Original Article

A comparison of different osteotomy techniques with and without pterygomaxillary disjunction in surgically assisted maxillary expansion utilizing modified hybrid rapid maxillary expansion device with posterior implants: A finite element study

ABSTRACT

Introduction: The study aims to evaluate the effect of osteotomies with and without Pterygomaxillary disjunction (PMD) during Surgical Assisted Rapid Maxillary Expansion on the displacement pattern and stress distribution of Dental and Skeletal structures of the Nasomaxillary (NM) complex by a modified rapid maxillary expansion (RME) Hybrid appliance.

Materials and Methods: A CT scan of a 20-year-old adult with maxillary constriction and the posterior bite was utilized for the restructuring of the finite element model. Five different meshed models were created individually with varying procedures of the osteotomy. A posteriorly anchored Hybrid-Hyrax appliance was utilized for RME. Groups included Group 0 - Control group without osteotomy; Group I - Only Midpalatal osteotomy; Group II - Only Subtotal Le fort I; Group III - Both Midpalatal and Subtotal Le fort I without PMD; Group IV - Midpalatal + subtotal Le fort I with bilateral PMD. The displacement pattern and stress distribution in all three dimensions were recorded and analyzed using analysis of variance and *post-hoc* Tukey test.

Results: Group IV with PMD exhibited the highest stress dissipation and displacement of the skeletal and dental structures followed by Group III osteotomies. The highest stress concentration was at midpalatal suture (292 MPa) for Group III osteotomies. There is no statistical difference between Group III and Group IV osteotomies for many of the parameters measured ($P > 0.05$).

Conclusions: Posteriorly anchored Hybrid appliance without PMD is as effective as that with of PMD.

Keywords: Displacement, Le Fort I, pterygomaxillary disjunction, rapid maxillary expansion, surgical assisted rapid maxillary expansion, stress

INTRODUCTION

The skeletal maxillary transverse deficiency (MTD) is one of the malocclusions that is frequently encountered in association with a mesio-normal occlusion. There is impairment of functional occlusal relationship, and hence, the correction of MTD is an essential component of an orthodontic treatment plan. The rapid maxillary expansion (RME)/rapid palatal expansion (RPE) is the modus operandi commonly employed in harmonizing the dental arches in MTD who are in the active phase of skeletal growth. The palatal expansion techniques by applying transverse

Access this article online	
Website: www.njms.in	Quick Response Code
DOI: 10.4103/njms.NJMS_28_20	

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Received: 20 March 2020, **Revised:** 18 June 2020, **Accepted:** 04 August 2020, **Published:** 15 July 2021

How to cite this article: Sankar SG, Prashanth B, Rajasekhar G, Prasad M, Reddy GV, Priyanka JS. A comparison of different osteotomy techniques with and without pterygomaxillary disjunction in surgically assisted maxillary expansion utilizing modified hybrid rapid maxillary expansion device with posterior implants: A finite element study. Natl J Maxillofac Surg 2021;12:171-80.

orthopedic forces unravel the midpalatal suture.[1,2] However, in adult patients, there is increased thickness of the bone with the plasticity and pliability of the bone reduced. Further, in skeletally matured individuals, there is the obliteration of the mid palatal suture (MPS)[3] and increased resistance from the circummaxillary sutures such as pterygomaxillary and the other zygomatico facial sutures.[4,5] Recognized areas of stresses that restrain the unrestricted opening of the maxilla are the midpalatal suture (medially), piriform aperture pillars (anteriorly), the zygomatic buttress (laterally), and the pterygoid junction (posteriorly).[6] In such cases, the efficient treatment modality suggested for MTD along with orthopedic appliance in adults is surgically assisted RME (SARME)[7] or otherwise called as surgically assisted RPE.[8] SARME releases the palatal plates from the fortification caused by the circumpalatal sutures and offers a true orthopedic effect with unwanted side effects such as lateral tipping of the posterior teeth, buccal fenestrations, failure to open the midpalatal suture, alveolar bending, extrusion of posterior teeth, pain, instability, and root resorption being zeroed.[9]

Since its first description of skeletal maxillary expansion by Brown 1938, several technical approaches have been advocated. He utilized a midpalatal osteotomy as it was hypothesized that this area was the most resistant to palatal separation.[10] Since then, several authors have proposed different areas of resistance and advocated several combined osteotomies to mobilize the maxillary halves.[5,11-15] More specifically, the need for releasing the maxilla from the posterior stresses of the pterygoid plates along with the midpalatal osteotomy has been advocated[5,11] for the distribution of stresses during RME. Combined with midpalatal separation and pterygomaxillary disjunction (PMD), Oztürk *et al*.[5] suggested Le fort I osteotomy and de Assis *et al*.[11] proposed a sub-total Le Fort I osteotomy with a step in the zygomatico-maxillary buttress for the stable expansion of the maxillary halves. However, Contar[12] proposed a modified Le Fort I Osteotomy, not including the separation of the pterygomaxillary suture and down fracture. whereas Lehman *et al*.,[13] Bays and Greco[14] and Seeberger *et al*.[15] have shared the more conservative approach that removing the resistance from the zygomatic buttress is sufficient for true orthopedic expansion without involving the pterygoid buttress. According to them, PMD is associated with patient discomfort and morbidity. Thus, a review of the literature reveals that there is no current unanimity and concurrence on surgical treatment to be followed.

