Effects Of Transverse Orthopedic Forces On Craniofacial Complex In Adult Human Skull – A Three-Dimensional Finite Element Study

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Abstract

With the increased interest in adult orthodontics, maxillary width problems in the nongrowing individuals have been encountered with greater frequency. In view of the negative outlook for successful nonsurgical palatal expansion in adult patients it seems appropriate to evaluate the biomechanical effects of nonsurgical rapid maxillary expansion (RME) in adults using the finite element method.

The analytical model in this study was developed from a dry human skull of an adult female with an approximate age of 20 years. Known transversal (X) displacement were applied on the maxillary canine and first permanent molar crown. The displacements and Von-Mises stresses in different planes were studied on different nodes located at various structures of the craniofacial complex.

Transverse orthopedic forces not only produced an expansive force at the intermaxillary suture but also high forces on various structures of the craniofacial complex, particularly at the base of the sphenoid bone and frontal process of the zygomatic bone. Lateral bending of the free ends of the pterygoid plates were noted, with increased resistance demonstrated in superior parts attached to the cranial base.

Rapid maxillary expansion must be used judiciously in adults, because of its far-reaching effects.

Key words: *Rapid maxillary expansion, Adult, Finite Element Study.*

Introduction

Interest in use of rapid maxillary expansion (RME) in adult patients has increased markedly during the past two decades. The correction of transverse discrepancies and the gain in arch perimeter as a potential nonextraction technique appear to be the most important reasons underlying this increased interest.[1] Although the major treatment effect is noticed clinically in the area of the dentition, transverse enlargement of the apical base or the skeletal structures throughout the nasomaxillary complex occur simultaneously.

The review by Bishara and Staley[2] and the orthodontic texts by Proffit[3] as well as by McNamara and Brudon[4], all state that the feasibility of palatal expansion beyond the late teens and early twenties is questionable.

This pessimistic view of rapid maxillary expansion in adults is based in part on anatomic studies of the maturing face, which show the midpalatal suture and adjacent circummaxillary articulations becoming more rigid and beginning to fuse by the midtwenties.

In order to overcome the resistance of the adult sutures to expansion, "surgically assisted" rapid maxillary expansion (SA-RME) has been advocated, but this surgery is not free of risks, and it behooves surgeons to be aware of its potential complications.

The aim of the present study was to make use of the finite element method to evaluate the biomechanical effects of RME on the craniofacial complex as applied to three-dimensional model of an adult human skull.

Material and Methods

The analytical model in this study was developed from a dry human skull of an adult female with an

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approximate age of 20 years, selected from the anatomic collection of Government Medical College, Nagpur [Fig. 1].

Fig 1: Dried adult human skull used in this study

Previous studies[5] have used photographs of cross-sections of skull. In the present study, CT scan images of the skull excluding the mandible were taken in the axial direction, parallel to the Frankfort horizontal plane at 1mm intervals to reproduce finer and detailed aspects of the geometry [Fig. 2]. This spacing of CT-images enabled a higher geometric accuracy than that used by Jafari et al (2003; 5 mm)[6]; Iseri et al (1998; 5 mm)[7] and Tanne et al (1989; 10mm).[5]

The CT scan images were read into visualization software – MIMICS. Materialise's Interactive Medical Image Control System (MIMICS) is an interactive tool for the visualization and segmentation of CT images as well as MRI images and 3D rendering of objects

In this model, Tet 10 solid elements (10 noded) were used. The model consisted of 7,13,009 nodes and 3,57,425 Tet 10 elements [Fig. 3].

