Original Article

Evaluation of stress patterns on maxillary posterior segment when intruded with mini implant anchorage: A three-dimensional finite element study

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Abstract

Introduction: The aim of this study is to evaluate stress and displacement effects of maxillary posterior intrusion mechanics with mini-implant anchorage by using finite element method. **Materials and Methods:** A computer stimulation of three-dimensional model maxilla with all teeth, PDL, bone, mini-implants, brackets, arch wire, force element, and transpalatal arch was constructed on the basis of average anatomic morphology. Finite element analysis was done to evaluate the amount of stress and its distribution during orthodontic intrusive force. **Results:** Increased Von Mises stress values were observed in mesio-cervical region of first molar. The middle third of second premolar and second molar and regions adjacent to force application sites also showed relatively high stress values. Minimum stress values were observed in apical region of first premolar as it is away from force application. **Conclusion:** Using three mini-implant and transpalatal arches, this study demonstrates that significant amount of true intrusion of maxillary molars could be obtained with lesser concentration of stresses in the apical area recorded.

Key words: Finite element study, mini-implant, molar intrusion

INTRODUCTION

Orthodontics is gradually changing from an opinion-based practice to evidence-based practice. In contemporary period, it is necessary to have scientific rationale for any treatment modality and the evidence of tissue response to it. The greatest progress lies in perceiving some unifying concepts in the abundant evidence and ideas. Molar intrusion is one of the most difficult tooth movements to achieve in orthodontics. In most studies, it was reported that traditional posterior intrusion mechanics such as bite-blocks and fixed appliances with vertical elastics and multi-loop archwire therapy often have limited intrusion and side effects from insufficient anchorage.[1-4]

Temporary anchorage devices have gained widespread popularity in orthodontics during the past decade. A broad spectrum of anchorage devices including miniscrews and on-plants have been introduced, advocated, and used in both research and clinical settings. The most frequently used temporary anchorage devices are miniscrews or "TADs" as they have been nicknamed. Miniscrews are generally straight forward to place and remove, are amenable to placement in various locations in the mouth, are widely adaptable to various orthodontic anchorage

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requirements, and are typically constructed from biologically compatible titanium. Although their design varies among manufacturers, TADs are generally 1–2 mm in width, 6–12 mm in length (thread area), and have a head which serves as a point of force application to allow desired tooth movement.

Mini-implants provide stable intraoral anchorage and enable the maxillary molars to be intruded without the usual side effects. There are challenges inherent in evaluating mechanical effects of miniscrew use on bone and miniscrew. These challenges include the inability to clinically measure stress levels in patient's bone and inability to visualize the stress patterns that are generated. In an attempt to overcome these challenges, researchers have utilized the finite element analysis (FEA) engineering tool. The finite element method (FEM), which has been successfully applied to the mechanical study of stresses and strains in the field of engineering, makes it practicable to elucidate stresses in the living structures caused by various internal and external forces. FEM offers a viable and non-invasive alternative for analysis of the stress and strain distribution, which is unique because of its ability to model geometrically complex structures.

Numerous investigations have been conducted to assess the stress and strain distribution and retraction effects using mini-implants, but limited literature is available regarding the intrusive effects using mini-implants for orthodontic anchorage. The aim of this study is to evaluate stress and displacement effects of maxillary posterior intrusion mechanics with mini-implant anchorage using FEM.

MATERIALS AND METHODS

A three-dimensional (3D) model of the maxilla with all teeth, PDL, bone, mini-implants, brackets, and arch wire was used in this study. The analytic model used in this study such as brackets, wire, and mini-implants was developed using reverse engineering technique extracting the dimensional details of the physical parts using precision measuring instruments.

The study was done using a 3D FEA using a spiral computed tomography (CT) scan machine. An X-force/SH spiral CT scan machine was used for taking the CT scan of the model.

