Comparison of Stress Distribution and Displacement of Skeletal, Dental, and Dentoalveolar Units in Slow Maxillary Expansion Using Quad Helix and Nickel Titanium Palatal Expander-2: A Finite Element Study

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Abstract

Introduction: Slow maxillary expansion is a common procedure for space gain in orthodontics. It has been used to correct maxillary transverse deficiencies. Several appliances, such as NiTi Palatal Expander-2 (NPE-2) and Quad Helix have emerged as some of the efficacious expanders. This finite element study was aimed at evaluating the stress distribution and displacement of skeletal, dentoalveolar, and dental units using Quad Helix and NPE-2 on a dry human skull.

Aims and objectives: The aim of the study was to compare three-dimensional stress distribution and displacement of skeletal, dentoalveolar, and dental units using Quad Helix and NPE-2.

Materials and methods: CT scan images of maxilla, Quad Helix appliance and NPE-2 were generated and converted to geometric model and then into finite element model for analysis. The expansion force was kept constant at 350 g for NPE-2 and 398 g for the Quad Helix model.

Results: Maximum stress was seen from canine-to-molar region in cortical bone and between central incisors in cancellous bone with both the appliances but the magnitude of stress generated was more with Quad Helix. Stress generated in PDL was more with Quad Helix as compared with NiTi expander-2. Expansion achieved with Quad Helix was greater as compared with NiTi expander-2.

Keywords: Corrective orthodontics, Displacement, Finite element method, Malocclusion, NiTi Palatal Expander-2Displacement, Orthodontics, Quadhelix, Slow maxillary expansion, Stress distribution.

Introduction

Maxillary expansion treatment has been used to correct maxillary transverse deficiencies. Skeletal expansion involves separating the right and the left maxillary halves at the midpalatal suture; dental and dentoalveolar expansion results from buccal tipping of the maxillary posterior teeth.

Slow maxillary expansion produces more physiologic response at the midpalatal suture as compared with rapid maxillary expansion. It provides consistent physiologic stress on the suture and promotes bone growth, thus produces less tissue resistance. Thus, both these factors help to minimize the post-expansion result. Slow maxillary expansion exerts about two pounds of force causing one mm of expansion per week.

Slow palatal expansion is brought about by several devices such as Nickel Titanium Palatal Expander-2 (NPE-2), Quad Helix, Coffin spring, Schwartz appliance, W-Arch, Y plate, Active Plate, etc. Of all these, NPE-2 and Quad Helix are most commonly used maxillary expanders and produce acceptable forces for orthopedic treatment.

Quad helix was designed by Dr Robert M Ricketts in 1975. He proved that Quad Helix exerts a palatal suture widening, as a result, new bone remodeling occurs.

The nickel titanium palatal expander-2 introduced by Wendell V. Arndt in 1993 has twin benefits of shape memory and transition temperature. It provides a constant, slow consistent force for maxillary growth. The expander’s transition temperature (set at 94°F) makes it easier to use its shape memory properties at oral cavity temperature.

Orthodontic research makes use of the finite element method which is an engineering tool used to determine the stress and deformation of complex structures. The FEM is an approximation technique that separates a structure’s region into discrete elements connected at nodes.
Using a finite element model analysis, this study examines the stress distribution and displacement of the craniofacial structures when NPE-2 and Quad Helix forces are applied. Few studies have been done to compare the differences between different slow maxillary expansion techniques; however, some have been done to compare differences between various slow maxillary expansion techniques.

**Materials and Methods**

In this study, a dry human skull was used to create a computer-aided design model. Extraction of maxilla was done from the CT scan images of the human skull which was done in all the plane of spaces (Fig. 1). CT scan data of the skull was processed in Materialise Interactive Medical Image Control System (MIMICS) Version 8.11 and only the region of interest, that is, maxilla was extracted using a thresholding process.

The files were then converted into geometric model and then FE-model was created using HyperMesh software (Fig. 2). Subsequently, geometric model of maxilla was generated along with cortical bone, cancellous bone, periodontal ligament, and teeth. Also, the physical parts like NiTi Expander and Quad Helix Expanders were created using reverse engineering techniques and imported into Hyper Mesh.

Quad Helix was fabricated from 0.9 mm SS wire (Fig. 3). The nickel titanium expander consists of central component which is an innovative palatal attachment (sheath) which is fabricated from a thermally activated nickel titanium alloy (Fig. 4).

Geometric model of maxilla generated was presented in following views: top, occlusal, frontal, rear, left side, right side, isometric view and view illustrating midpalatal suture. Separate models were generated to show the positioning of teeth with and without periodontal ligament (Fig. 5).

Geometric model was converted into FE-model using HyperMesh 2019.1 software which consisted of nodes and elements. Using this software, two finite element models of Quad Helix appliance and NPE-2 were generated (Fig. 6).