Various trans-palatal distraction devices include (1) tooth-borne expanders (**TBEs**) (2) bone borne expanders **(BBEs)** and (3) Hybrid Hyrax expanders (HHE) - attached to both the basal bone and teeth. Anterior palate within 5 mm of the midline is considered to be the safe zone for the use of orthodontic mini-implants. It has encouraged the use of the so-called hybrid expanders, which are partially tooth-borne and bone-borne.[16] The HHE appliance exhibited less pivoting effect when compared with tooth-borne and bone borne.[17] Further, the Finite Element Model (FEM) study of Jain *et al*.[18] on micro implant assisted RME has demonstrated the parallel mode of separation of midpalatal suture with mini implants being placed between premolars and molars. Kayalar *et al*.,[19] in his clinical study, established the advantages of the hybrid appliance, when combined with PMD over the tooth-borne appliance. It was anticipated that the placement of implants posterior to the Hyrax screw might cause separation of the palatal plates in a parallel mode in SARME patients with less splaying effect. Hence, the purpose of this study was to evaluate the effect of different osteotomy techniques with and without PMD during RME on the craniofacial structures when expanded with a Hybrid Hyrax appliance with posteriorly anchored implants. The FEM analysis was chosen for this study over experimental and conventional methods as it provides three-dimensional (3D) models with the freedom to simulate the orthodontic force system applied clinically.

MATERIALS AND METHODS

The study was carried out after obtaining the clearance from the Institutional ethical committee (RC. No. NDC/PG/DISS/2015-2016/EC 2015, date February 16, 2016). The details of the patient on the records were masked for the conduction of the study. A CT scan of the skull-128 sliced with 0.6 mm interval of a 20-year-old female (GE optima 660, GE health care, Buckinghamshire, United Kingdom, 2012 model) was retrieved from the archives of Medical records of Department of Oral and Maxillofacial Surgery, Narayana Dental College and Hospital, Nellore, India. The patient had transverse constriction of the maxilla and bilateral cross-bite of >10 mm, without a history of previous trauma or surgery of the craniofacial region. A 3D geometric model of the skull and the dentition for this FEM study was constructed in sequential steps utilizing the *DICOM* (Digital Imaging and Communications in Medicine) file format. The CT scan images were transferred into 3D Computer-Aided Design (CAD) and Computer-Aided Engineering Model. The software utilized in the sequence are Mimics innovation 14 suite software (Medical Image Segmentation for Engineering on Anatomy) for creating a stereolithographic (STL) file, *Rapidform XOR-3* (Inus software co. South Korea) for refining the model and solid works, and 2007 software (Solid works, USA) was used to fill the created volume from STL file to generate the finite model [Figure 1].

Different types of Osteotomy cuts of 1.5–2 mm thickness were incorporated on to the five different individual models created, categorized into five different Groups; GROUP 0 – A

Control Group with no osteotomy cut; GROUP I – Mid Palatine Osteotomy only; GROUP II – Sub-Total Le Fort I Osteotomy only; GROUP III – Sub-Total Le Fort I + Mid-Palatal Osteotomy; GROUP IV – Sub-Total Le Fort I + Mid-Palatal Osteotomy + Bilateral Pterygo-Maxillary Disjunction.

The original Hybrid Hyrax of Wilmes *et al*.[16] was modified, and it consists of two components: (1) Tooth-Borne component: Maxillary canine and 1st premolar are banded and made as a single unit for a better anchorage and fixed to the anterior arm of the Hybrid Hyrax model, and (2) Bone-Borne component: The posterior arm of the Hyrax model is attached to a mini-screw of 8.0 mm length and 2.0 mm diameter and implanted in the palatal cortical bone at an angle of 65°–70°, at the inter-dental space between maxillary 2nd premolar and 1st molar, The above-described CAD models with each of the different groups were fitted with the Hybrid appliance designed for the purpose. Later, the created volumes were individually divided into a finite number of elements; by the process known as MESHING, which was done by *Abaqus* (version 6.14, Vélizy-Villacoublay, France). The complete geometry now comprised an assemblage of discrete pieces, called Elements connected at a finite number of points, called Nodes. The isotropic mechanical properties, Young's Modulus (Y) in Mega-Pascal (MPa) and Poisson's ratio ('Y) were assigned adapted from previous studies.[18,20] The three-dimensional changes in the NM complex were measured between the selected anatomical points [Tables 1, 2 and Figures 2, 3].

