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British Journal of Oral and Maxillofacial Surgery 56 (2018) 177–181

BRITISH Journal of Oral and Maxillofacial Surgery

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# Evaluation of stress by finite element analysis of the midface and skull base at the time of midpalatal osteotomy in models with or without pterygomaxillary dysjunction

A. Esen[a,*], E. Soganci[b], E. Dolanmaz[c], D. Dolanmaz[d]

[a] *Necmettin Erbakan Universtiy, Faculty of Dentistry, Department of Oral and Maxillofacial Surgery, Konya, Turkey*
[b] *Necmettin Erbakan Universtiy, Faculty of Dentistry, Department Orthodontics, Konya, Turkey*
[c] *Medipol Mega University Hospital, Department Orthodontics, Istanbul, Turkey*
[d] *Selcuk Universtiy, Faculty of Dentistry, Department of Oral and Maxillofacial Surgery, Konya, Turkey*

Accepted 3 January 2018
Available online 1 February 2018

**Abstract**

Surgically-assisted rapid maxillary expansion (SARME) is commonly used to treat skeletally mature patients with transverse discrepancies. Some osteotomies are made in areas that resist expansion, but there is no clear consensus about the sequence in which the osteotomies are made. Some clinicians do the pterygomaxillary osteotomy last, while others do it before the midpalatal osteotomy. We used the finite element method to measure the stresses on the midface, cranial base and pterygoid plates at the time of midpalatal osteotomy in two models, one with and one without pterygomaxillary dysjunction (PMD). In both, SARME consisted of maxillary bilateral osteotomy from the piriform rim to the pterygoid plate. Midpalatal osteotomy was also done in both. In the PMD model, minimum principal stresses increased on the midface, and maximum principal and von Mises stresses increased at the cranial base and on the pterygoid plates. Our results suggest that the stresses on the midface and cranial base can be reduced during midpalatal osteotomy in adults if the pterygomaxillary osteotomy is done last.


*Keywords:* Cranial base; Mid-face; Finite Elements Method; Rapid maxillary expansion

## Introduction

Transverse deficiencies of the maxilla can be seen in both adolescents and adults, and are characterised by a narrow maxillary arch, unilateral or bilateral malocclusion, and severely crowded teeth, particularly in the anterior region.[1] They can be corrected by orthodontic and orthopaedic forces in young people, but in those who are skeletally mature, treatment is often by surgically-assisted rapid maxillary expansion (SARME), as orthopaedic maxillary expansion is inadequate in this group.[2,3] Although SARME is usually reliable, it can lead to serious complications such as retrobulbar haemorrhage, life-threatening delayed epistaxis, partial paralysis of the oculomotor nerve, carotid cavernous fistula, and massive infarction of the middle cerebral artery.[4–8]

In this procedure, osteotomies are made in areas of resistance such as the piriform rim, midpalatal suture, and zygomaticomaxillary buttress. However, there is no clear consensus about when to separate the pterygomaxillary region.[3,9] Some clinicians do the pterygomaxillary osteotomy last,[9–11] while others do it before the midpalatal osteotomy.[12–14] As far as we know, no published study has

* Corresponding author at: Necmettin Erbakan Universitesi, Dis Hekimligi Fakultesi, Ankara Cd. No:74/A, Konya, Turkey. Tel.: +90 332 220025-1223, fax: +90 332 2200045.

*E-mail address:* aesen@konya.edu.tr (A. Esen).

https://doi.org/10.1016/j.bjoms.2018.01.001
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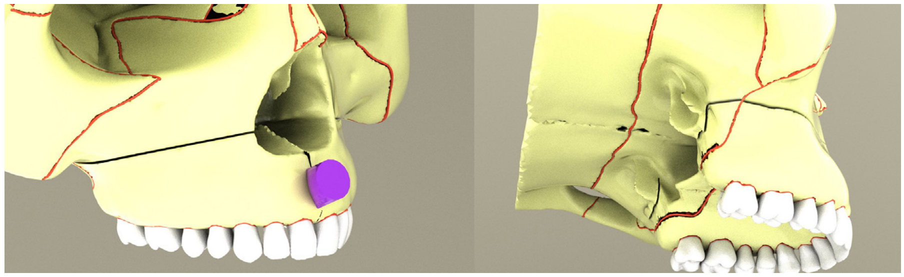

Fig. 1. A force was applied with a sharp osteotome to the inter-radicular midline region for the midpalatal osteotomy. Pterygomaxillary dysjunction (PMD) was done in the second model.