Computational facilities used for the study

Hardware

A PC workstation having an Intel Core 2 duo with 2.1 GHz, 2 GB of RAM, 2 GB Graphics card, 320 GB hard Disc, and 17" Monitor was used for the study.

Software

MIMICS 8.11: Materialize's Interactive Medical Image Control System (MIMICS) is a medical modeling software used for the visualization and segmentation of CT/MRI images.

ANSYS 12.1: Analysis System Software.

RAPID FORM 2004

Software used to convert cloud data points to surfaces. The converted surfaces are stored in IGES format.

HYPERMESH 11.0

Software used for converting geometric model into finite element model.

Construction of the geometric model

The CT scan of a skull is procured and then the DICOM data are converted into geometric model using mimics software. Data from mimics (cloud data points and lines) are exported to RAPID FORM in the STL format. Only region of interest such as maxilla is extracted from the entire skull.

Data from MIMICS are imported into RAPID FORM software to create the surfaces; these surfaces are then exported in IGES format using HYPERMESH. The anatomic model consists of only surface data. The anatomic model was used to construct geometric model of the maxillary teeth having the dimensions and morphology found in Wheeler's textbook using ANYSYS software. An average thickness of 0.2 mm of the periodontal ligament was assumed and generated around the roots of all teeth.

Mini-implants (1.3 × 9 mm) were placed between the roots of the second premolar and the first molar on vestibular side and the first and second molars on the vestibular and palatal sides. Mini-implants are placed at 6 mm height from alveolar crest.

Transpalatal arch connecting the first molars was modeled. In accordance with the clinical applications, transpalatal arch was adapted evenly 5 mm from the palatal bone to achieve clearance for the intrusion movement. In clinical applications, to minimize tipping movements, a rigid connection should be preferred at the transpalatal arch band interface.

Brackets were attached to the teeth so that the midpoint of the brackets overlapped the midpoint of the facial-palatal surface of the crowns. The posterior teeth were connected by full dimensional segmental archwires (0.019" × 0.025" S.S.) from the vestibular sides.

Conversion of geometric model to finite element model

Using the ANSYS software, this geometric model was converted into finite element model. The finite element model is the representative of the geometric model in terms of finite number of element and nodes. This process is called discretization. The main idea behind this discretization process was to improve the accuracy of the results. For a 3D analysis, the finite elements may be tetrahedron, rectangular prisms, or hexahedron. In this study, the geometric model was discretized into finite number of small tetrahedron pieces. Each such piece is called as element and these elements are connected to each other at the corners called as nodes. This model which consists of nodes and elements is called finite element model. The final model had 307283 hexahedral elements and 61618 nodes, and 3D tetrahedral elements were also used for the study. Finite element model showing brackets, full dimensional wire, mini-implants, and TPA, in buccal and occlusal view as shown in Figure 1 and 2 respectively.

Material property data representation

Assigning the material properties

In this study, the assumption was made that the materials were homogenous and linear and that they had elastic material behavior characterized by two material constants viz. Young's modulus and Poisson's ratio [Table 1].[3]

Application of forces

For model, FEA was realized by applying 300 g intrusive force to each dental segment and 100 g of force applied to each mini-implant.

By using the FEM, the initial vertical displacement of the posterior teeth and the Von Mises stress distribution along the root surface were evaluated. To determine tipping movements precisely, vertical displacements of the nodes, having the same coordinates in each model at the root apexes and the cusp tips, were assessed, and superimpositions were used.

Interpretation of results

Stress and displacement were presented as different color bands, which represented different magnitude. Red column of the spectrum indicated maximum level followed by different shades of orange, yellow, green, blue, while dark blue represented the minimum level.

Table 1: Material Properties

	Young's modulus (MPa)	Poisson's ratio
Alveolar bone	1370	0.3
Cortical bone	13700	0.26
Periodontal membrane	0.6668	0.49
Teeth	19613.3	0.15
Stainless steel	200000	0.3

RESULTS

The result of an analysis is called post-processing. Stresses were calculated and presented in colorful bands, different colors represented different stress levels in the deformed state. Red column of spectrum indicates maximum principal stresses and following colors such as orange, yellow, green, and blue represent decreasing level of stress.

