A Comparative Study of Three Types of Rapid Maxillary Expansion Devices in Surgically Assisted Maxillary Expansion: A Finite Element Study

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Abstract:
Objectives: The aim of this study was to analyze the displacement pattern and stress distribution during surgically assisted rapid maxillary expansion (RME) with three different types of RME devices by constructing a finite element model.

Materials and Methods: A finite element model is constructed from the computerized tomography scans. According to the type of RME device, 3 groups were simulated on this mesh model. The experimental groups were as follows: Group I (tooth borne appliance), Group II (bone borne appliance), and Group III (hybrid appliance). A Le fort I osteotomy with bilateral pterygomaxillary disjunction and midpalatal split osteotomy cuts were incorporated in all the groups. The displacement pattern and stress distribution for each 1 mm of activation of appliance up to 10 mm is noted and analyzed. The data were analyzed using Student’s t-test, Analysis of Variance and Duncan new multiple range test.

Results: Tooth borne appliance has more rotational tendencies. The bone borne and the hybrid appliance exhibited similar stress patterns for the dissipation of the forces produced by RME appliances. The pivoting effect decreased with the hybrid and the bone borne appliance and can be utilized in patient with hyper divergent growth.

Conclusion: The pivoting effect is least with the hybrid appliances.

Key Words: Displacement, finite element, rapid maxillary expansion, surgically assisted rapid maxillary expansion, stress

Introduction
The technique of rapid maxillary expansion (RME) is an effective treatment procedure commonly employed in the treatment for maxillary transverse deficiency (MTD) patients. Over the years, numerous types of RME appliances were designed ever since its inception by Emerson C. Angell in 1860 and reintroduction of Hass in 1960.¹ Orthodontic treatment of patients with narrow maxilla is usually done with some type of rapid maxillary palatal expanders. The palatal expansion techniques correct the maxillary deficiency by applying transverse orthopedic forces which open up the midpalatal suture. The treatment of a MTD by RME appliance in skeletally mature individuals should include surgically assisted RME (SARME).³ In adults, additional surgical weakening of certain anatomic structures of the midface is required to allow maxillary expansion and opening up of midpalatal suture. With the skeletal maturity, there is increased ossification in the circummaxillary sutures, increased thickness of the bony structures, reduction in the elasticity, and increased interdigitation of the median palatal suture. All these factors provide resistance to opening of the midpalatal suture and stable widening of the maxilla.³,⁴ SARME in adults produces stable maxillary expansion.² Various osteotomies have been proposed to weaken the midfacial skeletal structures to allow the maxillary expansion with transpalatal distraction devices. Le fort I osteotomy with pterygomaxillary disjunction and midpalatal split was found to be the best one as it distributes the distraction stresses uniformly in the craniofacial skeleton and accomplishes stable skeletal expansion of maxilla.³,⁴

The most commonly used RME appliances are tooth borne anchored to premolars and molars. The heavy force generated during RME produces undue mechanical stress on dental structures resulting in the buccal tipping and root resorption of the anchor teeth.³,⁴ To avoid such complications, mini-implants have been used successfully for bone borne palatal expansion.⁷ This method carries the risk of root injury and the need for surgical implantation and removal of the two titanium cylinders.⁷ As an alternative, Wilmes et al.⁸ introduced the bone- and tooth- borne hybrid hyrax, which is anchored by palatal mini-screws and first molar bands. The routine and safe use of orthodontic mini-implants in the anterior palate has encouraged the use of the so-called hybrid expanders, which are partially bone-borne and partially tooth-borne.⁸ There were no previous studies done in evaluating and comparing the efficacy of all the three types of RME appliances in SARME cases. A review of literature revealed that the studies were done to compare the effect of RME on different
dental and skeletal structures using single type of distraction appliance, comparison surgical over nonsurgical methods of RME, comparison of bone borne and tooth borne appliances, effects of different types of osteotomies, comparison bone borne and tooth borne appliances, effects of different types of bone borne microimplant assisted rapid palatal expansion on the nasomaxillary complex, effects of hybrid RME appliance on the craniofacial complex. The purpose of this study is, therefore, to evaluate the displacement patterns and stress distribution of various craniofacial structures following RME therapy with three different type of devices in SARME cases.

