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Rapid maxillary expansion in adults: cranial stress reduction depending on the extent of surgery

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SUMMARY The objective of this study on surgically assisted rapid maxillary expansion (RME) was to examine the extent of stress reduction in the midface and the cranial base with various surgical procedures. Four finite element models of the skull were generated (one without and three with different surgical incisions), in which a virtual RME (5 mm gap width) was simulated. In all four simulations, von-Mises stresses were measured at 30 anatomical structures of the midface and cranial base (in MPa) and compared.

The highest von-Mises stresses were measured with the model that did not involve any osteotomies. A reduction of the observed stresses was found after isolated weakening of the zygomaticoalveolar crest on both sides. The model with a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction clearly showed lower stresses than the model with isolated weakening of the zygomaticoalveolar crest. The lowest stress values, however, were seen on the model with a complete osteotomy at the Le Fort I level.

In order to prevent complications at the cranial base, surgical assistance is an important aspect of RME in adults. The extent of osteotomies can be varied. The older the patient and the less the bone elasticity, the more extensive should be the surgical weakening in order to minimize the stresses induced at the cranial base and the midface. In older patients, a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction seems to reduce stresses at the cranial base more effectively than isolated weakening of the zygomaticoalveolar crest.

Introduction

In adult patients, the realization of rapid maxillary expansion (RME) is complicated by the increasing rigidity of the bony structures with age (Basdra *et al.*, 1995) and to a lesser extent by the increasing degree of ossification in the median palatal suture (Knaup *et al.*, 2004) so that an additional surgical weakening of specific midfacial structures is required (Byloff and Mossaz, 2004). In addition to the lateral osteotomy, a palatal one is carried out to separate the two maxillary parts (Zöller and Ullrich, 1991; Bays and Grecco, 1992; Basdra *et al.*, 1995). There is no agreement in the literature regarding the extent of lateral osteotomies. While some authors (Zöller and Ullrich, 1991; Basdra *et al.*, 1995) consider a weakening of lateral maxillary sinus wall should be restricted to the area of the zygomatic process as sufficient, others favour considerably more extensive osteotomies extending from the pterygopalatal junction to the piriform aperture (Glassman *et al.*, 1984; Feller *et al.*, 1998; Schimming *et al.*, 2000).

Since stresses are induced in all bony structures of the skull during RME, it can be assumed that both the level and distribution of these stresses are influenced by the localization and extent of the osteotomies. However, an appropriate biomechanical comparison of these different procedures for lateral osteotomy has not yet been reported. Biomechanical, finite element method (FEM)-based analyses for conventional, i.e. not surgically assisted RME have been presented (Iseri *et al.*, 1998; Jafari *et al.*, 2003; Holberg, 2005), but appropriate analyses of the nature and extent of surgical relief have not been published. The objective of this research was therefore to carry out a biomechanical, FEM based analysis of surgically assisted RME that allows a direct comparison of different surgical procedures employed for lateral osteotomy.

Materials and methods

The presented study is based on a FEM numerical procedure. After creating a virtual three-dimensional (3D) structure, this is subdivided into a number of single 'finite' elements and the material properties of these elements are defined by Young's modulus and Poisson's ratio. For implementing virtual simulations of RME in adults with and without surgical assistance, four finite element (FE) models were generated: a skull model without additional osteotomies, a model with a restricted osteotomy in the region of the zygomaticoalveolar crest, a model with a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction, and, finally, a model with an additional osteotomy of the medial wall of the maxillary sinus (Figure 1). The geometric data for the simulation model were acquired with a 3D scanner (Minolta, Langenhagen, Germany) and an anatomical plastic model of the skull (Somso, Coburg, Germany), using a new

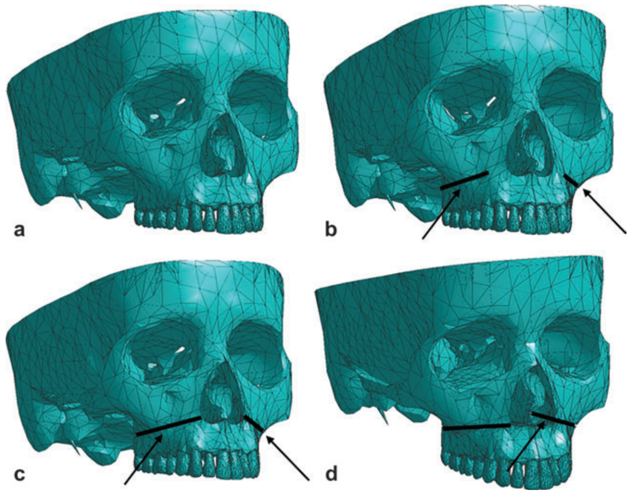

Figure 1 Four different finite element models used in the simulations (a: no surgery, b: weakening of the zygomaticoalveolar crest, c: complete lateral osteotomy from the piriform aperture to the pterygopalatal junction, d: additional osteotomy of the medial maxillary sinus wall).