The results were obtained as distribution of stresses and displacement of the teeth and periodontal ligament.

On application of 300 g of intrusive force by three mini-implants, two of which were placed on mesial and distal aspect of buccal surface of first molar and one in palatal surface between two molars and a transpalatal arch connecting the first molars.

Von Mises stress contours of periodontal ligament

First molar

The maximum Von Mises stress was observed at cervical region of mesiobuccal root (0.075 N/mm^2). The distal surface of middle third for the mesiobuccal, distobuccal, and palatal roots in middle third showed high stress values (0.050 N/mm^2). However, apical one-third of all the three roots showed low stress values (0.017 N/mm^2).

Second molar

The maximum Von Mises stress was observed at cervical third and middle third of buccal root (0.042 N/mm^2). Low stresses were recorded in the apical region. (0.017 N/mm^2).

Second premolar

The maximum Von Mises stress decreased from cervical third (0.058 N/mm^2) followed by middle third (0.050N/mm^2) and apical third (0.017 N/mm^2) of the buccal root [Figure 3].

Von Mises stress contours of posterior teeth

First molar

The maximum Von Mises stress was evident at the site of force application on the crown on the buccal surface (17.019 N/mm^2).

Second molar

The maximum Von Mises stress was registered at the site of force application on the buccal surface (11.357 N/mm^2) which was lesser than first molar and second premolar.

Second premolar

At the site of force application, maximum Von Mises stress was seen (13.244 N/mm^2) on the buccal surface [Figure 4].

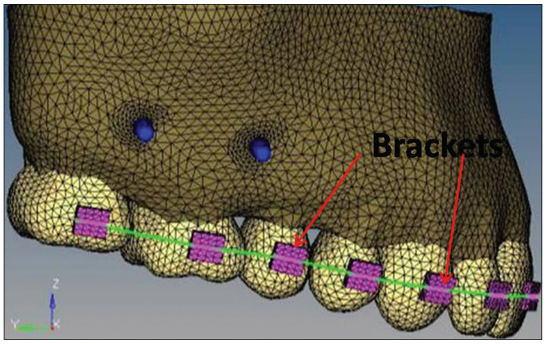

Figure 1: Finite element model with brackets full dimensional wire and mini-implants (buccal view)

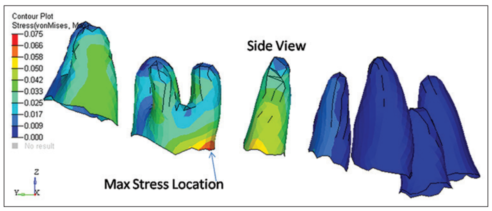

Figure 3: Von Mises stress contours of periodontal ligament

The maximum displacement contours of teeth as follows

First molar

Crown

The maximum displacement was recorded on the middle part of buccal and palatal surface of crown (0.0057 mm).

Among the cusps, maximum displacement was evident at palatal cusps (0.0045 mm) as compared to mesiobuccal (0.0039 mm) and distobuccal cusps (0.0035 mm).

Root

The maximum displacement was recorded for palatal root (0.0024 mm).

Second molar

Crown

The maximum intrusion was recorded at the middle part of buccal surface (0.0037mm) at the site of force application.

The maximum displacement observed was more at buccal cusps as compared to palatal cusps. The readings were mesiobuccal cusp (0.0027 mm), distobuccal cusp (0.0025 mm), mesiopalatal cusp (0.0016 mm), and distopalatal cusp (0.0017 mm).

Root

The maximum displacement was at the buccal root (0.0011 mm) [Figures 5-7 and Table 2].

Second premolar

Crown

The maximum displacement was recorded at the middle part of the buccal surface (0.0046 mm) at the site of force application.

