Study of Stress Distribution and Displacement of the Maxillary Complex Following Application of Forces using Jackscrew and Nitanium Palatal Expander 2 – A Finite Element Study

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The stress distribution patterns within the maxillary complex during the expansion by slow maxillary expansion plate and Nitanium palate expander 2 was analyzed. ***Objective:*** *This comparative study was done using a finite element model of a young maxillary bone. The model was generated using the data from computerized tomographic scans of a dried maxillary bone. The model was then strained to a dimensional pattern of displacement and stress distribution for the two appliances.* ***Results:*** *This present study showed the maximum lateral displacement for jack screw by 0.170mm at the region of cusp tips of posteriors indicating a tipping movement. Whereas NPE2, showed maximum displacement of 0.004mm corresponding to maxillary molars. Concentration of stress distribution ranging from 343.42 N/mm² to 412.60 N/mm² for 0.5mm of expansion was significantly depicted at the palatal bone beside the central incisors for jack screw, when compared to NPE2 which depicted low magnitude of stress ranging from 7.78 N/mm² to 9.08 N/mm² uniformly distributed along the midpalatal suture.* ***Conclusions:*** *The findings of this study suggests that NPE2 appliance basically an orthodontic appliance however is capable of producing mild to moderate orthopedic changes in maxilla.*

Keywords: *Finite element method (FEM), Stress distribution, Maxilla, NPE2, Jackscrew.*
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INTRODUCTION

Narrow maxilla or the maxillary arch discrepancy in the transverse plane has been recognized for a long time. Timely treatment of such transverse discrepancies by means of maxillary expansion during the primary or transitional dentition is recommended to re-establish optimal function in order to normalize dental, skeletal and neuromuscular growth during these times of active changes.[1–4]

Slow maxillary expansion produces more physiologic response at the mid palatal suture area which is opened at the same rate at which it is repaired. It produces less tissue resistance in the suture and allows better bone formation. Both these factors help to minimize the post-expansion relapse.[5, 6]

Nitanium palatal expander 2 (NPE2) delivers a uniform slow, continuous force for maxillary expansion, molar rotation and distalization and arch development. NPE2 delivers a force of 350gms for every 3 mm of increment. This expander has a transition temperature of 94ºF facilitating its action as the temperature in the oral cavity increases and restores shape memory. The appliance begins to exert a light continuous force on the teeth and palatal suture with the rise in temperature.[7]

Where are the areas of maximum force concentration? Is there possibility for a slow expansion to produce orthopedic forces in maxillary complex and if so which structures affected most? Is NPE2 better than Jack screw in producing forces to affect other skeletal tissues of maxillary complex? These questions were difficult to answer using the conventional methods. During expansion process, the maxillary complex is subjected to complex loading and it would be difficult to assess the mechanical reaction of this maxillary complex to this loading in three dimensional space by using conventional methods namely, strain gauge, photoelastic or laser holographic techniques. But in recent years, finite element (FE) analysis has been introduced to dentistry as a powerful research tool for solving various structural mechanical problems. It is recognized as a general procedure for mechanical approximation to all physical problems that can be modeled by deferential equation description.

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FE analysis has been applied to the description of physical form changes in biological structures, particularly in the form of growth and development and restorative dentistry. There are broadly two applications in biomechanical studies. One is the analysis of stress and strain with a given force system applied to the teeth or the cranial complex. The other is the evaluation of the craniofacial growth with the given skeletal displacement observed during the growth changes,[8]

This study explored the displacement and stress distribution in the maxilla by slow maxillary expansion appliances like jack screw and NPE2 using Finite element analysis.

MATERIAL AND METHODS

Preparation of Maxillary Model

The analytical model was developed from a dry young human maxillary bone with an approximate age of 13 years. The maxillary bone was checked for the full complement of the permanent dentition and gross defects or discontinuity in the craniofacial anatomy.

CT scan images of the maxillary bone were taken in axial direction, parallel to the occlusal plane. Sequential CT images were taken at 1 mm. intervals to reproduce finer and detailed aspects of the geometry. This methodology of model creation was aimed at improving over the previous methodologies where sections were taken at 5 and 10 mm. respectively. [9, 10]

Individual CT scan sections were imported into the AUTOCAD as a raster image and were traced, taking care so as not to distort the anatomy of the region. Each traced sections were then placed one above the other to give a maxillary model in AUTOCAD. This novel technique helped in minimizing the human error during model preparation in earlier studies.