Materials and Methods

The Institutional Ethical Committee Clearance (RC No. NDC/PG2012-13/EC/2012. dated 10-20-2012) was obtained for conducting the study and informed consent is obtained from the concerned patient for utilizing the patient’s medical records. The displacement and stress distribution is analyzed by finite element model in three different groups of maxillary expansion devices. Group I appliances that are tooth borne deriving anchorage entirely from the dental structures. Group II appliances that are bone borne deriving source of anchorage entirely from palatally placed implants. Group III are hybrid appliance deriving support from anterior placed palatal micro implants and posteriorly from dental structures. The first step in creating the finite element method (FEM) model is to generate a 3-dimensional geometric model of the skull and the dentition. A 128 slide computerized tomography (CT) scan (GE optima 660, GE health care, Buckinghamshire, United Kingdom, 2012 model) with 0.6 mm interval of the skull of a 20-year-old female patient is obtained from the previous medical records of the Department of Oral and Maxillofacial Surgery, Narayana Dental College, Nellore, India. Criteria for the selection included the skull with transverse constriction of the maxilla of more than 10 mm with bilateral crossbite, deep palatal vault without a history of previous trauma and surgery of the craniofacial region. The scans are taken parallel and perpendicular to the Frankfort horizontal plane (Figure 1). The FEM model in our study was constructed in sequential steps utilizing the digital imaging and communications in medicine file format (Figure 2). The software utilized in sequence are Mimics innovation 14 suite software (Medical Image Segmentation for Engineering on Anatomy), Rapidform XOR-3 (Inus software co. South Korea) and solid works 2007 software (Solid works USA) to generate the finish model (Figure 3). After creating an stereolithographic (STL) file anatomical structures such as sutures become less distinguishable. The sutures were drawn manually as close as possible to the original anatomy of the model. Le fort I osteotomy with bilateral pterygomaxillary disjunction and midpalatal split osteotomy cuts were incorporated. These computer aided design models were fitted with three rapid maxillary appliances (tooth borne, bone borne, and hybrid) as shown in Figure 4. The model of the expansion device for tooth borne appliance is created by placing actual HYRADEX screw® (dentaurum orthodontic

Figure 1: Computerised tomography scan slice of patient parallel (a) and perpendicular (b) to Frankfurt (FH) plane.

Figure 2: (a and b) Three dimensional (3-D) reconstruction image from digital imaging and communications in medicine format.

Figure 3: Meshing of the model with identification of different landmarks.

Figure 4: Computer aided design - finite element models fitted with (a) tooth borne, (b) bone borne, (c) Hybrid appliances.
products, ispringen, deutschland) on the occlusal surface of the model between the premolars. The lateral arms are designed to apply pressure at premolar and molars when activated. The model suggested in four Dual-Top Jet™ miniscrews (Institute Straumann, Waldenburg, Switzerland) is simulated for bone borne RME appliance. The screws (2-2.5 mm in diameter, 10-14 mm long) are inserted exactly perpendicular to the anterior palate, 3-9 mm lateral to the midpalatine suture. The anterior screws are placed tangent to a line between the canine and premolar, and the posterior are placed in line tangent to the contact point of premolar and molar. The Hybrid appliance is simulated by placing two mini implants of (2 mm wide and 9 mm length) as suggested by Wilmes for his hybrid appliance at the anterior end of the hyrax screw. The other aspects are similar to those described for tooth borne appliance. Later the created volumes were individually divided into a finite number of elements; this process is known as meshing which was done by ANSYS Workbench (version 13, Belcan Engineering Group, Downers Grove). The complete geometry now comprised an assembly of discrete pieces, called elements, that were connected at a finite number of points, called nodes. The mechanical properties of compact and cancellous bones, the teeth and the PDL in the model defined in FEM study by Jeon et al. and Gautam were adapted in our model.

