China) and constructed enamel surface, the final geometric model of bands and tubes was shaped using the CATIA software [Figure 1].

Model specifications

A 3D-simulated model was transferred to the ABAQUS/CAE 6.6 version (Hibbitt, Karlsson and Sorensen Inc., Providence, Rhode Island, USA) and mechanical properties such as Young's modulus and Poisson's ratio for various materials were applied for various elements [Table 1 and Figure 1].

Meshing

In the ABAQUS software, all parts are defined as homogeneous elastic solid materials. Model parts connected together, and elements were built for each part consequently (four node linear tetrahedral elements). The complete geometry included an assemblage of discrete pieces (elements) that were connected at a finite number of points (nodes). In total, 22,503 solid nodes and 85,874 elements were used for meshing through the utilizing of ABAQUS software [Figure 2].

Loading

A 150 g (1.47 *N*) distally force was applied at the same distance and parallel to the occlusal plan. So that, the total equivalent load was applied on the hachured area. Loading was in the form of surface traction and calculated as indicated:

$$F = 150\ \text{g} \rightarrow F = 0/15 \times 9/81 = 1/4715\ (N)$$

$$\text{Vertical tube area: } A = \frac{\pi}{2}(r_2^2 - r_1^2) = 0/6440\,\text{mm}^2$$

$$\sigma_t = \frac{F}{A} = \frac{1/4715}{0/6440} = 2/2489\ \text{MPa}\ \left(\frac{N}{\text{MM}^2}\right)$$

$$\text{Horizontal tube area: } A = 4/2\times(\pi \times 0/925 \times 2) = 24/410\ \text{mm}^2$$

$$\sigma_t = \frac{F}{A} = \frac{1/4715}{24/410} = 0/0603\ \text{MPa}\ \left(\frac{N}{\text{MM}^2}\right)$$

Fulcrum determination

The fulcrum was selected adjacent to and toward the bottom of the bone to prevent cortical and spongy bone displacement [Figure 2].

Table 1: Mechanical properties for various elements in the ABAQUS software

Model elements	Average thickness (mm)	Young's modulus (MPa)	Poisson's ratio
Enamel	-	84,100	0.20
Dentin	-	18,600	0.31
PDL	0.2	70.3	0.45
Lamina dura	0.5	15,000	0.30
Cortical bone	1.2	15,000	0.30
Spongy bone	2.9	1500	0.30
Stainless steel band	-	210,000	0.30

PDL: Periodontal ligament

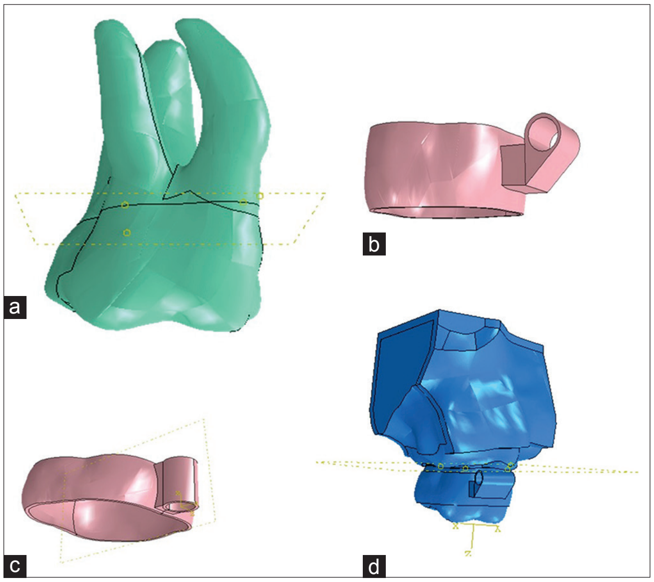

Figure 1: (a) Maxillary first molar model, (b) metal band with horizontal tube model, (c) metal band with vertical tube model, (d) complex of tooth, bone, and band with horizontal tube.