Nine craniofacial sutural systems incorporated in the study are MPS, sphenozygomatic (SZ), zygomaticomaxillary (ZM), zygomaticofrontal (ZF), zygomaticotemporal (ZT), frontonasal, frontomaxillary, NM and intranasal suture (IN).

A known total transversal (X) displacement of 10 mm (5 mm per side) with an incremental magnitude of +0.5 mm was applied at the point of insertion of palatal implants. The corresponding displacements (in mm) of various craniofacial structures were evaluated along the X, Y, and Z coordinates against the transverse displacement of palatal shelves. An orthopedic loading force of 1000 g per side was utilized based on the previous study.[20] 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 the vertical direction: +Ve (superior) and −Ve (inferior).

The stress distribution at constructed nodal points was calculated by using the von Mises Criterion because of the appropriateness and the validity of the von Mises theory of failure.[21,22] The von-Mises stress was used to calculate internal stress reaction (kg/mm^2 or N/mm^2). Restraints were established at all other nodes of the cranium lying on the symmetrical plane, and appropriate boundary conditions were imposed. In addition, a zero-displacement and a zero-rotation boundary

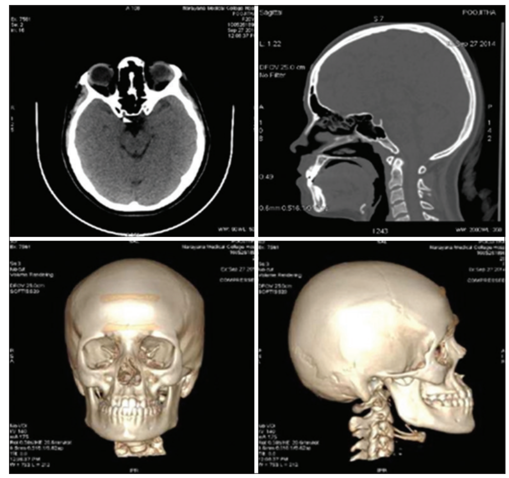

Figure 1: Construction of skull from computed tomography scan for Finite Element Model

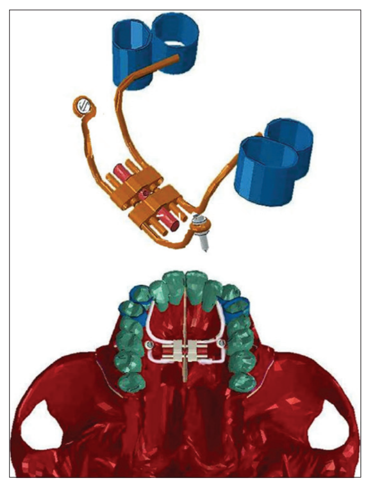

Figure 2: Fitting of Hybrid Hyrax appliance on the model

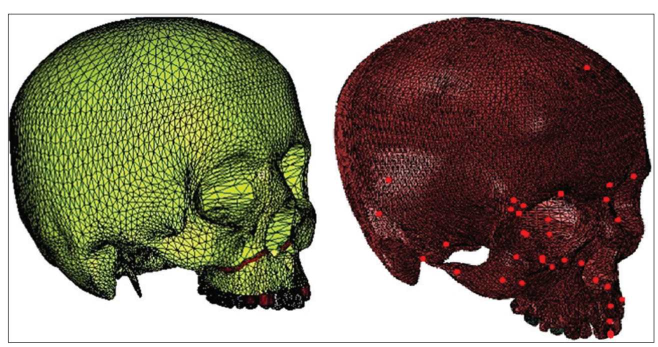

Figure 3: Meshing of the model

Table 1: Mean displacement (in mm) pattern of various craniofacial structures – dental and midline structures

Anatomical structure	Group	X		Y		Z	
		Mean	*P*	Mean	*P*	Mean	*P*
Mesio incisal tip edge	0	2.780	NS	0.724	NS	−0.724	NS
	I	4.044		0.696		−0.696	
	II	3.545		0.694		−0.694	
	III	4.654		0.654		−0.418	
	IV	4.754		0.625		−0.425	
Canine cusp tip	0	2.374	NS	0.664	NS	−0.635	NS
	I	3.795		0.616		−0.615	
	II	3.145		0.594		−0.634	
	III	4.234		0.584		−0.524	
	IV	4.345		0.564		−0.534	
MB cusp tip of the first molar	0	2.274	NS	0.612	NS	0.614	NS
	I	3.245		0.584		0.592	
	II	3.045		0.574		0.614	
	III	4.112		0.564		0.515	
	IV	4.254		0.545		0.505	
ANS	0	1.787	<0.01**	1.039	NS	−1.144	NS
	I	2.098		0.656		−1.051	
	II	2.562		0.591		−1.095	
	III	3.356		0.585		−1.060	
	IV	3.587		0.577		−1.048	
Point A	0	2.007	<0.01**	1.202	NS	−1.194	NS
	I	3.044		0.867		−1.125	
	II	2.839		0.822		−1.178	
	III	3.870		0.808		−1.156	
	IV	3.887		0.810		−1.160	
PNS	0	1.287	<0.01**	1.322	NS	0.636	NS
	I	1.550		0.770		0.725	
	II	1.923		0.749		0.727	
	III	2.678		0.741		0.687	
	IV	3.008		0.760		0.653	
Nasion	0	0.306	NS	0.227	NS	−0457	NS
	I	0.398		−0.314		−0.683	
	II	0.423		−0.314		0.659	
	III	0.454		−0.332		−0.724	
	IV	0.463		−0.333		−0.735	