The list of landmarks used in the model are:
1. Maxilla: Point A, ANS, supradentale, tuberosity, zygomatic butttess, inferior orbital rim, frontal process, posterior nasal spine (PNS)
2. Sphenoid bone: Inferior and superior surfaces of lateral pterygoid plate and medial pterygoid plate, nasion, greater wing (orbital), lesser wing (orbital) synchondrosis
3. Zygomatic bone: Frontal, temporal, maxillary, body
4. Frontal bone: Zygomatic process, superior orbital ridge
5. Superior and inferior orbital fissures: Lateral and medial surfaces (Table 1).

Nine craniofacial sutural systems were integrated into the model. For this, nodes corresponding to a suture were identified, and a duplicate node was created for each node at the sutural interface. The sutures included in the study are sphenozygomatic, zygomaticomaxillary, zygomaticotemporal, zygomaticofrontal, frontonasal, frontomaxillary, nasomaxillary, inferior nasal suture, midpalatal suture (Table 2).

The stress distribution at constructed nodal points was calculated using von Mises Criterion. The von Mises stresses were used for this analysis because of the appropriateness and the validity of the von Mises theory of failure. A known transversal (X) displacement with a magnitude of 5 mm was applied on the surface nodes and their corresponding duplicate nodes along the intermaxillary suture in the first molar region. A 10 mm transverse maxillary expansion was simulated. Displacements (in mm) of various craniofacial structures were evaluated along the X, Y, and Z coordinates.

The areas of stress are shown with the help of different colors. Different colors represented different stress levels in the deformed state. Positive or negative values in the column of stress spectrum indicate tension or compression, respectively.

### Table 1: Mean displacement (in mm) pattern of various craniofacial structures at different anatomical landmarks/points with different three types of rapid maxillary expansion devices in all three planes.

| Appliance and coordinates | Mean±SD | Point A | ANS | Supradentale | Tuberosity | Zygomatic buttess | Inferior orbital rim | Frontal process | PNS |
|---------------------------|---------|--------|-----|-------------|-----------|-------------------|--------------------|----------------|-----|
| Tooth borne - X | Mean | 0.200 | 0.141 | 0.260* | 0.263 | 0.062 | -0.073 | -0.127 | 0.124 |
| SD | 0.110 | 0.078 | 0.143 | 0.145 | 0.034 | 0.040 | 0.070 | 0.068 |
| Bone borne - X | Mean | 0.237 | 0.265 (NS) | 0.149 | 0.515 | 0.571** | 0.581 | 0.417 (NS) | 0.177 |
| SD | 0.130 | 0.146 | 0.082 | 0.283 | 0.315 | 0.320 | 0.230 | 0.231 |
| Hybrid - X | Mean | 0.276** | 0.216* | 0.309** | 0.285 | 0.245** | 0.235 | 0.189** | 0.185 |
| SD | 0.056 | 0.023 | 0.059 | 0.234* | 0.036 | 0.039 | 0.048 | 0.068 |
| Tooth borne - Y | Mean | -0.106 | -0.096* | -0.119** | 0.478 | 0.044* | -0.048 | -0.065 (NS) | -0.106 |
| SD | 0.058 | 0.053 | 0.065 | 0.263 | 0.024 | 0.027 | 0.036 | 0.025 |
| Bone borne - Y | Mean | 0.053 | 0.050 | 0.050 | 0.381 | 0.112 | 0.156 | -0.015 | -0.087 |
| SD | 0.029 | 0.028 | 0.028 | 0.210 | 0.062 | 0.086 | 0.008 | 0.048 |
| Hybrid - Y | Mean | 0.074 | 0.067 (NS) | 0.079 | 0.125 | 0.079* | 0.082 | 0.042 | 0.035 |
| SD | 0.041 | 0.037 | 0.043 | 0.069 | 0.043 | 0.045 | 0.023 | 0.019 |
| Tooth borne - Z | Mean | 0.156 | 0.163 | 0.159 | 0.574 | 0.007 | -0.002 (NS) | 0.119 (NS) | 0.409 |
| SD | 0.086 | 0.090 | 0.088 | 0.316 | 0.004 | 0.001 | 0.066 | 0.225 |
| Bone borne - Z | Mean | -0.449** | -0.456** | -0.444* | -0.536** | -0.361** | -0.465** | -0.481** | 0.497 |
| SD | 0.121 | 0.115 | 0.118 | 0.078 | 0.068 | 0.088 | 0.079 | 0.056 |
| Hybrid - Z | Mean | -0.207* | -0.204* | -0.211 | -0.124 | -0.156* | -0.179 | -0.177* | 0.092 |
| SD | 0.114 | 0.112 | 0.116 | 0.068 | 0.086 | 0.099 | 0.097 | 0.051 |