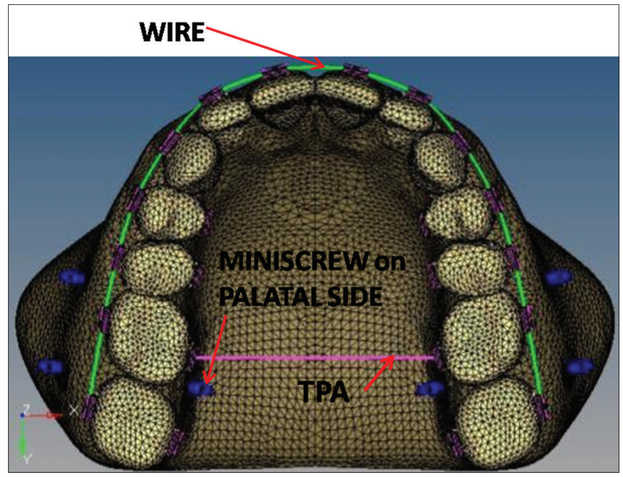

Figure 2: Finite element model showing brackets, mini-implants and transpalatal arch occlusal view

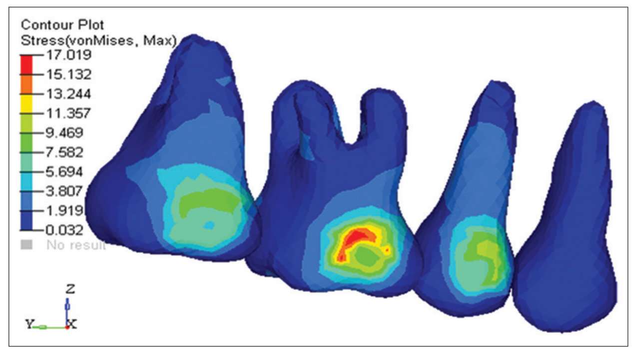

Figure 4: Von Mises stress contours of teeth

The maximum displacement was observed at the buccal cusps as compared to palatal cusps. The readings were buccal cusp (0.0032 mm) and palatal cusp (0.0017 mm).

Root

The maximum displacement was at the buccal root (0.0014 mm).

DISCUSSION

Intrusion of the posterior teeth has been a difficult issue in orthodontics because of the lack of anchorage. During conventional orthodontic treatment for intruding overerupted molars, it is difficult to avoid the side effect of extrusion of the anchorage teeth. Some appliances such as high-pull headgears could be used for molar intrusion, but the patient's compliance is essential.[5] Temporary anchorage devices have allowed clinicians to gain anchorage from many different sites for balanced intrusion with minimal side effects. But, there are still unclear data concerning the biomechanical issues.

This FEM study was carried out to evaluate the effects of various posterior intrusion mechanics with mini-implant anchorage. In FEM studies, the reliability of the results depends on the accuracy of the models. In this study, to

Table 2: Vertical displacement at the nodes of the cusp tips

Direction	Second Molar				First Molar				Second Premolar	
	A	B	C	D	A	B	C	D	A	B
X	-0.0013	-0.0018	-0.0012	-0.001	0.0006	0.0006	0.0011	0.0011	-0.0021	-0.0017
Y	0.0003	0.0003	-0.0001	-0.0001	-0.0006	-0.0004	-0.0001	-0.0001	0.0003	0.0005
Z	0.0025	0.0027	0.0016	0.0017	0.0035	0.0039	0.0045	0.0045	0.0032	0.0017