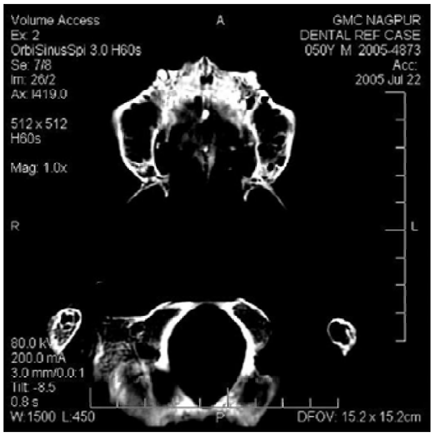

Fig 2: Sample CT slices

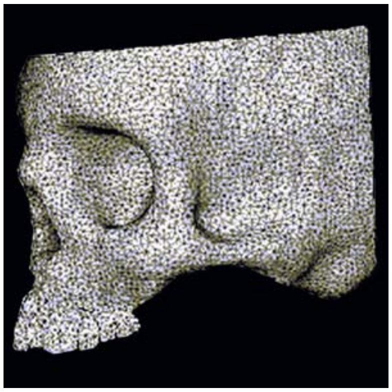

Fig 3: Lateral view of the final 3-D finite element model constructed using Tet 10 solid elements

The materials in the analysis were assumed to be linearly elastic and isotropic. The mechanical properties of the compact and cancellous bones and teeth in the model were defined according to the experimental data in previous studies[5-7] as shown in Table I. All sutures were assumed to have the same mechanical properties as the surrounding bone material except at the palatinal bone.

Table I: Material Properties

Material	Young's Modulus (kg/mm^2)	Poisson's ratio
Tooth	2.07×10^3	0.3
Compact bone	1.37×10^3	0.3
Cancellous bone	7.90×10^2	0.3

The two parts of the palatinal bone that are separated by the vertical plane of symmetry were assumed to be unconnected, so that they moved freely in lateral directions with respect to the vertical plane of symmetry. All other points of the cranium lying on the symmetry plane were constrained to have no motion perpendicular to this plane.

Even though application of a known force is possible with FE modeling, known transversal (X) displacement with magnitudes of 1mm, 3mm and 5mm were applied on the maxillary canine and first permanent molar crown. It was assumed that the two plates of transversal orthopedic appliance moved apart by a total of 2mm, 6mm and 10mm respectively.

The displacements and Von-Mises stresses in different planes were studied on different nodes located at various structures of the craniofacial complex. The stress distribution patterns were analyzed; the results were tabulated and graphically represented.

Results

Displacements of the craniofacial structures were studied in 3 dimensions: transversal – (X) plane, sagittal – (Y) plane and vertical – (Z) plane. Positive value (+) indicated an anterior movement in a sagittal (Y) plane and an upward movement in the vertical (Z) plane. Negative value (-) indicated a posterior movement in a sagittal (Y) plane and a downward movement in the vertical (Z) plane. **(Table II).**

Table II: Comparison of the transversal (X), sagittal (Y), and vertical (Z) displacement of the various structures of the craniofacial complex with varying amounts of expansion

Region	Selected nodes on	X (mm)			Y(mm)			Z (mm)		
		1 mm	3 mm	5 mm	1 mm	3 mm	5 mm	1 mm	3 mm	5 mm
Dentoalveolar	Incisal edge of 1	0.95	2.8	4.45	0	0.11	0.35	-0.12	-0.3	-0.65
	Cusp tip of 3	0.82	2.4	4.28	0	0.03	0.15	0	0.12	0.32
	Cusp tip of 6	0.91	2.6	4.27	0	0.24	0.74	0	0.08	0.26
Maxilla	Pt. "A"	0.2	1.4	3.9	0	0.18	0.54	-0.01	-0.45	-1.02
	ANS	0.14	1.21	3.41	0	0.21	0.72	0	-0.34	-0.98
	Tuberosity	0.07	1.01	2.89	0	0.02	0.12	0	0.09	0.17
	Zyg. buttress	0.07	0.8	1.92	0	0	0	0.07	0.17	0.36
	Inf. orb. rim	0	0.31	0.82	0	0	0.02	0	0.09	0.22
	Frontal process	0	0.21	0.57	0	0	0.02	0	0	0.07
Palate	Anterior	0.27	1.34	3.54	0.17	0.74	1.21	0	-0.3	-0.87
	Posterior	0.02	0.94	1.84	0.09	0.68	1.09	0	-0.24	-0.92
Nasal cavity wall	Anteroinferior	0.51	1.06	3.24	0	0.09	0.24	0	0	-0.24
	Anterosuperior	0.02	0.76	1.08	0	0	0.12	0	0	-0.03
	Posteroinferior	0.01	0.8	1.7	0.07	0.15	0.21	0	0	-0.14
	Posterosuperior	0	0.16	0.35	0	0	0	0	0	-0.03
Nasal bone	Superior	0	0	0	0	0	0	0	0	0
	Inferior	0	0.03	0.15	0	0	-0.12	0	-0.09	-0.37
Sphenoid bone	Medial pterygoid inferior	0	0.97	2.04	0	-0.2	-0.6	0	-0.31	-0.82
	Medial pterygoid superior	0	0.5	1.18	0	-0.07	-0.12	0	0	0.9
	Lateral pterygoid inferior	0	1.1	2.34	0	0.1	0.26	0	-0.31	-0.87
	Lateral pterygoid superior	0	0.11	0.32	0	0	0.1	0	0.14	0.1
	Greater wing	0	0.06	0.21	0	-0.06	-0.21	0	0.08	0.24