This block was then imported into UNIGRAPHICS, the geometric modeling software present in the FE modeling software (ANSYS 7.1). This step was to generate geometric areas by joining lines.

The next step was to convert the geometric model into a FEM. The geometric entities created in the previous step were replaced with finite elements and nodes at this stage. The complete geometry is now defined as an assemblage of discrete pieces called elements and are connected together at a finite number of points called nodes. In this study 3-D 10 nodal tetrahedral solid element commercially named as SOLID92 was used as an element type. SOLID92 has quadratic displacement behavior and is well suited to model irregular shapes. The element is defined by ten nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions. The element also has plasticity, creep, swelling, stress stiffening, large deflection and larger strain capabilities. The total number of elements and nodes created in this model were 1, 87,134 and 2, 33,138 respectively.

Defining Mechanical properties to the model

The mechanical properties of the compact and cancellous bones,[9] suture,[11] acrylic[12] and teeth[9] in the model were defined according to the experimental data in previous studies as shown in Table 1.

Table 1. Material property Data representation:

Material	Young's Modulus (Newton/mm^2)	Poisson's Ratio
Tooth[14]	20.3 X 10^3	0.3
Compact bone[14]	13.7 X 10^3	0.3
Cancellous bone[14]	79 X 10^2	0.3
Suture[10]	6.9	0.49
Acrylic[11]	2400	0.35

Laying boundary conditions

Restrains were established at all nodes lying at the frontal and zygomatic process of the maxillary bone lying on the symmetric plane and appropriate boundary conditions were imposed. It is a well known fact that the midpalatal suture separates after initial application of orthopedic forces.[2, 5] Even though the midpalatal suture element was created in this study, the nodes of this suture that were placed on the symmetrical plane were left unconstrained. This was done to investigate the stress distribution in the maxillary complex during palatal expansion. (Figure 1)

In this study a force of 350 gms.[7] was used in case of NPE2 model and for the Jack screw expansion appliance the two plates of the expansion plate were moved apart by a distance of 0.25 and 0.50 mm.. (It is based on each quarter turn).

The displacements, von Mises stresses in different parts were studied. Von Mises is a criteria used in predicting the onset of yield in ductile materials. (In simple words von Mises stress, is a calculation which takes complicated loads

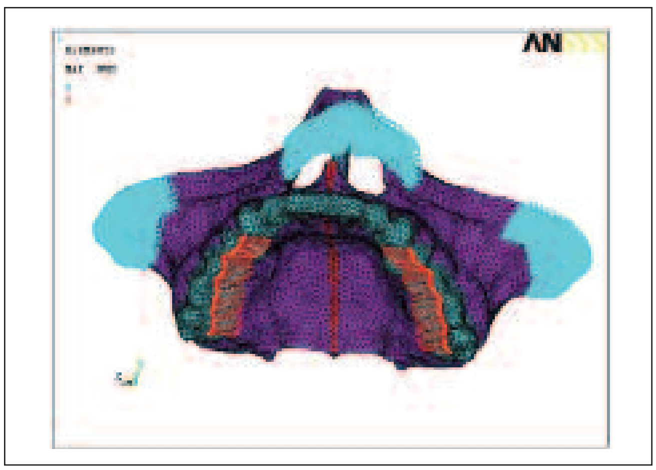

Figure 1. Finite element model of maxilla with boundary conditions assigned—The boundary conditions in the finite element model basically represent the load imposed on the structures under study and their fixation counter parts. The points at the frontal process and the zygomatic process were constrained to have no motion in any direction. However, the two parts of the palatine bone, which were separated by the vertical plane of symmetry, was assumed to be unconnected so that they move freely in lateral direction with respects to the vertical plane of symmetry. Therefore the points at the midpalatal suture were left completely unconstrained.

like twisting, bending, shearing on any material and figures out what their stretching equivalent is.) In this study the stress distribution pattern was analyzed; the results were generated along the maxillary bone.