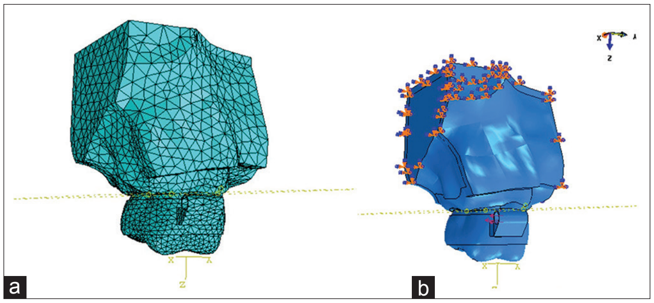

Figure 2: (a) Meshing of tooth, bone, and band with horizontal tube complex, (b) force and fulcrum of tooth, bone, and horizontal tube.

RESULTS

Von Mises and the Principal stresses distribution in the root, PDL, Lamina dura, spongy bone, and cortical bone, all were assessed and compared between the vertical and horizontal headgear tube. Von Mises stress shows the distribution of areas as well as the amount of minimum and maximum stress in the periodontium; it does not define the compression and tension stress. According to the liner color scale, warm colors indicate high stress, whereas cold colors show low stress areas. Principal stress distribution demonstrates areas of maximum tension and compression. Positive (+) and negative signs (−) indicate tension and compression, respectively. Warm colors in the figures illustrate areas of maximum amount of tension stress while cold colors show areas of maximum amount of compression stress. As a result, the numerical value of Von Mises stress in the maxillary first molar periodontium was significantly less in the vertical headgear tube than in the horizontal headgear tube ($P < 0.05$). The extension of Von Mises stress area by applying vertical tube headgear does not differ in comparison with the horizontal tube, except in spongy bone [Table 2 and Figures 3, 4].

In addition, the numerical value of Principal stress in the maxillary molar periodontium decreases when using straight pull headgear in a vertical tube as compared with the horizontal tube. Although this finding was not statistically significant ($P > 0.05$), there was no difference between the extension of maximum

Table 2: Comparison of Von Mises stress between horizontal and vertical tubes

Von Mises stress	Roots	PDL	Lamina dura	Spongy bone	Cortical bone
Maximum stress in horizontal tube (Mpa)	0.43	0.1	0.27	0.029	0.22
Minimum stress in horizontal tube (Mpa)	0.003	0.00005	0.0052	0.0000086	0
Area of maximum stress	Distal of cervical one-third of mesiobuccal root	Cervical one-third between palatal and distobuccal roots	Distal of cervical one-third of mesiobuccal root	Distal of cervical one-third of mesiobuccal root	Cervical one-third between mesiobuccal and palatal roots
Maximum stress in vertical tube (Mpa)	0.34	0.081	0.21	0.023	0.19
Minimum stress in vertical tube (Mpa)	0.0021	0.000043	0.0045	0.000007	0
Area of minimum stress	Distal of cervical one-third of mesiobuccal root	Cervical one-third between palatal and distobuccal roots	Distal of cervical one-third of mesiobuccal root	Distopalatal area, far from roots	Cervical one-third between mesiobuccal and palatal roots