‡Computation for each half of the maxilla (5 mm of transverse expansion on each side), $^{**}P<0.01$: Very significant, $^{*}P<0.05$: Significant, NS: $P>0.05$. Displacement - X-axis: Transverse, Y-axis: Sagittal, Z: Axis vertical, +Ve values: Outward, upwards and forwards, −Ve values: Inward, downwards and backwards, NS: Not significant

condition were imposed on the nodes along with the foramen magnum. The nodes of the mid-palatal suture that were placed on the symmetrical plane were left unconstrained. This was done to investigate the stress distribution and the deformation of the craniofacial complex after splitting the mid-palatal suture. The interpretation of the stress around mini-screws was not considered separately in the study.

The output is primarily in the form of color-coded maps, which can be interpreted as the quantitative data. Positive values and negative values in the column of the stress spectrum correspond to tensile and compressive forces, respectively. The quantitative data were presented in the form of mean and standard deviation. The data collected were analyzed using Statistical software, *IBM SPSS* Software, Version 22 (Armonk, NY, USA: IBM Corp). The differences between the mean coordinates for each aspect of the craniofacial sutures and structures were calculated and statistically analyzed. One-way analysis of variance test was utilized for the comparison of intragroup and intergroup variability. *Post hoc* Tukey test was utilized for comparison between any two sets of individual groups.

RESULTS

The mean and standard deviation of the net amount of displacement of different craniofacial structures and stress distribution at the marked sutures for each of the

Table 2: Mean displacement (in mm) pattern of various craniofacial structures – lateral structures

Anatomical structure	Group	X		Y		Z	
		Mean	*P*	Mean	*P*	Mean	*P*
Tuberosity	0	1.670	<0.01**	0.875	NS	0.234	NS
	I	2.044		1.143		0.345	
	II	2.139		−1.134		0.512	
	III	2.100		−1.194		0.556	
	IV	3.234		−1.334		0.602	
Zygomatic buttress	0	0.876	<0.01**	0.019	NS	0.513	NS
	I	1.295		0.046		0.713	
	II	1.313		−0.054		0.707	
	III	1.485		−0.074		0.723	
	IV	1.658		−0.094		0.693	
Lateral pterygoid plate (inferior)	0	0.829	NS	−0.591	NS	−0.391	NS
	I	0.987		−0.592		−0.413	
	II	1.363		−0.599		−0.425	
	III	1.426		−0.613		−0.495	
	IV	1.654		−0.694		−0.523	
Lateral pterygoid plate (superior)	0	0.279	NS	−0.112	NS	−0.102	NS
	I	0.582		−0.184		−0.134	
	II	0.622		−0.196		−0.146	
	III	1.106		−0.216		−0.224	
	IV	1.415		−0.424		−0.384	
Medial pterygoid plate (inferior)	0	0.423	NS	−0.191	NS	−0.224	NS
	I	0.996		−0.292		−0.270	
	II	1.012		−0.399		−0.302	
	III	1.114		−0.412		−0.392	
	IV	1.424		−0.465		−0.412	
Medial pterygoid plate (superior)	0	0.075	NS	−0.191	NS	−0.123	NS
	I	0.123		−0.292		−0.142	
	II	0.186		−0.399		−0.168	
	III	0.224		−0.412		−0.224	
	IV	0.824		−0.465		−0.384	
Nasion	0	0.306	NS	0.227	NS	−0457	NS
	I	0.398		−0.314		−0.683	
	II	0.423		−0.314		0.659	
	III	0.454		−0.332		−0.724	
	IV	0.463		−0.333		−0.735	
	I	0.058		−0.088		0.054	
	II	0.058		−0.084		0.058	
	III	0.084		−0.086		0.058	
	IV	0.086		−0.087		0.062	

‡Computation for each half of the maxilla (5 mm of transverse expansion on each side), ***P*<0.01: Very significant, **P*<0.05: Significant, NS: *P*>0.05. Displacement - X-axis: Transverse, Y-axis: Sagittal, Z: Axis vertical, +Ve values: Outward, upwards and forwards, −Ve values: Inward, downwards and backwards, NS: Not significant

incremental activation for a total of 10 mm of transverse expansion was calculated [Tables 1 and 2]. The highest displacement in sagittal direction is found at the incisal tip in all the groups. In general, stress is increased with the increasing amount of expansion in all types of appliances, at all the sutures. The highest stress values were found at the mid-palatal sutures compared to the other sutures [Tables 3 and 4]. Group III osteotomy cuts exhibited the overall highest value (292.99 Mpa) at the posterior end of MPS. The difference in stress patterns exhibited by the four types of osteotomy cuts at different sutures is statistically very significant at most of the sutures that are present laterally in the skull [Table 5].