RESULTS

The biomechanical changes seen in this study were evaluated under the headings

- Displacement of different structures in the maxillary complex for Jack screw and NPE2
- Stress distribution in the maxillary complex for Jack screw and NPE2

The displacements, von Mises stresses in different planes were studied and the stress distribution patterns were analyzed; the results were tabulated (Table II – Table V)

Maximum X-displacement (lateral displacement) of 0-077 mm. and 0.1540 mm. was seen which corresponds to cusp tip of maxillary first and second molars for jackscrew expansion of 0.25 and 0.5 mm respectively. Maximum lateral displacement for NPE2 was 0.0040 mm which corresponds to upper molars. Maximum negative Y–displacement (backward displacement) of 0.097 to 0.195 mm was seen representing the upper central incisors for jackscrew expansion of 0.25 and 0.50 mm respectively. Maximum backward displacement of 0.0014 mm was seen representing the base of nasal septum for NPE2. Maximum negative Z-displace-

Table II. Computational results of the Transversal (X), Sagittal (Y) and Vertical (Z) displacement of various skeletal structures of the maxillofacial complex following 0.25 mm expansion by the Jack screw

Region	Selected nodes on	X (mm.)	Y (mm.)	Z (mm.)
DentoAlveolar	Cusp tip of Central Incisor	0.0081	-0.097	-0.0299
	Cusp tip of Canine	0.0541	0.0347	-0.0083
	Cusp tip of First permanent molar	0.0770	0.0450	-0.0127
	Apical region of Central Incisor	0.0119	-0.0157	-0.0339
	Apical region of Canine	0.0269	0.0012	-0.3130
	Apex region of First permanent molar	0.0473	0.0178	0.0229
Palate	Anterior	0.0424	-0.0188	-0.0583
	Posterior	0.0182	-0.0041	-0.0681
Nasal	Nasal septum	0.0192	-0.0256	-0.0536
	Anterior nasal spine	0.0105	-0.0157	-0.0494
Zygomatic	Zygomatic Process	0.0401	0.0107	0.0072

Table III. Computational results of the transversal (X), Sagittal (Y) and vertical (Z) displacement of various skeletal structures of the maxillofacial complex following 0.5 mm expansion by the Jack screw

Region	Selected nodes on	X (mm.)	Y (mm.)	Z (mm.)
DentoAlveolar	Cusp tip of Central Incisor	0.0162	-0.195	-0.0598
	Cusp tip of Canine	0.1081	0.0694	-0.0165
	Cusp tip of First permanent molar	0.1540	0.0900	-0.0253
	Apical region of Central Incisor	0.0259	-0.0336	-0.0887
	Apical region of Canine	0.0557	0.0026	-0.0628
	Apical region of First permanent molar	0.0968	0.0377	-0.0437
Palate	Anterior	-0.0848	-0.0377	-0.1165
	Posterior	0.0365	-0.0081	-0.1363
Nasal	Nasal septum	0.0363	-0.0493	-0.1252
	Anterior nasal spine	0.0245	-0.0323	-0.1048
Zygomatic	Zygomatic process	0.0810	0.0223	0.0143

Table IV. Computational results of the transversal (X), Sagittal (Y) and vertical (Z) displacement of various skeletal structures of the maxillofacial complex following expansion by NPE2

Region	Selected nodes on	X (mm.)	Y (mm.)	Z (mm.)
DentoAlveolar	Cusp tip of Central incisor	0.0002	0.0004	-0.0013
	Cusp tip of Canine	0.0020	0.0020	-0.0004
	Cusp tip of First permanent molar	0.0040	0.0031	-0.0006
	Apical region of Central Incisor	0.0120	-0.0157	-0.0339
	Apical region of Canine	0.0269	0.0012	-0.3130
	Apical region of First permanent molar	0.0473	0.0178	0.0229
Palate	Anterior	0.0002	0.0004	-0.0009
	Posterior	0.0001	0.0002	-0.0075
Nasal	Nasal septum	0.0004	-0.0014	-0.0012
	Anterior nasal spine	0.0012	-0.0013	-0.0024
Zygomatic	Zygomatic process	0.0004	-0.0011	-0.0004