*P<0.01 - significant at 1 level (highly significant); **P=0.011-0.050, significant at 5 level (significant); P=0.051-1.000, Not significant at 5 level (NS). If the P=0.000 then put it as<0.001**. SD: Standard deviation
### Table 2: Stress distribution at various sutures (all values in N/mm² = 1 Mpa).

| Suture                     | Aspect/region | Tooth borne | Bone borne | Hybrid  |
|----------------------------|---------------|-------------|------------|---------|
|                            | Mean          | SD          | Mean       | SD      |
| Sphenoid zygomatic suture  | Lateral       | 2.60        | 1.43       | 3.10    | 1.71    | 38.04    | 20.94   |
|                            | Medial        | 4.67        | 2.57       | 6.12    | 3.37    | 92.62    | 50.99   |
|                            | Middle        | 1.99        | 1.10       | 1.66    | 0.91    | 21.50    | 11.83   |
|                            | P value       | 0.007**     | <0.001**   | <0.001**|
| Zygomaticomaxillary suture | Anteromedial  | 35.33       | 19.05      | 16.14   | 9.95    | 351.52   | 234.42  |
|                            | Posteroomedial| 11.65       | 6.41       | 30.45   | 16.76   | 599.15   | 329.82  |
|                            | Posterolateral| 31.76       | 31.47      | 24.67   | 18.74   | 452.81   | 405.94  |
|                            | P value       | <0.022*     | <0.017*    | <0.001**|
| Zygomatico temporal suture | Lateral       | 9.95        | 6.43       | 4.29    | 2.33    | 68.16    | 47.19   |
|                            | Medial        | 8.64        | 5.52       | 16.38   | 16.58   | 232.01   | 237.01  |
|                            | P value       | <0.022*     | <0.017*    | <0.001**|
| Zygomatico frontal suture  | Anteromedial  | 9.06        | 4.99       | 36.69   | 20.20   | 636.78   | 350.54  |
|                            | Posteroomedial| 0.57        | 0.31       | 0.34    | 0.19    | 8.79     | 4.84    |
|                            | Posterolateral| 12.36       | 6.81       | 18.99   | 10.45   | 352.74   | 194.18  |
|                            | P value       | <0.002*     | <0.017*    | <0.001**|
| Frontonasal suture         | Lateral       | 22.79       | 12.55      | 25.23   | 13.89   | 538.08   | 296.20  |
|                            | Medial        | 24.96       | 13.74      | 27.53   | 15.15   | 567.78   | 312.55  |
|                            | Middle        | 0.51        | 0.28       | 0.31    | 0.17    | 14.67    | 8.08    |
|                            | P value       | <0.002**    | <0.000**   | <0.000**|
| Frontomaxillary suture     | Lateral       | 6.45        | 3.55       | 7.76    | 4.27    | 180.03   | 99.10   |
|                            | Medial        | 0.43        | 0.23       | 0.26    | 0.14    | 11.10    | 6.11    |
|                            | Middle        | 6.70        | 3.69       | 9.88    | 5.44    | 211.45   | 116.40  |
|                            | P value       | <0.002**    | <0.000**   | <0.000**|
| Nasomaxillary suture       | Lateral       | 8.88        | 4.89       | 23.15   | 12.74   | 352.07   | 193.81  |
|                            | Medial        | 3.16        | 1.74       | 20.54   | 11.30   | 371.15   | 204.51  |
|                            | Middle        | 20.34       | 11.20      | 25.87   | 14.24   | 366.10   | 201.53  |
|                            | P value       | <0.002**    | <0.000**   | <0.000**|
| Inferior nasal suture      | Middle        | 17.45       | 9.61       | 25.19   | 13.86   | 360.31   | 198.35  |
|                            | Inferior      | 22.55       | 12.41      | 26.67   | 14.68   | 394.41   | 217.11  |
|                            | Superior      | 9.65        | 5.31       | 20.98   | 11.55   | 277.06   | 152.52  |
|                            | P value       | <0.019*     | <0.022*    | <0.032**|
| Midpalatal suture          | Anterior      | 22.28       | 12.27      | 191.75  | 105.55  | 209.00   | 115.05  |