Displacement in the transverse plane: (X-displacement)

With 1 mm of separation of expansion device on each side, changes were evident only in the dentoalveolar region and anterior maxillary region. As the expansion device was further separated, displacements of the adjacent structures were noticeable. Expansion was more in anterior maxillary area compared to the posterior. From the frontal view, pyramidal displacement of maxilla away from the midline was evident.

The width of the nasal cavity at the floor of the nose increased markedly where as the posterosuperior part of the nasal cavity had moved minimally in the lateral direction. No significant lateral displacement was observed at the temporal, frontal and sphenoid bone. The inferior parts of the pterygoid plates, however, demonstrated lateral displacement or bending. But minimum displacement was observed in the region close to the cranial base, where the plates were more rigid.

Displacement in the anteroposterior plane

(Y - displacement)

Maximum positive Y-displacement (forward displacement) was 1.21 mm at node representing the anterior aspect of palate followed by 1.09 mm at posterior aspect. All the dentoalveolar structures, maxillary structures, and structures on nasal cavity wall demonstrated forward displacement to varying extent. These changes were evident when the expansion was beyond 3 mm on each side.

Displacement in the vertical plane

(Z - displacement)

Maximum positive Z-displacement (upward displacement) was 0.98 mm at node representing the frontal process of the zygomatic bone. Maximum negative Z-displacement (downward displacement) was 1.02 mm of point ‘A’, indicating a downward displacement of maxilla. Considering both these points, it is evident that the nasomaxillary complex rotated in such a manner that the lateral structures had moved upward and midline structures downward. The anterior part of the maxillary bone (point A and ANS) and maxillary central incisors were displaced downward.

Comparison of maximum Von-Mises stresses on various structures of the craniofacial complex with varying amounts of expansion

Table III shows the comparison of maximum Von-Mises stresses on the various craniofacial structures with varying amounts of expansion. The findings show that the stresses at the nodes varied linearly for the given displacement boundary conditions due to RME.

Table III: Comparison of maximum Von-Mises stresses

Region	Selected nodes on	Max. Von-Mises stress (Kg/mm^2)		
		1 mm	3 mm	5 mm
Dentoalveolar	Incisal edge of 1	0.22	0.45	0.81
	Cusp tip of 3	0.9	2.1	2.7
	Cusp tip of 6	1.4	2	3.4
Maxilla	Pt. "A"	0.8	1.8	2.6
	ANS	0.8	1.64	2.14
	Tuberosity	0.92	1.72	3.24
	Zyg. buttress	2.5	4.72	6.04
	Inf. orb. rim	0.62	1.24	2.02
	Frontal process	0.57	1.12	2.12
Palate	Anterior	0.49	0.92	1.21
	Posterior	0.8	1.27	3.24
Nasal cavity wall	Anteroinferior	5.24	13.84	20.42
	Anterosuperior	1.02	3.41	4.98
	Posteroinferior	1.82	4.27	6.28
	Posterosuperior	0.71	1.37	2.02
Nasal bone	Superior	2.4	7.34	12.14
	Inferior	4.1	10.21	15.28
Sphenoid bone	Medial pterygoid inferior	2.1	8.94	14.24
	Medial pterygoid superior	7.24	57.24	74.24
	Lateral pterygoid inferior	1.84	7.53	12.24
	Lateral pterygoid superior	8.24	55.14	68.17
	Greater wing	3.24	34.27	51.24