Table 1
Young's modulus and Poisson's ratio for the structures.

| Structure | Young's modulus (Gpa) | Poisson's ratio |
|---|---|---|
| Cortical bone | 13.7 | 0.3 |
| Cancellous bone | 1.37 | 0.3 |
| Suture | 0.069 | 0.45 |

related the stresses that occur in the midface, cranial base, and pterygoid plates, to the sequence of the osteotomies.

The aim of this study was therefore to measure the stresses in these areas at the time of midpalatal osteotomy in models with or without pterygomaxillary dysjunction (PMD) by the finite element method.

## Material and methods

This research was done by linear static with 3-dimensional finite element stress analyses. To model the bone, we used cone-beam computed tomography (CT) (ILUMA® CBCT Scanner, 3M Imtec) to scan an adult maxilla and obtained 601 sections. Volumetric data were then reconstructed with slices 0.2 mm thick, and the reconstructed sections exported in DICOM 3.0 format into 3D-Doctor (Able Software Corp). This software reconstructs images obtained by various methods including magnetic resonance and CT, and allows them to be modified. Radiographic images were exported into the 3D-Doctor software and the bone tissue separated by looking at Hounsfield values using interactive segmentation. After the decomposition process, complex 3-dimensional rendering produced a model that included the bone texture, which was transformed into a smooth surface that consisted of elements with uniform proportions using the 3D-Doctor software. It consisted of 397 975 elements and 114 166 nodes.

We used 3-dimensional modelling software (Rhinoceros® 4.0, McNeel) and analysis programs (VRMesh Studio, VirtualGrid Inc, and Algor Fempro, ALGOR Inc) on a computer (Intel® Xeon® R CPU 3, Intel Corp) to regulate the network structure and make it more homogeneous, to create the solid model, and do the stress analysis of the finite elements procedures. After the geometric model was created with VRMesh software, it was transferred to Algor Fempro software in a stereolithographic (STL) format for analysis. No information was lost in the transfer, as the coordinates of the nodes were also stored in this format. We used the anatomical study by Cheung et al[15] to standardise the posterior maxilla and pterygoid structures, and defined the mechanical properties of cortical and cancellous bone in the model according to the experimental data in a previous study.[16] Table 1 shows Young's modulus and Poisson's ratios of the bone structures used in the analysis.

We used two different surgical approaches. In both models, SARME consisted of bilateral maxillary osteotomy from the piriform rim to the pterygoid plate. One model had PMD, the other did not. Midpalatal osteotomy was then done in both (Fig. 1). For this procedure, we used a sharp osteotome to apply a force of 150 N to the area around the inter-radicular midline and measured the peak force with a digital force gauge (Shimpo FGN-50B, Shimpo). To reproduce the force used during the operation we placed a flat head on top of the device and hit it 10 times with a hammer. At the time of the osteotomy in both models, we measured maximum and minimum principal stresses (PS max and PS min, respectively) and von Mises stresses in the midface, cranial base, and pterygoid plates.

We used the von Mises criterion (also known as the maximum distortion energy criterion) because it is a well-tested theory of failure that can be used to predict the yield of ductile materials.[17] It states that failure occurs when the energy of distortion reaches the same energy for yield or failure in uniaxial tension, and provides a reasonable estimate of fatigue failure, particularly for repeated tensile and tensile-shear loading. The principal stresses are the maximum and minimum normal stresses in a plane, always perpendicular to each other, and oriented in directions for which the shear stresses are zero. PS max values indicate the most tensile stress while PS min values indicate the most compression.[17]

## Results

*The stresses are shown in Table 2*

*PMD model*
In the midface, PS min values increased on the spina nasalis anterior, and nasofrontal and zygomaticomaxillary areas (Fig. 2). At the cranial base, PS max values increased consid-