*P<0.01 - significant at 1 level (highly significant); **P<0.01 - significant at 5 level (significant); P=0.051-1.000, Not significant at 5 level (NS). If the P<0.000 then put it as <0.001, different alphabets between region denotes significant at 5% level using Duncan multiple range test. Homogenous subsets were marked with superscript with alphabets “a,” “b,” “c” etc.,

**Results**

The results involve calculation of stresses by von Mises criteria and displacement patterns in X, Y, and Z co-ordinates. The stress and displacement produced was analyzed for each 1 mm of expansion up to 10 mm of expansion. The displacements were measured on X - (transverse plane), Y - (anteroposterior plane), and Z - (sagittal plane) axis (Table 1). The internal stress reaction (kg/mm² or N/mm²) was measured by von-Mises stress (Table 2). The results for displacement were grouped based on the different surfaces and aspects of the particular craniofacial structure individually. The following sign convention was used for interpretation of displacement.

1. **X-axis**: Displacement in transverse direction: +Ve (expansion) and -Ve (contraction)
2. **Y-axis**: Displacement in sagittal direction: +Ve (anterior) and -Ve (posterior)
3. **Z-axis**: Displacement in vertical direction: +Ve (superior) and -Ve (inferior)

The data were analyzed using statistical software (SPSS software version, 2010) for various analyses. For statistical purposes, analysis of the data was done at individual sutures in case of stress patterns. In case of analysis of displacement, different anatomical points and surfaces at a particular craniofacial structure are compared. The differences between the mean coordinates for each aspect of the craniofacial sutures and structures were calculated. One-way Analysis of Variance test is utilized for comparison within the group and for intergroup variability. Student’s t-test was used to determine if two sets of data are significantly different from each other. Levenes test was utilized used to assess the quality of variances for a variable calculated for two or more groups. Duncan new multiple range test is utilized for comparing the range of the subset of the sample means with a calculated least significant range. Interpretation of the results and analysis display from this finite element analysis is primarily in the numerical form. It usually consists of nodal values of the field variables and its derivative. The output is primarily in the form of color-coded maps. The quantitative analysis is determined by interpreting these maps (Figures 5 and 6).
Discussion

The finite element model is a standard tool used in engineering to precisely assess local stress/strain/displacement distribution in geometrically complex structures. The point of application, magnitude, and direction of force may easily be varied to stimulate the clinical situation. Our finite element model is constructed from a CT scan of transverse maxillary deficient patient records. The technique that involves obtaining anatomy using the CT scans showed that only minor positional errors (of the order of 1 mm) were introduced by the CT scans.\textsuperscript{3,5} Previous finite model studies done by Gautam,\textsuperscript{10} Jafari,\textsuperscript{11} Iseri\textsuperscript{18} have taken CT scan images of 2.5 mm, 5 mm, and 10 mm for FEM generation. In the present study, modeling of the skull was done using CT scan images taken at 0.6 mm interval which means that when compared to earlier FEM studies the STL model generated was in detail with higher accuracy.