Table V. von Mises stresses seen at various structures in the maxilla

Type of expansion	Region	Selected nodes on	von Mises stress N/mm^2
0.25 mm	Palate	Anterior	309.46
		Posterior	16.67
	Nasal	Nasal septum	3.06
		Anterior nasal spine	6.07
	Zygomatic	Zygomatic process	27.11
0.5 mm	Palate	Anterior	618.91
		Posterior	24.45
	Nasal	Nasal septum	7.52
		Anterior nasal spine	14.28
	Zygomatic	Zygomatic process	50.16
NPE2	Palate	Anterior	7.68
		Posterior	3.84
	Nasal	Nasal septum	3.90
		Anterior nasal spine	2.68
	Zygomatic	Zygomatic process	2.25

ment (downward displacement) of 0.029 to 0.0598 mm was seen representing the upper central incisors for jack screw expansion of 0.25 and 0.50 mm respectively. Maximum downward displacement for NPE2 was 0.0013 mm which corresponds to the upper central incisors.

The magnitude and distribution of von Mises stresses produced at various parts of the maxillary complex by activation of both the expansion appliance. (Table V). The areas of the stress are shown with the help of different colors. The pellets of colors representing the tensile and compressive stresses are shown just below the diagram. (Figures 2 and 3)

Using the computer generated color diagrams the following results were obtained.

Magnitude and distribution of maximum von Mises stresses produced at various areas of the maxillary complex by activation of expansion plates by 0.25, 0.5mm and by NPE2 are shown.

The image (figure 4) here represents the von Mises stress distribution in the maxillary complex with 0.25mm of expansion by the expansion plates. Here the maximum concentration of stress of 309.45 Newtons/mm^2 (N/mm^2) was seen at the palatal region of the central incisors at the tip of midpalatal suture. A stress range from 68.76 N/mm^2 to 103.15 N/mm^2 was seen at the palatal region of the bone surrounding the first, second permanent molar and also the central incisors. Compressive stress of 16.67 N/mm2 was seen at the posterior part of the mid palatal suture.

Since the concentration of stress distribution was more significantly depicted at the central incisors, the less significant stress distribution to other and dental structures were noticed by unselecting the elements at the central incisors (figure 5). (*Unselect is a process in ANSYS to remove particular elements from the model for visualization of stress distribution in other areas*.) After unselecting, the stress distribution ranging from 36.22 N/mm^2 to 42.26 N/mm^2 was seen in the palatal bone adjacent to the first and second permanent molars. A uniform stress distribution ranging from 12.07 N/mm^2 to 18.11 N/mm^2 was seen in the palatal shelves, zygomatic arch and fronto-nasal process. A stress of 27.10 N/mm^2 was seen at the zygomatic process. 3.06 N/mm^2 at the nasal septum 12.07 N/mm^2 concentrating at the base of the septum and as high as 36.22 N/ mm^2 at the lateral wall of the nasal cavity respectively.

Stress plotting done for 0.5 mm expansion by the jack screw showed same distribution of the stress on the skeletal and the dental structures but of a higher magnitude. Stresses were concentrated at the palatal bone beside the central incisors ranging from 343.42 N/mm^2 to 412.60 N/mm^2 with

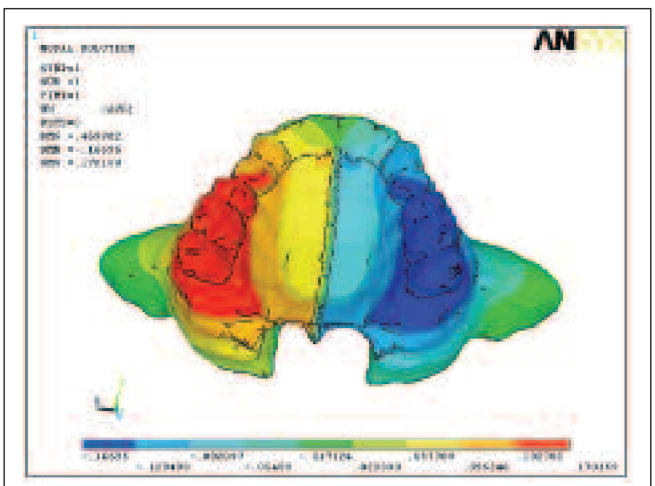

Figure 2. Pattern of transverse (X) displacement in the maxillary complex with 0.50mm expansion with jackscrew. Displacement in the maxillofacial complex in the X axis on activation of expansion on either side is represented by respective colors which denote amount of displacement at different regions.