DISCUSSION

The present study was based on the parametric analysis of 3D finite element analysis of computed tomography (CT) scan of the skull in maxillary crossbite to investigate the stress distribution and displacement patterns of various craniofacial structures with different osteotomy cuts during SARME. Further, the study explored the feasibility of placing the implant anchors in

Table 3: Stress distribution at various sutures (all values in N/mm^2=1 Mpa) – midline structures

Suture	Aspect	Osteotomy Groups					ANOVA	
		0	I	II	III	IV	*F*	*P*
Fronto nasal	Lateral	10.46	20.88	21.12	7.86	4.13	9.226	<0.001**
	Middle	12.42	24.34	24.58	8.97	4.81	9.234	<0.001**
	Medial	10.74	21.19	21.27	7.54	3.98	9.531	<0.001**
Fronto maxillary	Anterior	10.00	19.55	19.74	7.63	4.18	8.743	<0.001**
	Middle	11.07	21.20	21.33	8.66	4.87	8.218	<0.001**
	Posterior	10.25	19.26	19.20	8.41	4.852	7.503	<0.001**
Naso maxillary	Superior	13.95	26.89	27.18	10.25	5.55	8.906	<0.001**
	Middle	2.35	5.623	5.537	2.30	1.67	8.004	<0.001**
	Inferior	8.46	18.11	20.30	9.91	7.38	6.024	0.001**
Inter nasal	Anterior	7.53	14.76	17.79	12.95	12.70	2.505	0.06 (NS)
	Middle	11.47	18.60	20.03	21.45	21.35	1.576	0.20 (NS)
	Posterior	13.18	17.66	18.98	22.44	18.53	1.075	0.38 (NS)
Midpalatal	Anterior	34.25	77.59	78.33	79.66	82.44	2.574	0.05 (NS)
	Middle	163.54	253.75	253.23	245.19	244.08	0.89	0.48 (NS)
	Posterior	181.72	256.00	270.10	292.99	282.72	3.63	0.01*

Group 0: No osteotomy, Group I: Only MPO, Group II: Only subtotal LF; Group III: MPO + LF, Group IV: MPO + LF + bilateral PMD. MPO: Midpalatal osteotomy, LF: Le fort I, PMD: Pterygo-maxillary disjunction, ANOVA: Analysis of variance, NS: Not significant. ***P*<0.01 -very Significant; **P*<0.05 –Significant; *P*>0.05-NS

Table 4: Stress distribution at various sutures (all values in N/mm2=1 Mpa) – lateral structures

Suture	Aspect	Osteotomy groups					ANOVA	
		0	I	II	III	IV	*F*	*P*
Spheno zygomatic	Lateral	2.03	4.96	4.99	1.88	1.27	9.121	<0.001**
	Middle	2.35	5.62	5.53	2.30	1.67	8.004	<0.001**
	Medial	3.21	7.93	7.66	3.03	1.35	10.209	<0.001**
Zygomatico maxillary	Anteromedial	5.64	14.60	13.47	2.62	2.49	12.942	<0.001**
	Posteromedial	6.66	15.93	16.25	5.65	2.84	10.557	<0.001**
	PosteroLateral	3.40	5.72	5.75	2.96	1.91	5.422	0.001**
Zygomatico temporal	Lateral	5.85	8.87	9.18	3.45	4.12	5.108	0.002*
	Medial	4.56	9.12	8.84	4.11	3.04	6.368	<0.001**
Zygomatico frontal	Anteromedial	2.61	8.70	8.64	2.86	1.53	12.093	<0.001**
	Posteromedial	2.03	4.96	4.99	1.88	1.27	9.121	<0.001**
	Anterolateral	3.45	14.99	15.25	1.89	1.66	17.167	<0.001**
	Posterolateral	4.34	15.85	16.41	1.92	1.05	17.499	<0.001**