In the dentoalveolar region, the stresses were high in apical region of canine and first molar and they continued to increase as the expansion progressed. In the maxilla, zygomatic buttress demonstrated high stress values compared to the other areas evaluated. The posterior region of the palate demonstrated higher stress values compared to the anterior region. The anteroinferior region of the nasal cavity demonstrated stresses in range of 5.24 - 20.42 kg/mm^2, which were highest for the areas assessed.

Highest stress levels were observed in the pterygoid plates of sphenoid bone. The findings indicated that high stresses produced by RME are especially located in the superior parts of the pterygoid processes of the sphenoid bone (74.24 kg/mm^2 at medial and 68.17 kg/mm^2 at lateral pterygoid). The greater wing of sphenoid also demonstrated high stress levels (51.24 kg/mm^2).

Initial stress images of the three-dimensional model of skull are as shown in Fig. 4 A, B and C**.** The areas of stress are shown with the help of different colours. The pellets of colours representing the tensile and compressive stresses are shown on the right-hand side of the diagram.

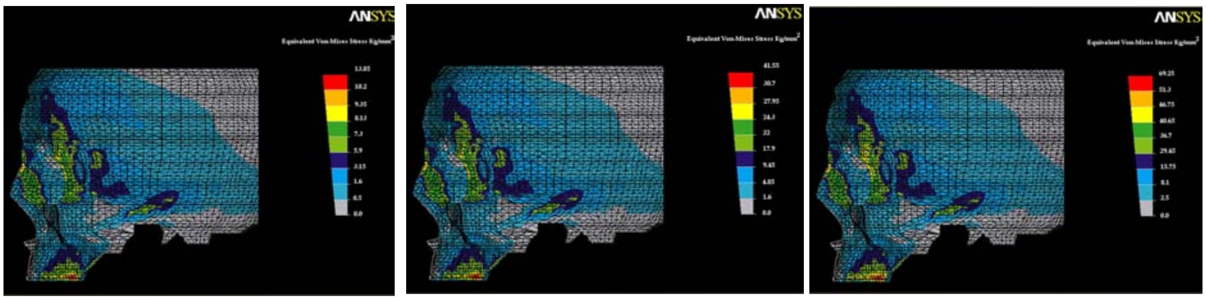

Fig 4: Contour plots for stress distribution in craniofacial complex with (A) 1 mm, (B) 3 mm and (C) 5 mm of expansion

Discussion

Finite element analysis is a mathematical method in which the shape of complex geometric objects and their physical properties are computer constructed. This method was first used in orthodontics by Thresher and Saito (1973)[8] to study stresses in human teeth. Ever since, this method has proved effective in many dental fields such as simulation of tooth movement and optimization of orthodontic mechanics. Such an extensive use has been primarily done because of its advantages. The method is non-invasive; 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; the displacement of the tooth and the craniofacial complex 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.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 the varied responses of the craniofacial components on loading in vivo. Thus, the results of this study are valid only for a single specific human skull.

This can be seen as a problem in generalizing the findings obtained in this study. On the other hand, studies done by Iseri et al[7] and Jafari et al[6] yielded same results in spite of the differences in method used and the variation in skull geometry. Iseri et al[7] used CT images of a 12-year old patient while Jafari et al[6] constructed the model from CT images of dry human skull with an approximate age of 12 years. They showed that, although there were differences in the craniofacial structures between subjects, the responses to the same mechanical forces were same in the FEM.