PDL: Periodontal ligament

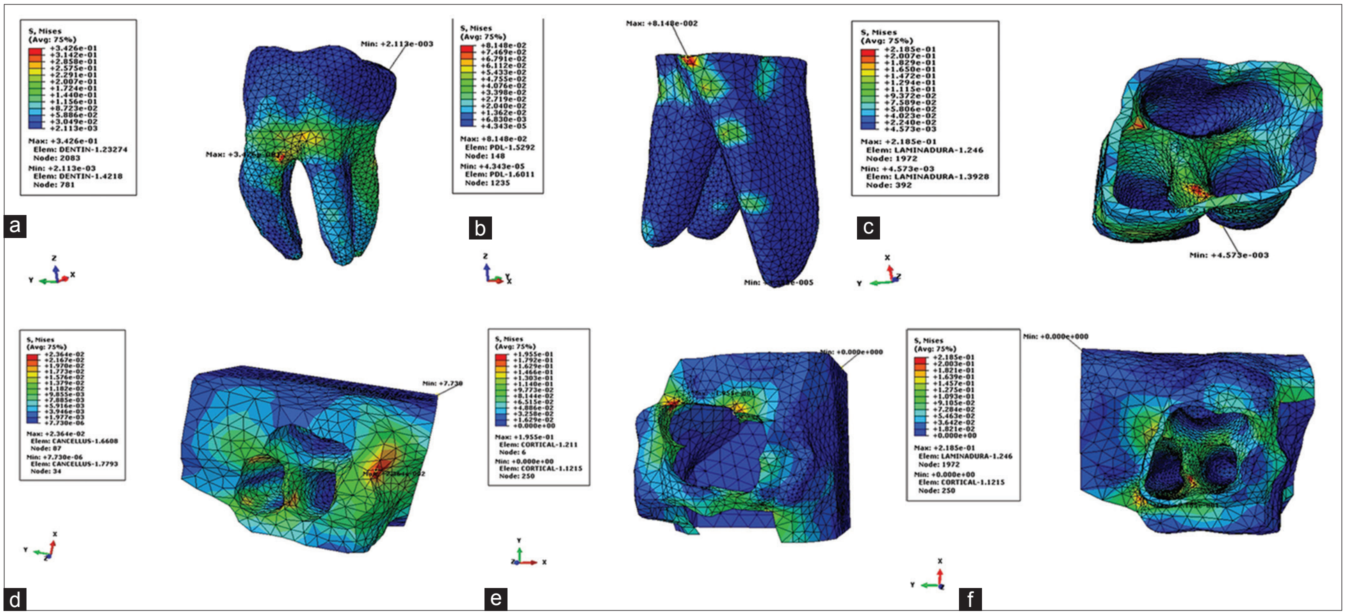

Figure 3: The extension of Von Mises stress area by applying vertical tube: (a) Roots, (b) periodontal ligament, (c) lamina dura, (d) spongy bone, (e) cortical bone, (f) combination of lamina dura, spongy, and cortical bone.

tension and compression region in the periodontium except in spongy bone [Table 3 and Figures 5, 6].

DISCUSSION

The comparison of periodontium in the utilizing of a horizontal tube and vertical tube showed that maximum tension was in the mesiobuccal root, lamina dura, cortical bone, and ultimately in the PDL and spongy bone, respectively. Consequently, among the dental periodontium, the highest and the lowest stress allocated to the mesiobuccal root and spongy bone, respectively. Among the roots, the highest amount of stress was in the mesiobuccal