X mesio-distal, Y bucco-lingual, Z axial

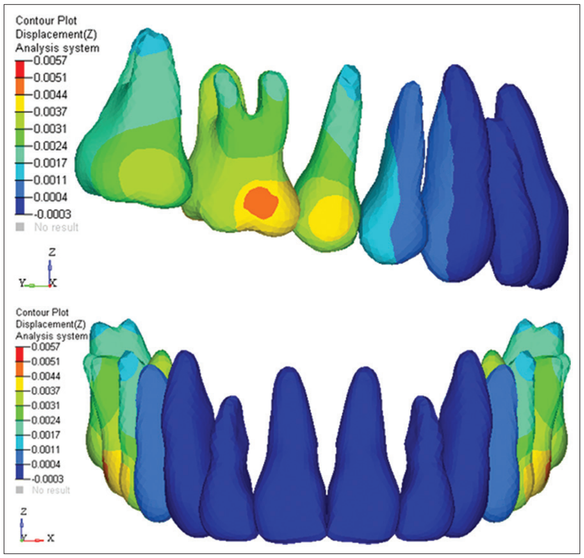

Figure 5: Displacement contours of teeth

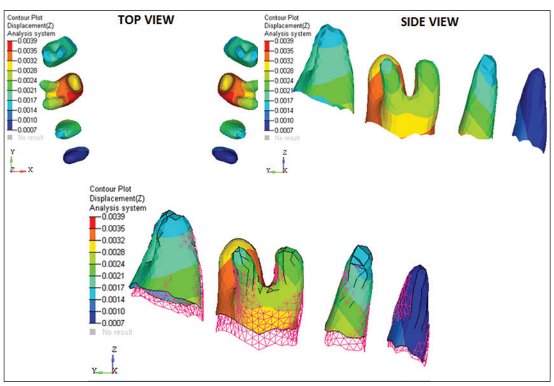

Figure 7: Displacement contours of periodontal ligament showing superimposition

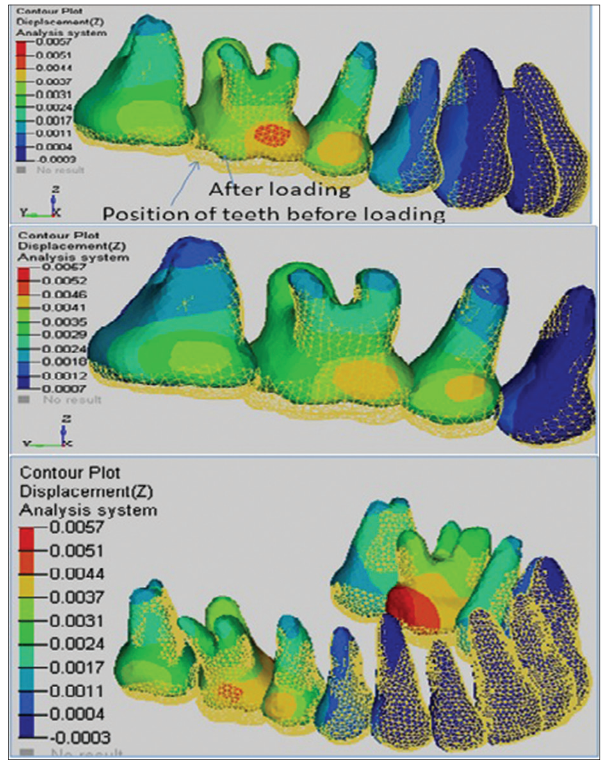

Figure 6: Displacement contours of teeth showing superimposition

maximize the similarity of the models with the maxilla, models were generated from CT images. In addition, maxillary cortical bone thicknesses were generated manually; this is an important parameter in tooth movement. Another parameter affecting the precision of the FEA is the number of elements and nodes comprising the models.

Çifter *et al.*[6] studies three models in which various combinations of mini-implants and transpalatal arches were used, In model 1:Four mini-implants with no transpalatal arch, model 2:two mini-implants with two transpalatal arches, and model 3: one mini-implant with one transpalatal arch. The results of this study suggest that the apical region of the first premolar root and the apical region of the first molar mesial root should be considered to be prone to resorption during posterior intrusion treatment. Posterior intrusion systems with force application from counterbalancing sites lead to a more uniform stress distribution and balanced intrusion than the mechanics with a transpalatal arch. In our study, using three mini-implants and a transpalatal arch, true intrusion was observed, with maximum forces acting on the site of delivery force to the crown and in the middle one-third region for the periodontal ligament.