Table IV: Comparison of transversal (X), sagittal (Y), and vertical (Z) displacement of the various structures of the craniofacial complex with previous studies*

Region	Selected nodes on	X (mm)			Y (mm)			Z (mm)		
		Iseri et al	Jafari et al	Present study	Iseri et al	Jafari et al	Present study	Iseri et al	Jafari et al	Present study
Dentoalveolar	Incisal edge of 1	5	5.31	4.45	1.4	0.85	0.35	-1.4	-0.45	-0.65
	Cusp tip of 6	5	5.31	4.27	1.4	0.74	0.15	-0.8	0.26	0.26
Maxilla	Anterior part of palate	4.9	3.22	3.54	2.1	1.03	1.21	-1.1	-0.61	-0.87
	Posterior part of palate	4.8	2.06	1.84	2.1	1.05	1.09	-0.2	-1.02	-0.92
Sphenoid bone	Lateral pterygoid inferior	4.9	2.07	2.34	1.8	0.59	0.26	-0.04	-0.44	-0.87
	Lateral pterygoid superior	1.4	0.44	0.32	1.6	0.08	0.1	-0.7	0.13	0.1
Nasal cavity wall	Anteroinferior	4.8	3.25	3.24	2.1	0.52	0.24	-1.1	0	-0.24
	Anterosuperior	4.8	1.26	1.08	2.1	0.16	0.12	-0.02	-0.02	-0.03
	Posterosuperior	-0.3	0.65	0.35	0.2	0.02	0	-1.1	-0.02	-0.03
Nasal bone	Body	0.3	0.23	0.15	-1.2	-0.5	-0.12	-1.1	-0.59	-0.37

So, though there were quantitative differences, qualitatively, the mechanical response was predicted in the same manner, which is a positive indication for the validity of the qualitative conclusions (Table IV).

Though we used an adult human skull to develop the finite element model, the displacements of the various craniofacial structures were compared with similar corresponding structures of the previous studies.[6,7]

Overall pattern of displacement

The pattern of displacement revealed that the greatest widening was observed in the dento-alveolar structures, with the expansion effect gradually decreasing towards the superior structures. The results of the present study support those of the previous studies,[6,7] which reported the maxillary suture to separate supero-inferiorly in a non-parallel manner, the separation being pyramidal in shape with base of the pyramid located at the oral side of the bone and the centre of rotation located near the frontonasal suture.

In the sagittal (Y) plane, the structures along the midline showed an anterior displacement while the lateral structures demonstrated a posterior displacement.

In the vertical (Z) plane, the entire maxillary complex descended downwards more or less in a parallel manner while the lateral structures demonstrated an upward displacement.

Overall pattern of stress distribution

Stresses produced by the expansion appliance were concentrated in the anterior region of the palate. The initial effects of the expansion were observed at region of central incisors.

With increased activations, stresses radiated from the midpalatine area superiorly along the perpendicular plates of the palatine bone to deeper anatomic structures. The buttressing of the maxillary tuberosity with the pterygoid plates of the sphenoid bone allowed the forces to then radiate to the base of the medial pterygoid plate. From this region, the stresses then spread further superiorly toward the malar and the zygomatic bones.

Heavy stresses were observed in the area of the base of pterygoid plates of sphenoid bone. These areas of stress concentration indicate regions of potential weakness or regions where major biologic responses may be expected.

Unlike the maxillae, the pterygoid processes are not individual bones, but parts of the same cranial bone - the sphenoid. So, even if surgically assisted rapid maxillary expansion (SA-RME) is advocated, the osteotomized maxillae and palatine bones would move apart on application of expansion forces, but the fused pterygoid processes which cannot separate, tend to splay outward.

Contrary to conventional perception, this study along with the previous studies[6,7,9,10] disclosed that resistance provided by the pterygomaxillary articulations was greater than that of the zygomaticomaxillary buttresses.

The results of the present study using the three-dimensional FEM of an Adult Human Skull provided explanation about the mechanical reactions of the bony tissues, which are the first steps in the complex and dynamic process of tissue response to maxillary expansion.

However, as stated previously, FE method has certain limitations, most important being the results applicable only to the FE model created. It may not necessarily apply to all individuals quantitatively. However, what is important is that most of them, would give qualitatively the same results as were obtained in the present study, which can prove useful if employed judiciously.

The present study is precisely for the purpose of highlighting the qualitative differences in biomechanical effects of RME employed in an adult. Simulation models that are being used for diagnostic, operational planning or rehearsal purposes in the field of medical sciences can be effectively and efficiently employed in the field of orthodontics and maxillofacial surgery.

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