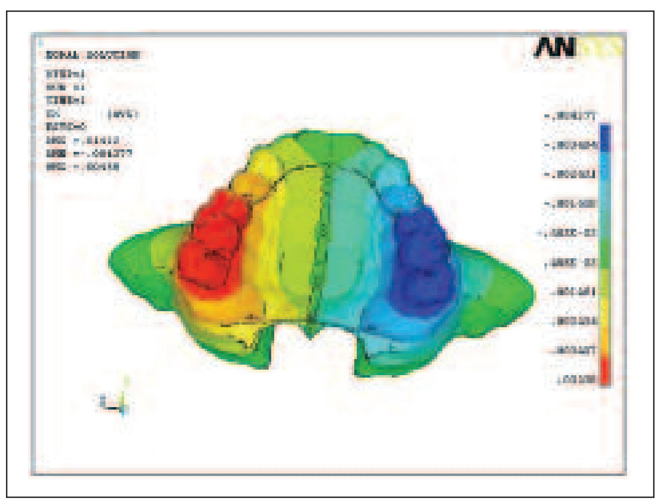

Figure 3. Pattern of transverse (X) displacement in the maxillary complex with NPE2

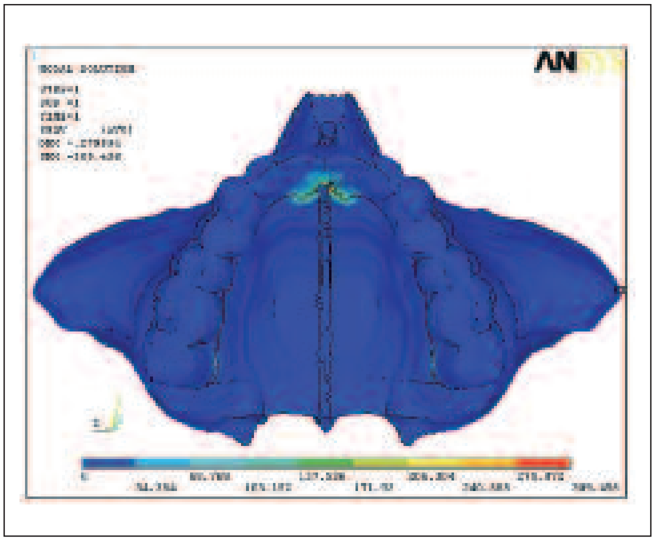

Figure 4. The pattern of computed von Mises stress distribution in the maxillary complex with 0.25mm expansion with Jackscrew. Initial stress images of the three dimensional model of the maxilla shows concentration of stress at the incisor region. The pellets of colors representing the tensile and compressive stresses are shown below the diagram.

a maximum stress of 618.51 N/mm^2 concentrated at the tip of the mid palatal suture. Stress of 24.45 N/mm^2 was seen at the posterior part of the mid palatal suture.

The less significant stress distribution to other dental structures was noticed by unselecting the elements at the central incisors (fig 5). Stress distribution pattern was seen similar to the 0.25 mm expansion, with 60.37 N/mm^2 of compressive stress seen at the palatal bone covering the molars and the premolars. Compressive stress of 50.16 N/mm^2 is seen at the zygomatic process. At the nasal septum 7.52 N/mm^2 was seen.

Stress distribution for the NPE2 was of a low magnitude as compared to the 0.25 mm and 0.5 mm of expansion by Jack screw. Here the concentration of stress was more at the posterior part of the midpalatal suture ranging from 7.78