Previous study by Provatidis\textsuperscript{1} calculated only displacement rather than stress and strain. Moreover, in the present study both stress and displacement patterns were calculated. The present study included the comparison of three types of RME devices which is not done in any of the previously conducted experiments utilizing the finite element analysis.\textsuperscript{1,3,7,18} To add this, we have incorporated the effects of surgical osteotomies in our study along with RME. The results obtained with the present FEM, even though boundary conditions were at the upper limits of the clinical situation for easier recognition of the changes produced, were qualitatively similar with the above studies. Matteini and Mommaerts\textsuperscript{2} stated that the midpalatal suture, the zygomatic buttress, the piniform aperture, and the pterygomaxillary junction are the primary sites of resistance to maxillary expansion with increasing interdigitation in the palatal suture and maturation of the facial skeleton, the need to release the resistance in the suture and to section the lateral and posterior buttresses become obvious. The palatal mucoperiosteum constitutes a secondary site of resistance. In this study to reduce the resistance from these areas, surgery often involves Le fort I type osteotomy with pterygomaxillary disjunction and midpalatal split as it helps in distribution of distraction stress uniformly in the craniofacial skeleton and accomplishes stable skeletal expansion of maxilla. This is one of the reasons higher values of displacement were noted in our study at maxillary tuberosity area.

In the present study, the hybrid appliance exhibited highest stress when compared to tooth borne and bone borne RME appliances in all the sutures as shown in Table 2. Stress distribution is more pronounced along sutures in transverse plane like zygomaticomaxillary suture. The dissipation of the stress pattern follows from outside to inside with the medial structures exhibiting more stress pattern at various sutures that are particularly connected to the base of the cranium such as sphenoidozygomatic suture. The stress pattern further showed a descending mode from superior to inferior aspects in the sutures that are located in cephalocaudal direction. Maximum amount of stress concentration is noted at the anteromedial aspect of the zygomaticofrontal suture, posteromedial surface of zygomaticomaxillary and medial aspect of frontonasal suture. The splaying effect on the craniofacial structures as demonstrated by their displacements is more marked with tooth borne appliances as shown in Table 1. However, the fanning effect which is common with RME appliances is seen with all three types of appliances. This effect is least displayed by the hybrid appliances. Tooth borne appliances utilize tooth as anchors consequently the moment arm is increased displaying more fulcrum effect. The point of pivoting is
seen at nasomaxillary suture as indicated by the contractile displacements at this point. The displacements produced by the hybrid appliance are of uniform magnitude in the midline structures as well as lateral structures of the craniofacial skeleton. This effect is more seen in a transverse plane compared to Y - axis and Z - axis. Moreover, our study revealed actually there is shortening of the maxillary anterior posterior dimensions with all the three types of appliances as measured on the Y - axis. The points representing the anterior segment of the maxilla such as point-A, ANS and supradentale showed marked posterior and concurrently the posterior structures such as PNS, tuberosity, zygomatic buttress of maxilla moved anteriorly. This effect seems to be grading away to the structures adjacent to the maxilla in a posterior direction. The anterior components rotated downward with posterior segments in the upward direction. Surprisingly, the rotational tendencies in this aspect are minimum with the tooth borne appliance compared to the hybrid appliance and bone borne appliance. However, there is no marked disparity observed in the hybrid and bone borne appliances in the mean displacements in superior and inferior directions among the different nodal points. The minimum splaying effect of the hybrid appliance can be taken advantage in patients with vertical maxillary excess and longitudinal growth pattern. The reduced rotational effects of the maxilla by this appliance will be beneficial in these patients.

Shortcomings of the study: The study is basically an in vitro study. When the RME forces are applied there are opponent forces acting from muscles and soft tissues but in this finite element model effect on RME on the bone was measured and muscles and soft tissue effects were not incorporated. In the present study, only one surgical procedure utilizing two osteotomy cuts is utilized and different surgical procedures with varied osteotomy cuts for SARME are available. In case of bone borne and hybrid appliance the stresses created by the implants was not considered. The finite element data processing provides results which include errors as a consequence of the geometry idealization, characteristic material properties and boundary conditions. However, the results vary from one appliance to another.

Conclusion
The following statements can be concluded from our study.
1. Tooth borne appliance has more rotational tendencies
2. The bone borne and the hybrid appliance exhibited similar stress patterns for the dissipation of the forces produced by RME appliances
3. The pivoting effect or the rotational tendencies is least with the hybrid appliances. This can be utilized for patients with vertical maxillary excess and backward rotation of the mandible.

Since this is an in vitro study, clinical evaluation in particular case has to be carried out with the hybrid appliance to substantiate the findings in the FEM study.

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