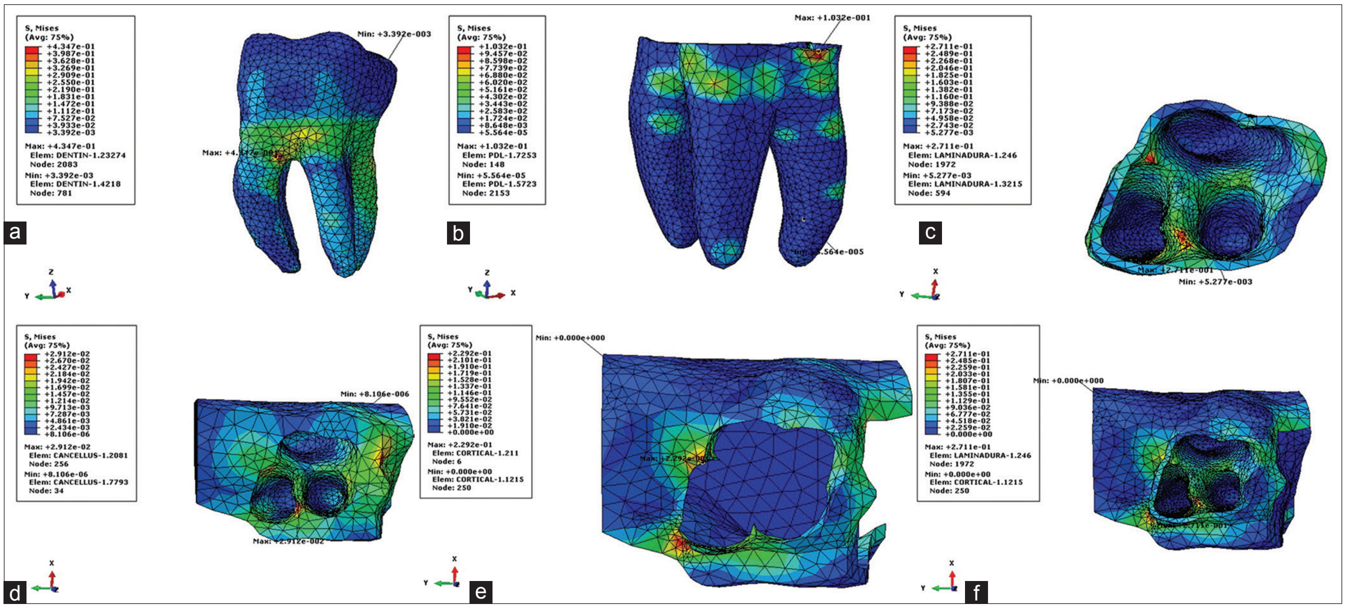

Figure 4: The extension of Von Mises stress area by applying horizontal tube: (a) Roots, (b) periodontal ligament, (c) lamina dura, (d) spongy bone, (e) cortical bone, (f) combination of lamina dura, spongy, and cortical bone.

Table 3: Comparison of principal stress between horizontal and vertical tubes

Principal stress	Roots	PDL	Lamina dura	Spongy bone	Cortical bone
Maximum tension stress in horizontal tube (Mpa)	0.34	0.18	0.23	0.024	0.23
Area of maximum tension stress in horizontal tube	Cervical one-third between mesiobuccal and palatal roots	Cervical one-third between mesiobuccal and distobuccal roots	Cervical one-third between mesiobuccal and palatal roots	Cervical one-third between mesiobuccal and palatal roots	Cervical one-third between mesiobuccal and palatal roots
Maximum compression stress in horizontal tube (Mpa)	−0.101	−0.15	−0.044	−0.0017	−0.014
Area of maximum compression stress in horizontal tube	Distal of cervical one-third of mesiobuccal root	Distal of cervical one-third of mesiobuccal root	Distal of cervical one-third of mesiobuccal root	Distal of cervical one-third of mesiobuccal root	Palatal bone
Maximum tension stress in vertical tube (Mpa)	0.26	0.15	0.19	0.020	0.20
Area of maximum tension stress in vertical tube	Cervical one-third of the bone between mesiobuccal and palatal roots	Cervical one-third between mesiobuccal and distobuccal roots	Cervical one-third between mesiobuccal and palatal roots	Cervical one-third between mesiobuccal and palatal roots	Between mesiobuccal and palatal roots
Maximum compression stress in vertical tube (Mpa)	−0.09	−0.12	−0.033	−0.00014	−0.011
Area of maximum compression stress in vertical tube	Distal of cervical one-third of mesiobuccal root	Distal of cervical one-third of mesiobuccal root	Distal of cervical one-third of mesiobuccal root	Distal area	Palatal bone