ANOVA: Analysis of variance. ***P*<0.01 -very Significant; **P*<0.05 –Significant; *P*>0.05-NS

the posterior segment in a Hybrid RME appliance to maximize the transverse expansion at the posterior palatal region. The three-dimensional model provides the freedom to stimulate orthodontic force systems and osteotomy procedures applied clinically and allows analysis of the response of the craniofacial skeleton to the orthodontic loads in 3D space. Matteini and Mommaerts[23] and Glassman *et al*.[24] stated that the mid-palatal suture, the zygomatic buttress, the piriform aperture, and the pterygomaxillary junction are the primary sites of resistance to maxillary expansion. With increasing inter-digitation 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. In the literature, various types of osteotomies and also the number of osteotomies to be done to reduce the circum-maxillary resistance has been proposed.[5,11-18] The disjunction of pterygoid plates during surgical procedures has been the topic of debate. Regarding the type of orthopedic appliances for RME, Mommaerts[25] suggested the bone-borne appliance with the SARME technique to prevent these side effects from overcoming the undesirable side effects associated with the TBEs. The BBE appliances transmit the transverse forces directly to the palatal bone, resulting in more skeletal expansion closer to the center of resistance. However, BBE appliances are associated with periodontal damage, root infections, asymmetric widening. In addition, BBE devices are invasive with insertion, and removal requires reflection of the flap, and there is further dislodgement of the distractor modules.[26-28] To overcome these problems, Wilmes *et al*.[16] introduced a hybrid RME device (Hybrid Hyrax), an expander that is both tooth-borne and bone-borne. This original hybrid RME device was designed with two orthodontic mini-implants in the anterior palate and tooth support from the first molars.

Table 5: Pairwise comparison of combined average stresses at different sutures in between groups

	Group (I)	Group (J)	Mean difference (I−J)	Standard error	*P*
Spheno zygomatic	0	1	−4.726	1.317	0.007*
		2	−4.458	1.317	0.01*
	1	3	4.903	1.317	0.005*
		4	6.578	1.317	<0.001*
	2	3	4.635	1.317	0.008*
		4	6.310	1.317	<0.001*
	3	4	1.675	1.317	0.71 (NS)
Zygomatico maxillary	0	1	−9.274	2.703	0.01*
		2	−9.592	2.703	0.008*
	1	3	10.284	2.703	0.004*
		4	13.093	2.703	<0.001*
	2	3	10.603	2.703	0.003*
		4	13.411	2.703	<0.001*
	3	4	2.809	2.703	0.84 (NS)
Zygomatico frontal	0	1	−6.094	1.427	0.001*
		2	−6.036	1.427	0.001*
	1	3	5.843	1.427	0.002*
		4	7.169	1.427	<0.001*
	2	3	5.784	1.427	0.002*
		4	7.110	1.427	<0.001*
	3	4	1.326	1.427	0.88 (NS)
Fronto nasal	0	2	−12.163	4.200	0.04*
	1	3	15.363	4.200	0.006*
		4	19.524	4.200	<0.001*
	2	3	15.605	4.200	0.005*
		4	19.766	4.200	<0.001*
	3	4	4.161	4.200	0.86 (NS)
Fronto maxillary	0	2	−9.740	3.390	0.04*
	1	3	11.920	3.390	0.009*
		4	15.369	3.390	<0.001*
	2	3	12.115	3.390	0.007*
		4	15.563	3.390	<0.001*
	3	4	3.448	3.390	0.85 (NS)
Naso maxillary	1	3	16.645	4.662	0.007*
		4	21.338	4.662	<0.001*
	2	3	16.935	4.662	0.006*
		4	21.627	4.662	<0.001*
	3	4	4.693	4.662	0.85 (NS)
Mid palatine posterior	0	1	−74.28	123.116	0.03*
		2	−88.38	123.116	0.03*
		3	−101.00	123.116	0.04*
		4	−113.53	123.116	0.04*
	3	4	12.532	123.116	1.00 (NS)

+Only parameters between the groups with statistical significance are given except for Groups III and IV… Tukey *post hoc* test, $^{**}P<0.01$: Very significant, $^{*}P<0.05$: Significant, NS: $P>0.05$. NS: Not significant

Previous clinical studies demonstrated that the more posterior the point of application of distraction closer is the anterior: posterior expansion with RME appliances.[29,30] This can be further augmented by the PMD. Posterior insertion of two mini-screws between the second premolar and first molar, located approximately 5–6 mm from the tooth, seems to be preferable and harmless for teeth. This area was described as a safe place for the placement of mini-screws.[18,31] Hence, this study was taken to see the effects of different surgical osteotomy procedures with or without PMD during SARME with a Hybrid Hyrax appliance designed with posterior implants.

Displacement pattern

Displacement at different landmarks in all the five groups was analyzed in all the three planes of space [Tables 1 and 2].