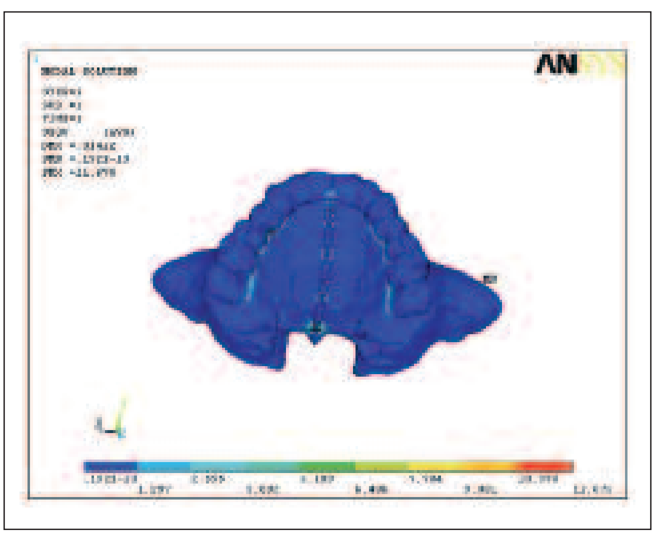

Figure 6. The pattern of computed von Mises stress distribution in the maxillary complex with NPE2—Uniform stress distribution is seen in this image although it is of lesser magnitude.

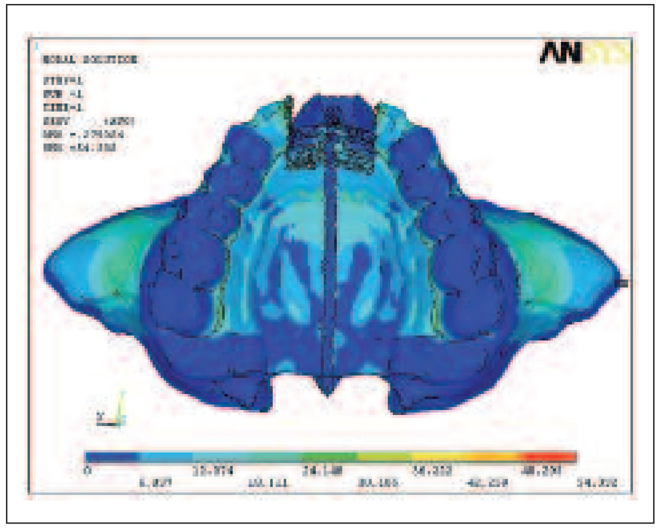

Figure 5. The pattern of computed von Mises stress distribution in the maxillary complex with 0.25mm expansion Jackscrew after unselection. By unselecting the incisor region the lesser stress distribution is visualized in other areas of the maxilla.

N/mm^2 to 9.08 N/mm^2. A range of 2.59 N/mm^2 to 3.89 N/mm^2 was seen at the palatal part of the bone covering the molars, the premolars, the central incisors and also uniformly distributed along the midpalatal suture (fig 6). Stress concentration ranging from 1.247 N/mm2 to 1.496 N/mm^2 was seen at the zygomatic bone and uniform distribution of 0.25 N/mm^2 to 0.50 N/mm2 at the fronto-nasal process.

DISCUSSION

The three dimensional FEM used in the present study provides the freedom to simulate orthodontic force systems applied clinically and allows analysis of the response of the various craniofacial structures to the orthodontic loads in three dimensional space.

The FE analysis has the following advantages: It is a non invasive technique; the actual amount of stress experienced at any given point can be theoretically measured; the tooth, alveolar bone, periodontal ligament and craniofacial bones can be simulated and the material properties of these structures can be assigned to the nearest one that possibly can simulate the oral environment in vitro; the displacement of the tooth can be visualized graphically; the point of application, magnitude and direction of a force may easily be varied to simulate the clinical situation; reproducibility does not affect the physical properties of the involved material; and the study can be repeated as many times as the operator wishes.[8]

FE method is a powerful contemporary research tool and plenty of literature is available on the study of stress distribution and deformation of nonliving as well as natural and restored craniofacial structures affected by three – dimensional stress fields which are difficult to asses otherwise.[8,13-15] But experimental or clinical confirmation of the theoretical prediction should be the goal in any simulation study. In this FE analysis, direct validation of the theoretical results was not possible, therefore the results of the present study were compared with the results of the previously published human studies[2, 3, 16, 17] and were found to be in conformity.

In previous studies on humans[2, 18] or animal skulls[5] it was possible only to determine the response of surrounding bones to high level forces and the experiment could not be repeated. The experimental method employed in this study permitted the visualization of bone reactions, even with the lowest loading degree. One should be aware that the structural and spatial relationships of various craniofacial components vary among individuals. It is important to realize that these factors may contribute to varied responses of the maxillofacial components on loading. Thus, the results of this study are valid only for a single specific human skull.