In our study, increased Von Mises stress values were observed in mesio-cervical region of first molar (0.075 N/mm^2). The middle third of second premolar and second molar and regions adjacent to force application sites also showed relatively high stress values. Minimum stress values were observed in the apical region of first premolar as it is away from force application and no force applied on palatal surface. Hence, root resorption chances are very less.

The maximum intrusion value was evident at the palatal cusps of first molar (0.0045 mm) followed by the buccal cusps of the first molar (0.0039 mm). Intrusion values decreased from the first molar to the anterior and posterior of the dental segment. Minimum intrusion values were observed at the palatal cusps of first premolar (0.0017 mm). The slight buccal tipping of the teeth can also be realized from slight variation of intrusion between the buccal and palatal cusps except for first molar. As per the results, no tipping was observed at first molar root during intrusion, transpalatal arch was used to inhibit buccal tipping.

In clinical situations, extrusion of the palatal cusps can create interferences between the antagonist teeth and lead to a decreased overbite. However, the static FEA used in this study only simulated the initial tooth movement in the periodontal membrane because of the extremely large difference between Young's modulus of the periodontal membrane and the bone layers. In clinical situations, if a transpalatal arch with sufficient resistance used, it will exhibit its uprighting effect through a long-term process of bone remodeling, and most of the initial interferences will disappear with time of the palatal cusps.

Thus, in most open-bite patients, it is crucial to prevent buccal tipping during posterior intrusion. With simultaneous force applications from the buccal and palatal sides, this can be easily controlled. However, through mechanics with buccal force application and transpalatal arch, the horizontal component of the forces at each segment should be intersegmentally balanced. For this process to have a sufficient force transition between the segments, the resistance of the transpalatal arch should be adequate, and the connection between the transpalatal arch and teeth has to be rigid. No buccal tipping was observed due to sufficient resistance of the transpalatal arch. Clinically, with similar force levels, a thicker transpalatal arch would lead to better stress distribution and better buccal tipping control. In this study, the connection between the teeth and the transpalatal arch was considered to be fully bonded. In clinical applications, a welded or soldered connection would be appropriate to prevent any rotational movement at this junction.

The use of four mini-implants is biomechanically ideal, but the clinical application and acceptability can be difficult because four mini implants on each side will be too much for the patient. In our study where three mini-implants and transpalatal arch were used, the results obtained more effective intrusion with lesser concentration of stresses in the apical area was recorded.

Because of individual variations, it is essential to use unique mechanics and force systems for each patient. Even with perfect mechanics and exact force systems, after the initial tooth movement, the biomechanical effect of the force system changes, and modifications are required during treatment. Any study using static FEA only simulated the initial tooth movement in the periodontal membrane and the initial stress distribution along the root surfaces. At the present state of our knowledge, it is impossible to derive what precisely happens over certain length of time, when the same loading conditions continue. This drawback applies to the present investigation also. During the treatment cycle, ongoing movements and stresses can differ because of the changes in force systems and biologic responses.

Other limitations of this study were the constant values used for the physical properties of the tissues, which would normally alter clinically through the histologic process, and the assumption that the periodontal membrane was homogeneous, isotropic, and uniform in thickness. These limitations can cause differences between clinical applications and simulation studies. Also, because of individual variations, it is impossible to simulate an exact mathematic model to validate each case. However, similarities between the results of this study and clinical studies with parallel mechanics show that the finite element models generated were accurate enough to simulate clinical conditions.[5]

CONCLUSION

By using three mini-implants and transpalatal arches, this study demonstrates that significant amount of true intrusion of maxillary molars could be obtained with lesser concentration of stresses in the apical area recorded.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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