Transverse plane (X-axis)

A pyramidal mode of displacement of the naso-maxillary complex is seen in frontal and axial plane similar to other FEM studies.[32,33] The structures close to the base of the cranium exhibited less transverse expansion than the inferiorly located structures. This manner of expansion is seen in all the groups, surgical or nonsurgical, with the apex of the pyramid at nasion and base toward the occlusal surface in the coronal plane. The anterior dental structures, as measured at the tip of the incisors, exhibited a maximum displacement of 4.7 mm per each half of the maxilla and is highest for Group V surgical osteotomies. The ratio of Inter-canine and Inter-molar width are found to be near unique in all the groups. This may be an anchorage effect obtained by the anterior arms of the hybrid appliances from the canine and premolar teeth. Point A, ANS, Supradentale, Zygomatic buttress, PNS and tuberosity displayed a significant difference between the groups [Tables 1 and 2 and Figure 4]. The effect of the mid-palatal osteotomy seems to have more effect on the anterior structures, and the lateral osteotomies by Le Fort I and PMD seem to have a profound influence on the posterior structures during the transverse expansion. This is evident in Group IV with the highest displacement along X-axis at most of the points measured, and this may suggest that the combination of all 4 of the osteotomies used in this group is helpful to increase the amount of expansion in transverse axis when compared to other groups. The earlier FEM results from the study[18] showed that ratio of displacement of PNS to ANS is 70% when the anchoring implant is placed anteriorly. With a posteriorly placed bone-anchoring unit in the present hybrid appliance, it was noted that ANS: PNS is 79% Group 3, and in Group IV, the same is calculated to 83% (3.6:3.0) [Figure 5]. When analyzed, the difference in displacements was found to be insignificant between these two groups at PNS and tuberosity. The ratio of anterior to posterior expansion is higher in patients with no pterygoid separation; in contrast, those who underwent pterygoid osteotomy. This might be considered at an individualized treatment to achieve more distractions on either the posterior or the anterior level.[26] Thus, it can be categorically stated that PMD has a bearing effect in increasing the transverse displacement of palatine plates in general and particularly at the posterior end. Further, it can also be assumed that the posterior skeletal expansion may be augmented by a posteriorly anchored distractor. Thus with reference to these study groups, additional surgical procedures with different osteotomies help decrease the stress pattern during RME.

Sagittal plane (Y-axis)

The incisors, canines, and molars exhibited a positive (forward) displacement. The zygomatic buttress, tuberosity in the case of the le fort I and PMD osteotomies exhibited a backward displacement as seen in Group II, Group III and Group IV as compared to the positive displacement of these structures in nonsurgical (Group 0) and mid-palatal osteotomies only (group I). Maximum displacement is exhibited by Group III and Group IV osteotomies.

Vertical plane (Z-axis)

The Nasion, point-A, supradentale, canine cusp tip located anteriorly to the implants exhibited negative (downward) displacement, whereas the molars, PNS, tuberosity, and zygomatic buttress exhibited positive (superior) displacements. It can also be seen that the lateral structures exhibited an upward movement, whereas the midline structures exhibited downward movement during transverse expansion in this study. This may be advantageous in long face patients with the posterior inclination of the maxillary structures. The difference in displacement between all the

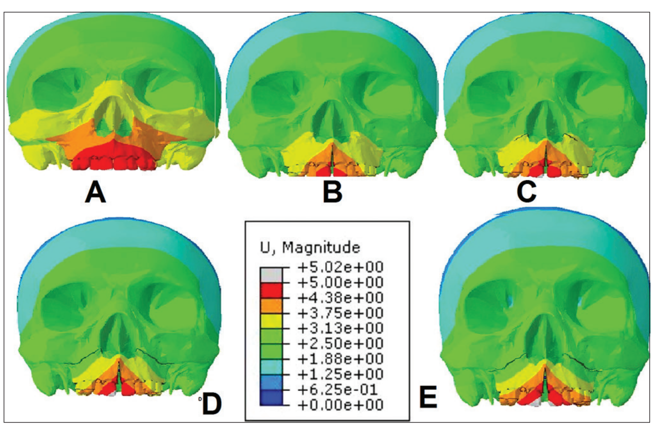

Figure 4: Frontal view. Displacement pattern A-Group 0- No osteotomy; B- Group I- only Midpalatal osteotomy (MPO); C-Group II- only Subtotal Le fort I (LF); D-Group III-MPO+LF; E-Group 4- MPO+LF+ Bilateral Pterygo-Maxillary Dysjunction (PMD)

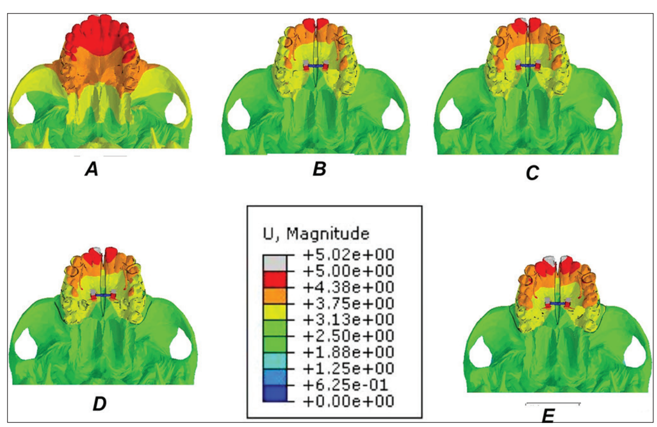

Figure 5: Occlusal view. Displacement pattern A-Group 0- No osteotomy; B- Group I- only Midpalatal osteotomy (MPO);C-Group II- only Subtotal Le fort I(LF); D-Group III-MPO+LF; E-Group 4- MPO+LF+ Bilateral Pterygo-Maxillary Dysjunction (PMD)

five groups at most of the sutures in Y axis and Z axis is nonsignificant [Table 1].