PDL: Periodontal ligament

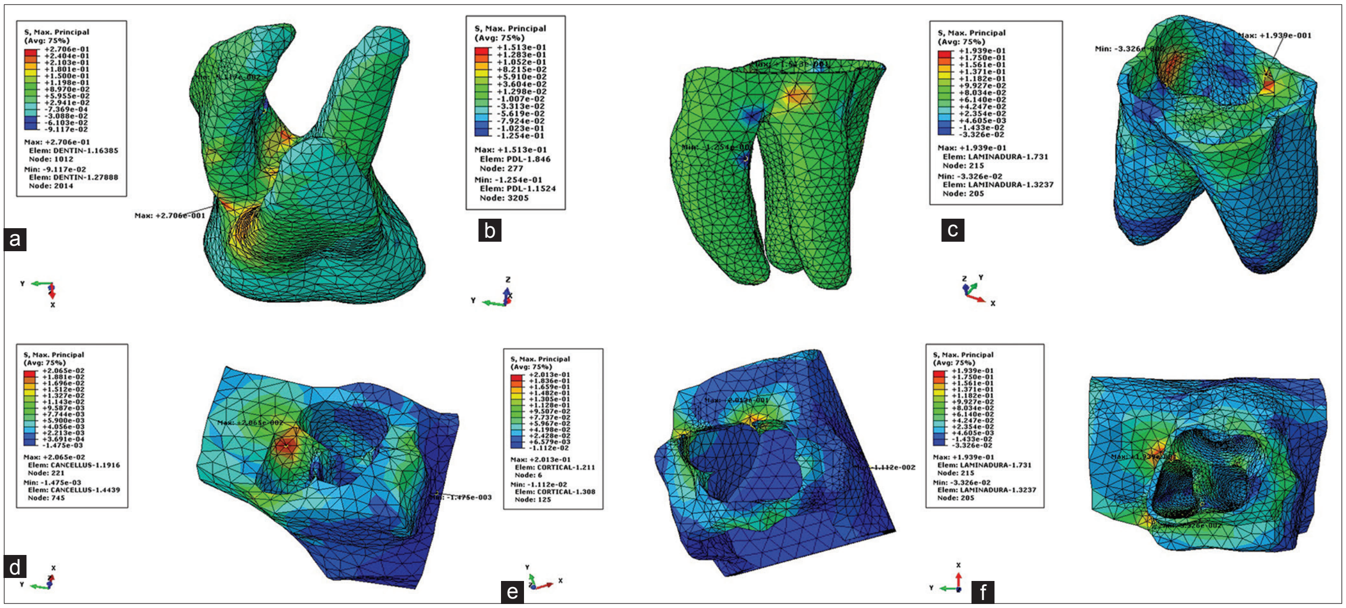

Figure 5: The extension of Principal stress area by applying vertical tube: (a) Roots, (b) periodontal ligament, (c) lamina dura, (d) spongy bone, (e) cortical bone, (f) combination of lamina dura, spongy, and cortical bone.

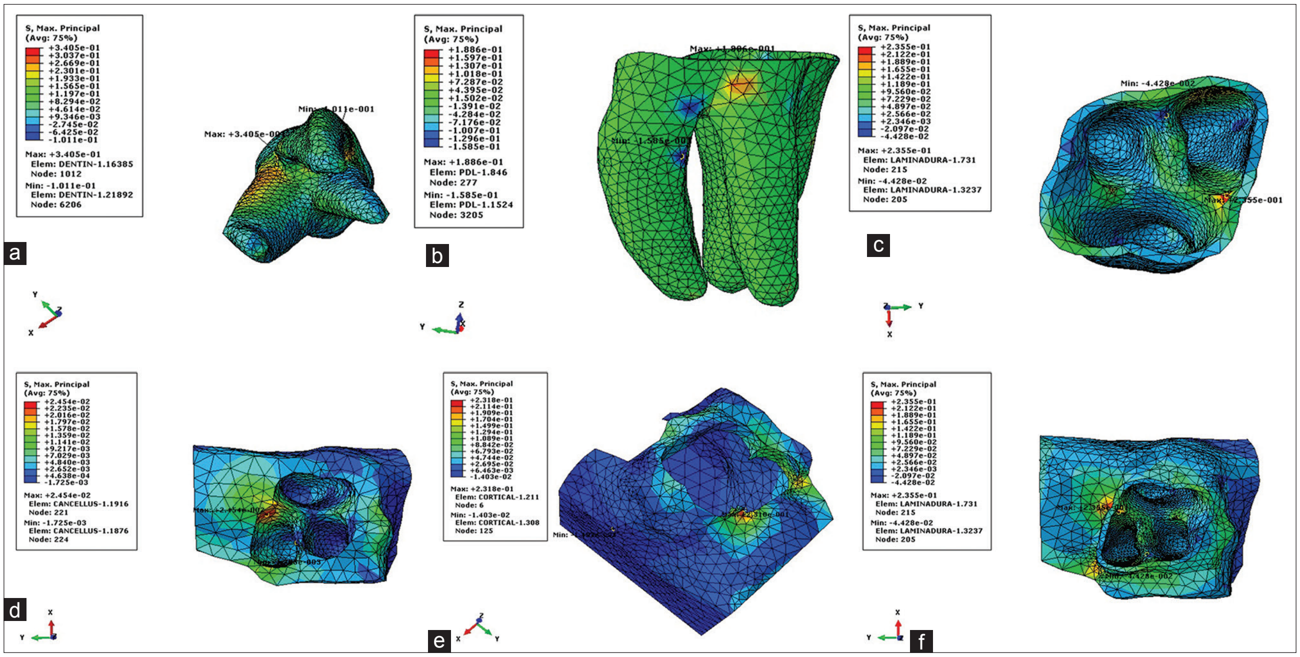

Figure 6: The extension of Principal stress area by applying vertical tube: (a) Roots, (b) periodontal ligament, (c) lamina dura, (d) spongy bone, (e) cortical bone, (f) combination of lamina dura, spongy, and cortical bone.

root and the lowest amount of stress is in the palatal root.