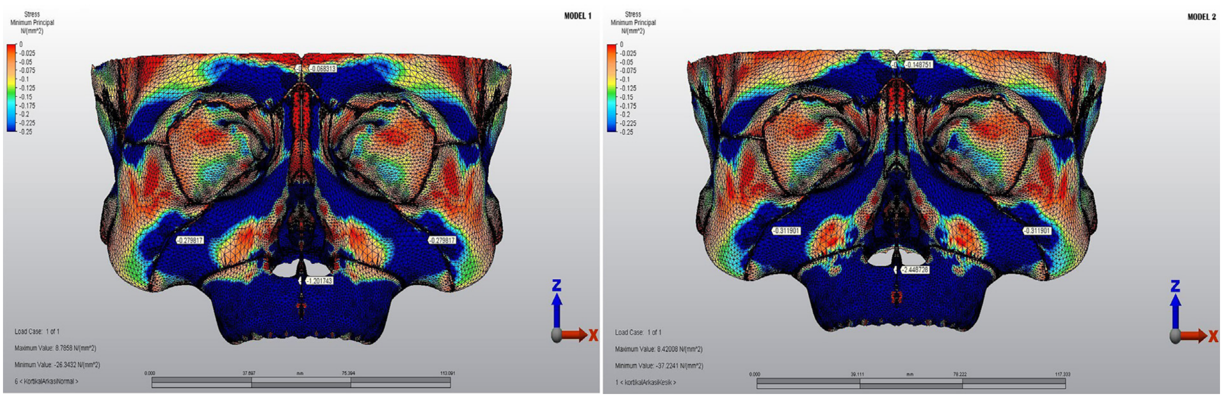


Fig. 2. Minimum principal stresses (PS min) increased on the spina nasalis anterior, nasofrontal and zygomaticomaxillary areas in the PMD model.

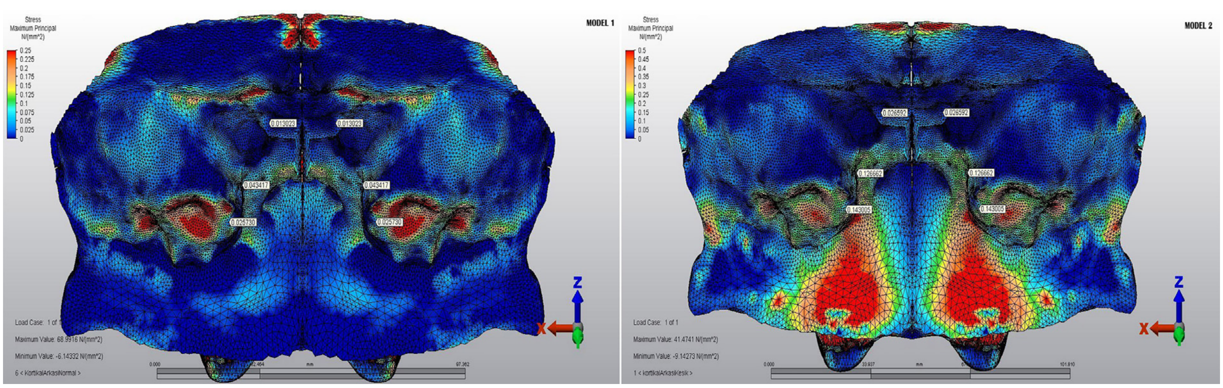


Fig. 3. Maximum principal stresses (PS max) increased on the canalis opticus, sulcus caroticus, and foramen rotundum in the PMD model.