Stress concentration

The stress distribution is more pronounced along sutures located in the midsagittal plane such as Midpalatal, InterNasal, Naso Maxillary, Fronto Maxillary, Fronto Nasal in the decreasing order [Table 3]. In this study, the lateral stresses were dissipated laterally to ZM suture and further to the distant sutures not directly attached to the maxilla, as evidenced by stress values at SZ, ZT, and ZF sutures. There is gradual dissipation of the stresses in the cephalic direction as evidenced by the stress concentration of sutures located at the level of the palate compared to those situated toward the base of the skull. In the present study, stress concentration at different sutures was least in Group IV, followed by Group III except for IN and mid palatine suture [Tables 3 and 4 and Figure 6].

To reduce the resistance from the areas of buttressing bone and ossified sutures, surgery often involves subtotal Le Fort I type osteotomy, including along with PMD and mid-palatal split. These osteotomy procedures aids in removing stress barriers and dissipation of the stresses built up by distraction forces uniformly in the craniofacial skeleton and accomplished stable skeletal expansion of maxilla. This is one of the reasons higher values of displacement were noted in this study in Group IV.

Another finding is that the highest stress concentration is pronounced in all the groups along the sutures in the sagittal plane that expand the palatal shelves in the transverse direction such as a mid-palatine suture. From the results of this study, it can be extrapolated that all the RME appliances are capable of opening up of the midpalatal suture. The same amount of expansion is produced by a posteriorly anchored hybrid appliance with and without PMD, as seen with most of the parameters under study. Clinically, this implies that some form of individualization is required for the osteotomy procedures depending on the area of resistance.

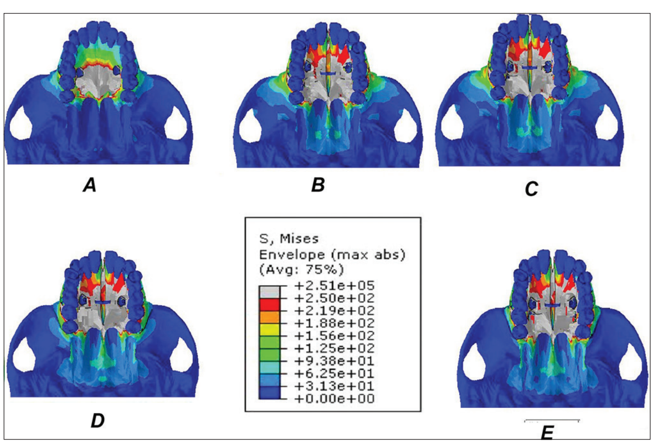

Figure 6: Stress pattern A-Group 0- No osteotomy; B- Group I- only Midpalatal osteotomy (MPO); C-Group II- only Subtotal Le fort I (LF); D-Group III-MPO+LF; E-Group 4- MPO+LF+ Bilateral Pterygo-Maxillary Dysjunction(PMD)

The human craniofacial complex remains a geometrically complex structure with buttressing bones that topographies network of sutures spreading in different directions that interconnect the bones of the craniofacial skeleton. To study all the biological phenomena that take place, a number of assumptions were made in the construction and the analysis of the FEM developed in this study that may, in theory, lead to less precision in the results. In the clinical situation between each turn of the screw, there is a quiescent period with consequent tissue rebound. This cannot be incorporated into the experimental setup. Further, the study tried not to differentiate the effects of RME appliance and osteotomy cuts individually. This is basically an *in-vitro* study. The effects of aging, soft-tissue resistances cannot be encompassed in the model.

CONCLUSIONS

1. All the osteotomies generally are associated with an increased displacement of palatal shelves and dissipation of the stresses at different sutures.
2. The posteriorly anchored Hybrid Hyrax produces favorable posterior to anterior skeletal expansion
3. The PMD increases the magnitude of displacement of the posterior palate in particular and overall sagittal displacement in general.
4. The effects of the posterior Hybrid appliance and the PMD are synergistic.
5. Posterior Hybrid Hyrax without PMD is equally effective as one with PMD.

Acknowledgments

Special thanks to Mr. Mahesh Rayakota, Lead engineer, for fabricating this Finite element model.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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