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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

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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

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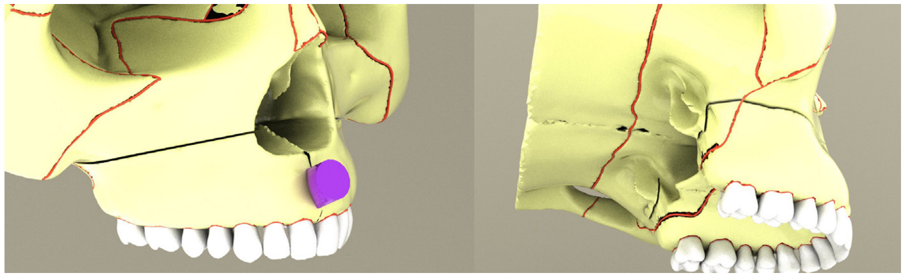

Fig. 1. A force was applied with a sharp osteotome to the inter-radicular midline region for the midpalatal osteotomy. Pterygomaxillary dysjunction (PMD) was done in the second model.

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-