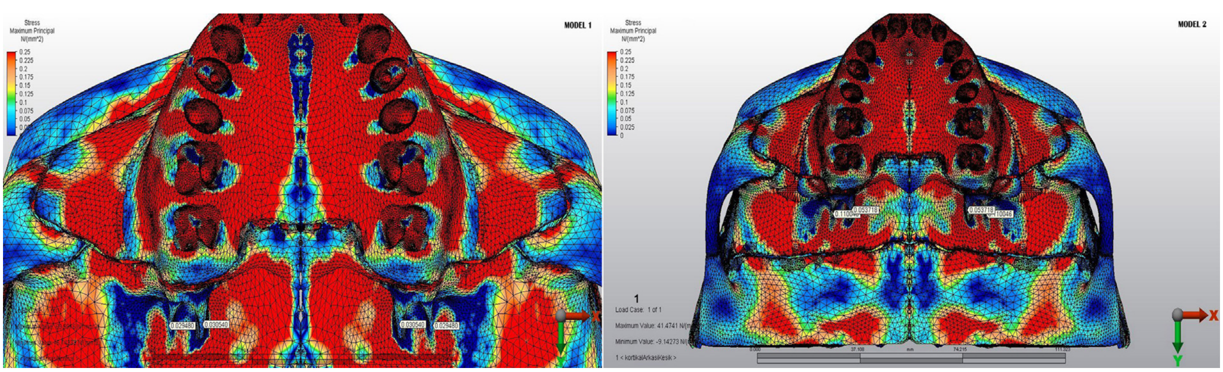


Fig. 4. Maximum principal stress (PS max) increased on the medial and lateral pterygoid plates in the PMD model.

erably on the canalis opticus, sulcus caroticus, and foramen rotundum (Fig. 3), and von Mises stresses increased around the sulcus caroticus and foramen rotundum. PS min values and von Mises stress decreased on the pterygoid plates, but the PS max values increased on the medial and lateral pterygoid plates (Fig. 4).

## Discussion

Previous studies that have reported finite element methods in relation to SARME have focused on the stresses associated with distraction in the craniofacial bones (sphenoid, frontal, temporal, nasal, and occipital bones) and sutures (frontomaxillary, nasomaxillary, zygomaticotemporal, zygomaticomaxillary, and zygomaticofrontal).[17–19] They showed that osteotomies in the pterygomaxillary and zygomatic buttresses are necessary for successful maxillary expansion, and that PMD should be done in adults to reduce stresses at the cranial base and in the midface. However, to our knowledge, no studies have evaluated stresses at the cranial base and pterygomaxillary regions at the time of osteotomy. We therefore investigated these stresses at the time of midpalatal osteotomy in models with and without PMD.

Table 2
Stress values in anatomical regions ($N/mm^2$).

| Anatomical region | Model without PMD | | | Model with PMD | | |
|---|---|---|---|---|---|---|
| | P max | P min | von Mises | P max | P min | von Mises |
| Midface: | | | | | | |
| Spina nasalis anterior | 4.206 | −1.201 | 4.739 | 4.210 | −2.448 | 5.959 |
| Nasofrontal area | 0.322 | −0.068 | 0.341 | 0.119 | −0.148 | 0.235 |
| Zygomaticomaxilllary area | 0,070 | −0,279 | 0,315 | 0,058 | −0,311 | 0,339 |
| Canalis opticus | 0.013 | −0.037 | 0.044 | 0.026 | −0.017 | 0.038 |
| Base of the skull: | | | | | | |
| Sulcus caroticus | 0.043 | −0.010 | 0.049 | 0.126 | −0.028 | 0.144 |
| Foramen rotundum | 0.025 | −0.179 | 0.191 | 0.143 | −0.207 | 0.306 |
| Pterygoid plates: | | | | | | |
| Medial | 0.030 | −0.302 | 0,317 | 0.053 | −0.0003 | 0,051 |
| Lateral | 0.029 | −0.218 | 0,235 | 0.110 | −0.019 | 0.119 |

PMD: Pterygomaxillary disjunction, P max: principal maximum stress, P min: principal minimum stress

Finite element methods have been used in orthognathic surgery to investigate the effects of operations or appliances, and an appropriate model is essential. We took CT images at 1 mm intervals to provide an accurate model that was modified with typical dimensions of bony structures.[15] Previous studies have used 40 000 to 60 000 elements and 75 000 to 100 000 nodes to measure the stresses on the cranial base.[18,19] The model used by Gautam et al[17] contained 108 709 elements and 193 633 nodes. Our model consisted of 397 975 elements and 114 166 nodes, which provided more detailed formation of the anatomical structures.