The mechanical characteristics of the tooth, cortical bone, cancellous bone, suture, alveolar bone, periodontal ligament, stainless steel, and nickel titanium were specified in the model (Table 1). The total number of elements and nodes created in this model were 2,94,774 and 49,607, respectively.

The 3D FEM model of maxilla with NPE-2 and Quad Helix, cortical and cancellous bone, and teeth with periodontal ligament was constructed (Fig. 7).

The finite element model consisting of nodes and elements of dental, dentoalveolar, skeletal, Quad Helix and NPE-2 were transferred to ANSYS Professional NLS (Version 16; ANSYS Inc.) software to carry out the analysis. In this study, a force of 350 g was used in case of NPE-2 model and the force of 398 g was applied on the Quad Helix model.
The nodes of midpalatal suture element that were generated in this study were symmetrically positioned and unrestrained. The appropriate boundary conditions were established, and all other cranial nodes that were placed on the symmetric plane were restricted. Additionally, a boundary condition with zero-displacement and zero-rotation was applied to the nodes along the foramen magnum.

RESULTS
The results were divided into two sections: Stress distribution and displacement of various structures in all planes (X – transverse, Y – sagittal, Z – vertical).

Stress Distribution
After the expansion force of 350 gm and 398 gm was applied with NPE-2 and Quad Helix respectively, it was observed that very minimal stresses were seen distributed throughout the crown portion of central incisor, lateral incisor and canine which were not significant, and maximum Von Misses stresses were seen on the cervical portion of these teeth. While in the first, second premolar and first molar, maximum stress was observed on the middle-third portion of the palatal aspect of crown. In cortical bone, maximum stress was seen from canine-to-molar region with both NPE-2 and Quad Helix appliances but the magnitude of stress generated was comparatively more with Quad Helix. In cancellous bone, it was seen that the maximum amount of stress generated was between the central incisors regardless of the appliance used but Quad Helix generated more stress as compared with NPE-2 (Figs 8 and 9, Table 2). Stress generated in midpalatal area showed gradual increase postero-anteriorly with both the appliances. Lesser stress magnitude was observed with NPE-2 when compared with Quad Helix (Fig. 10).

Stress generated in PDL was more with Quad Helix as compared with NPE-2 but the amount of stress around the root apex of all the teeth with both the appliances was relatively low (Figs 11 and 12, Table 2).

Displacement
It was observed that although the expansion achieved with Quad Helix was greater as compared with NPE-2, the difference was not much significant. Maximum expansion was observed in canine-to-molar region with the Quad Helix, and with NPE-2, the expansion was maximum in the premolar region. Both the appliances showed opening of midpalatal suture, and the maximum amount of displacement was observed at the posterior region with higher magnitude in Quad Helix appliance. The anterior opening of midpalatal suture was almost same with insignificant difference of displacement with both the groups (Fig. 13, Table 2).

DISCUSSION
In young patients, slow maxillary expansion is said to provide the maximum rate at which the mid-face sutures can adapt, with minimum tearing and hemorrhaging compared with rapid maxillary expansion. Due to the forces exerted by the expanders, periodontal ligament fibers pull was generated in the midpalatal suture area, there was bending of alveolar bone and cortical bone leading to opening of midpalatal suture with maximum stress of 0.036 MPa and 0.061 MPa with NPE-2 and Quad Helix, respectively, in the anterior most part of midpalatal suture which gradually decreased to the middle part and was further reduced to 0.004 MPa and 0.008 MPa with NPE-2 and Quad Helix, respectively in the posterior region of the midpalatal suture. These findings are in agreement with the study done by Kapadia et al. and Shetty et al. However, Sandlkolu and Hazar and Kumar et al. showed more expansion in the posterior region of the palate which is not in agreement with this study. After the activation of appliance, orthopedic forces were transferred to the periodontal ligament and cortical and cancellous...
Fig. 5: Geometric models of maxilla: top view, occlusal view, frontal view, rear view, right view, left view, isometric view, midpalatal suture defined, model showing cortical bone and cancellous bone.
bone; however, stresses were of very low magnitude. This could be attributed to the orthopedic expansion forces that radiate to the base of medial pterygoid plate and then branched superiorly to the malar and zygomatic bones.\textsuperscript{11} As the forces were distributed to a larger area, so minimal forces were observed in the cortical and cancellous bone. These findings were in agreement with studies done by Kumar et al.,\textsuperscript{3} Sandikolu and Hazar,\textsuperscript{10} and Jafari et al.\textsuperscript{12}

Finite element investigation by Preeth Shetty et al.\textsuperscript{9} and Marzban and Nanda\textsuperscript{13} found that the stress distribution of NPE-2 was of low magnitude and uniform throughout the maxilla, which was similar with the results of the present study. Similar to the findings

Table 1: Material property data representation

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus (N/mm\textsuperscript{2})</th>
<th>Poisson’s ratio (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth</td>
<td>$2.07 \times 10^4$</td>
<td>0.30</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>$1.37 \times 10^4$</td>
<td>0.30</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>$7.9 \times 10^3$</td>
<td>0.30</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>50</td>
<td>0.49</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>$2.1 \times 10^5$</td>
<td>0.3</td>
</tr>
<tr>
<td>Nickel titanium</td>
<td>$44 \times 10^3$</td>
<td>0.33</td>
</tr>
<tr>
<td>Suture</td>
<td>7</td>
<td>0.40</td>
</tr>
</tbody>
</table>
of this study, some stresses were observed at the palatal portion of the bone covering the molars, premolars, and central incisors.