Numerical values showed significantly less tension through the application of a vertical rather than horizontal tube ($P < 0.05$). The difference in the amount of stress between both groups can be summarized as the difference in surface where the force was applied on, the method of applying force on tubes and the moment of creating force. Moreover, increased resistance of the horizontal tube against the rotation of a molar can lead to additional stress in the application of the horizontal tube.

Farahani *et al*. conducted a finite element analysis on stress distribution of maxilliary first molar PDL with high pull headgear traction. They applied a 350 g force by means of a high pull headgear to the maxillary first molar in the stabilized arch on a rectangular full size arch wire in (022) slot bracket. Their study showed that the buccal surface of PDL of mesiobuccal root and the buccal, palatal, and distal surface in cervical region of PDL of distobuccal root and the distal surface of the PDL of palatal root had received a great amount of stress. In addition, the overall stress distribution in roots of molar had intrusive nature.[18]

However, in the current study, we applied an optimum distalizing force of 150 g only on the maxillary first molar is applied. Therefore, differences between stress distribution pattern in our findings and their study are summarized in various lines of action, direction, and magnitude of force.

According to Wilson *et al*., who evaluated intrusive and extrusive forces on the PDL of the canine teeth, the PDL of the alveolar crest bears more compression than the apical region.[19] Similarly in this study, the highest stress level is in the cervical of the tooth (alveolar crest) although the direction and tooth movement pattern along with details of stress pattern was different. This is truly certified that stress distribution pattern in the periodontium depends on type of tooth movement, modality, and direction of force.

Tanne *et al*. described stress distribution following orthodontic force on periodontal tissue of a lower premolar model. Based on their observation, the highest tension level was in the root, alveolar bone, and PDL.[20] This is consistent with this study as we found the highest tension level in the roots following cortical bone, lamina dura, PDL, and spongy bone. However, it should be considered that the type of tooth, loading force, and pattern of stress distribution was excluded from our study.

Based on the stress distribution pattern and aggregation of maximum stress in the cervical area of the tooth periodontium, it can be concluded that molar distalization through the application of an optimum force of 150 g straight pull headgear in both the vertical and horizontal tubes; the cervical region of teeth endures the highest stress and maximum amount of bone remodeling and displacement. Whereas in the palatal area of bone and apically along one-third of the root, the least amount of tension was induced and minimum bone remodeling and displacement took place. By centering the site on the cervical zone and the low-tension site on apically one-third of the root of the maxillary first molar may be indicative of lower root resorption risks as a result of straight pull headgear application.

Limitations

In cases with mesiolingual movement of the maxillary first molar, the inner bow of the horizontal headgear can be used to correct this condition. This is done routinely using an expanded inner bow together with a toe in bend. However, in our study, we compare vertical and horizontal headgear tubes without any modification in the inner bow, to ease the comparison of two headgear tubes and to eliminate the contributing factor of inner bow action. Nonetheless, a FEM analysis in comparison of horizontal headgear tube with toe in bended inner bow and vertical tube headgear is highly recommended.

Currently, it is impossible to place strain gages in the PDL to measure stress distributions; hence, knowledge of stress phenomena has to depend on another technique. For example, as the same as this study, mathematic model of the tooth and surrounding structures can be constructed, and theoretic stress levels can be calculated from these models. Unfortunately, these mathematic models are no better than the assumptions on which they are based. As a result, we propose that above calculation should be verified by following clinical or animal experimentation whenever possible.

CONCLUSION

Based on the results, when force was applied to the straight pull headgear with a vertical tube Von Mises stress was reduced significantly in comparison with the conventional horizontal tube. Therefore, if mesiolingual movement of the maxillary first molar occurs due to an early loss of the deciduous second molar, using a vertical headgear tube is recommended.

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Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or non-financial in this article.

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