Maxillary expansion is a very useful procedure for arch length augmentation, treatment of posterior crossbite and correction of cross arch interferences.[19] Expansion of maxilla by means of slow maxillary expansion undoubtedly has created a great impact on the contemporary orthodontic thinking and therapy. In this present study an attempt has been made to understand the displacements and the stress distribution done by two expansion appliances, one being a conventional jack screw and another being the newly introduced Nitanium palatal expander[2].

This present study showed the maximum dental and skeletal effects in the transverse plane. Similar observations have been reported by Alireza.[9] When viewed occlusally, it was found that the palatine plates of the maxilla were separated in a non parallel manner with widest opening being at the ANS and diminishing posteriorly. Wertz[2] study of dry skulls also indicated that shape of the antero posterior palatal separation was not parallel. Similar observations were noticed by Hicks.[3]

Chaconas and Caputo[20] in their photoelastic analysis said that the stress produced by the stable removable appliance was comparatively more than the other fixed appliances like Haas, Hyrax and Minne expander. He also said that the stress produced by these appliance were concentrated in the anterior region of palate with the initial effect observed in the alveolus between the central incisors and radiated towards the incisive foramen. These findings were seen in the present study with 0.25 and 0.5mm of expansion. Similar findings were observed by Haas[6] and Wertz.[21]

Present study has shown that there is a downward and forward displacement of the maxilla except for the slight backward displacement seen at the central incisors and the anterior nasal spine which coincides with other literatures[1, 21] but the final position of maxilla. After completion of expansion is unpredictable and has been reported to return partially[6] or completely[21] to its original position.

During expansion not all changes is caused by alveolar bending, but is partly due to the tipping of teeth in the alveolar bone. This tipping is usually accompanied by some extrusion.[3] Similar findings were seen in the present study where tipping and slight extrusion of the molars were seen.

Ciambotti[22] suggested that the NiTi expansion produces a less obvious radiographic separation of the midpalatal suture when compared to rapid palatal expansion appliance. One possible explanation is that NiTi expansion appliance produce slow continuous forces and physiological sutural adjustment may occur, leading to bony deposition as expansion occurs. Our present study also showed that the lateral displacement of the palate was much less compared to the jack screw expansion appliance (0.25 and 0.5mm).

Though Jack screw incorporated in a removable expansion plates produces orthopedic forces, the efficacy lies in the stability and retention ability of the appliance. Hence the clinician has to fabricate the appliance while keeping the anatomy of the palate in mind.[20] Most of the cases after certain amount of turns the appliance usually displaces out. Hence the efficacy of the appliance is lost. This kind of appliance also requires patient co operation for achieving good results. Since NPE2 is a fixed/ removable expansion appliance producing a slow continuous force which can be controlled by the patient himself gives a better physiologic response and stability and a better patient co-operation. Studies[22-24] has shown that it produces orthopedic forces and requires a shorter retention period and less patient discomfort. Also for the clinician the appliance is placed in the chair side without any laboratory procedures.[7]

The results of the present study using the three-dimensional FEM of a human maxilla provided some additional explanation about the bony tissue mechanical reactions, which are the first steps in the compound process of tissue response to maxillary expansion. Acquaintance with these initial mechanical reactions helps us to understand better the final therapeutic effects and the way the slow expansion appliance actually acts on the surrounding structures including the sutures of the maxillary complex.

CONCLUSION

In this present study we have seen:

- The maximum stress initially is concentrated at the palatal region of central incisors in both jack screw and NPE2.
- NPE2 even though being an orthodontic appliance showed orthopedic changes.
- In both Jack screw and NPE2 maxilla displaced downward and forward with mild posterior displacement of central incisors, anterior nasal spine and nasal septum.
- Concentration of minimal stress was also seen at the zygomatic process and nasal septum in both cases.
- There was a mild increase in the intermolar width in the maxillary arch, which was more with Jack screw as compared to NPE2

Since NPE2 provides a uniform and continuous force as compared to Jackscrew which is localized and periodic (activation dependent), NPE2 makes a fair superior expansion appliance than Jackscrew.

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