In a study conducted by Kapadia et al.\textsuperscript{8} it was found that stresses of low magnitudes were seen on the contact point between central incisors, cusp tip of canines, cemento-enamel junction of central incisors and canines, the findings were consistent with the results of the present study in which even lower magnitude of stresses were observed in all these areas.

Among skeletal landmarks, the anterior tip of the mid-palatine suture showed the highest stress concentration with both the expansion appliances which substantially reduces toward the posterior end. These results concur with the study conducted by Kapadia et al.\textsuperscript{8} and Shetty et al.\textsuperscript{9}

In a study conducted,\textsuperscript{14–16} it was found that there was a significant increase in the inter-canine width and inter-molar width because of the action of the Quad Helix appliance. The findings were consistent with the results of the present study in which the greatest amount of expansion with Quad Helix was seen in the canine and molar region.

However, both models in the current investigation showed stronger anterior expansion of the midpalatal suture than in the posterior region.\textsuperscript{17,18} Sandikolu and Hazar\textsuperscript{10} achieved more posterior

<table>
<thead>
<tr>
<th>Teeth</th>
<th>Region</th>
<th>NiTi Expander-2</th>
<th>Quad Helix</th>
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<tbody>
<tr>
<td>Central incisor</td>
<td>Tip</td>
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<td>0.001</td>
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<td></td>
<td>CEJ</td>
<td>0.8</td>
<td>1.28</td>
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<tr>
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<td>Apex</td>
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<tr>
<td>Lateral incisor</td>
<td>Tip</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>CEJ</td>
<td>1.79</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Apex</td>
<td>0.79</td>
<td>0.91</td>
</tr>
<tr>
<td>Canine</td>
<td>Tip</td>
<td>0.013</td>
<td>0.031</td>
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<td>CEJ</td>
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<td>5.85</td>
</tr>
<tr>
<td></td>
<td>Apex</td>
<td>0.98</td>
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</tr>
<tr>
<td>First premolar</td>
<td>Tip</td>
<td>0.023</td>
<td>0.37</td>
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<tr>
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<td>CEJ</td>
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<td>Apex</td>
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</table>
Stress Distribution and Displacement of Skeletal, Dental, and Dentoalveolar Units in Slow Maxillary Expansion

Fig. 11: Stress distribution in periodontal ligament in central incisor, lateral incisor and canine with NPE-2 and Quad Helix

Fig. 12: Stress distribution in periodontal ligament in first, second premolar and first molar with NPE-2 and Quad Helix
expansion of the palate in his study. The difference in the current study could be attributed to the various expansion forces and levels of posterior activation.

The findings of the current study, which used a three-dimensional FEM model of a human maxilla, added to our understanding of the mechanical reactions of the bony tissue, which are the initial stages of the complicated process of tissue response to maxillary expansion.

**Conclusion**

Quad Helix and NPE-2 provide adequate forces for orthopedic treatment even after being used as orthodontic appliances; nevertheless, due to the fact that these devices’ effects are mostly age-dependent, clinical application of these devices needs to be carefully planned. Both of these devices can be utilized in place of one another as expansion appliances when skeletal alterations are needed at a younger age. The following conclusions from this study were drawn:

- Both the slow expansion devices studied herein were capable of producing skeletal expansion apart from their known dental and dentoalveolar effects.
- For both the models, maximum Von Misses stresses was observed on the first, second premolar, and first molar. Stress generated at root apex and periodontal ligament was more with Quad Helix as compared with NPE-2 but the magnitude of stresses was relatively low with both the appliances.
- Stress generated in midpalatal area showed gradual increase postero-anteriory with both the appliances.
- Maximum expansion was observed in the canine-to-molar region with both Quad Helix and NPE-2, but the expansion was relatively more with Quad Helix. Quad Helix is made of stainless-steel wire and exerts more force with each activation, whereas the NPE-2 is composed of shape memory NiTi wires, which produces gentler forces and does not require frequent activations. Hence, keeping the NPE-2 for a slight longer duration will give the desired expansion with less stresses in the teeth and surrounding structures.

**References**


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**Fig. 13:** FEM model with NPE-2 and Quad Helix showing expansion