Many studies on SARME have described pterygomaxillary separation after midpalatal osteotomy,[9–11] but as pterygomaxillary separation is sometimes done first,[12–14] there seems to be no clear sequence of osteotomies in these procedures. We found that compression increased in the midface when midpalatal osteotomy was done in the PMD model, and tension increased considerably at the cranial base. There was also roughly twice as much tension on the canalis opticus, three times as much on the sulcus caroticus, and seven times as much on the foramen rotundum when compared with the model without PMD. This could be because PMD removed the posterior support (and the stress-absorbing effect of the pterygoid plates) from the maxilla, which increased compression in the midface and tension at the cranial base. When the pterygoid plates were separated, compression on them decreased but tension increased slightly. This was probably because the continuity of the pterygoid plates and the base of the skull was preserved although the pterygomaxillary connection was separated.

Biological and mechanical forces affect immature and mature bones differently.[17,20] Some authors have reported that stresses at the cranial base are greater when the elasticity of the bone is reduced,[18] so compared with adolescents, osteotomy or distraction in adults can place more stress on the bone and lead to easier fracture. Lanigan and Mintz[6] reported a case of temporary partial paralysis of the oculomotor nerve in a 19-year-old man with severe transverse deficiency after SARME. CT showed a fracture that extended from the posterior maxillary sinus to the left body of the sphenoid bone. In another case, orbital compartment syndrome from a retrobulbar haemorrhage resulted in permanent blindness in a 34-year-old woman with transverse maxillary deficiency.[4] Although the osteotomies were not those associated with a typical SARME procedure, the authors thought that incomplete cuts might have resulted in excessive force being applied to the posterior maxillary segments, which could have propagated fractures upwards through the maxillary sinus walls to cause the orbital fracture. Carneiro et al[7] reported a case of carotid cavernous fistula, which was caused by a fracture that involved the body of the sphenoid bone, in a 34-year-old woman after SARME.

Published reports show little consensus about the separation of the pterygomaxillary junction in SARME.[3,9] Some authors advocate PMD with SARME in patients over 20 years of age because of increased ossification,[10] but others think that the pterygomaxillary region is one of the most important points of resistance against maxillary expansion, and is likely to be responsible for postoperative relapse. Therefore, for rapid maxillary expansion to be successful in adults, they prefer to do a pterygomaxillary osteotomy.[10,12–14] Some, however, advocate SARME without PMD because of a reduced risk of perioperative complications, and because of the favourable surgical outcomes.[9,11]

PMD may be preferred depending on the patient's periodontal status, biological age, or site of transverse maxillary deficiency.[3,11] When this is not done, Koudstaal et al stated that the maxillary segments tend to widen in a V-shape with the apex pointing dorsally, and there is a lack of expansion in the posterior region.[2] PMD therefore has been considered necessary in patients with severe transverse deficiencies that include the posterior maxilla.[10,21] As previously reported, stress at the base of the skull during pterygomaxillary osteotomy seems to be the most important factor in the development of complications such as bleeding or nerve palsies,[22,23] and damage by a curved osteotome may be a direct cause. Weaknesses at the cranial base that are caused by the osteotomy can also lead to complications, as they can develop into fractures during distraction. A reduction in stress therefore may effectively reduce their incidence. Our results suggest that stresses at the cranial base and on the pterygoid plates can be reduced effectively when PMD is done last.

Increased ossification in the median palatal suture in adults[19] may also make separation more difficult, and result in the need for greater force. We found a considerable increase in compression at the midface during the midpalatal osteotomy in the model with PMD. Clinically, we think that midpalatal osteotomy should be done before PMD to reduce complications such as eccentric interdental separation[12] or mobility of the teeth.[14]

In conclusion, it is beneficial to avoid PMD in patients with a mild deficiency, particularly when the posterior maxillary deficiency is slight. When PMD is needed, the midpalatal osteotomy should be done before the pterygomaxillary osteotomy to reduce stresses at the cranial base, and on the midface and pterygoid plates, and to avoid complications.

## Conflict of interest

We have no conflicts of interest.

## Ethics statement/confirmation of patients' permission

Not required.

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