Table 1 Properties of experimental parameters.

Parameter	Conditions in study
Young's modulus: adult bone	15.0 GPa
Young's modulus: teeth	22.0 GPa
Poisson's ratio	0.3
Number of models	4
Osteotomies	
Model no. 1	No osteotomy
Model no. 2	Weakening of the zygomaticoalveolar crest
Model no. 3	Complete lateral osteotomy
Model no. 4	Additional osteotomy of the medial wall of the maxillary sinus
Parts of each model	1 skull, 16 teeth
Number of elements	54 000
Number of nodes	98 000
Zero displacement	Nodes at the edge of the foramen magnum
Area of displacement	Nodes at the palatal side of the upper first molars and canines
Magnitude of transversal displacement	5 mm (2.5 mm each side)

procedure for converting numerical raw data into analytical geometric representations.

The model was a precise copy of a 25-year-old male skull. As the cavity of each maxillary sinus was constructed virtually, the cavities of other sinuses were ignored. The model was used as the geometric basis because this model represented an average anatomical situation. All surgical osteotomies were then integrated into the basic geometry at the computer-aided design level using Boolean operations (differences). The details of the properties of the experimental parameters for all the models are shown in Table 1. Each model consisted of the bony structures of the skull, the individual teeth, and, in three of the four simulation models, the individual scopes of the various osteotomies. For all virtual experiments, a fixed displacement in a transverse direction was defined at the palatal surfaces of the first upper molars and canines. The boundary condition was defined by fixed nodes at the rear edge of the foramen magnum and was identical for all four simulations. The extent of transveral expansion at 5 mm was also the same size for all four simulations (Figure 2). On completion of the four simulations, the von-Mises stresses arising during the virtual RME were measured at different anatomical structures of the midface and the cranial base, particularly at the sutures, using an interactive measurement tool. The centre of the anatomical structure was always defined as the measurement point. The individual values obtained in the various simulations could be measured and compared with each other for each anatomical measurement point (Table 2).

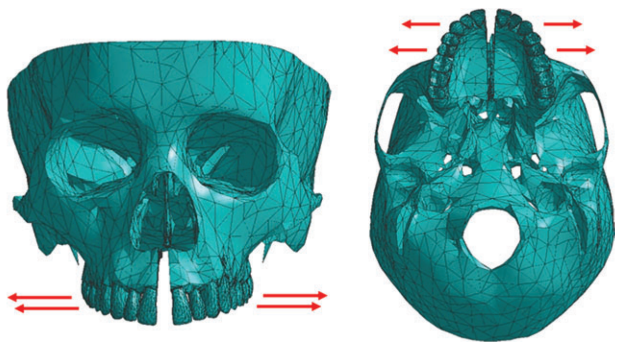

Figure 2 When implementing the virtual rapid maxillary expansion, both maxillary parts were displaced 2.5 mm laterally. Targets for the set displacement were in the area of the first premolars and in the area of the first molars.

Results

A dependence of the measured von-Mises stresses on the extent of surgical weakening appeared at all anatomical structures. The more extensive the surgical osteotomy, the smaller were the stresses measured at the midface and the cranial base. The stresses were highest during RME without surgical assistance. If a weakening of the zygomaticoalveolar crest was carried out, there was a reduction in stresses. This stress reduction was, however, much smaller than with a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction or after a Le Fort I osteotomy of the maxilla (Table 2 and Figures 3 and 4). The stress-reducing effect was more marked after a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction than after local weakening of the zygomaticoalveolar crest. However, the measurement point at the anterior wall of the maxillary sinus was an exception. Here the stresses for the model without surgical weakening were far lower than they were for those with weakening of the zygomatico alveolar crest or with a complete lateral

Table 2 Comparison of the von-Mises stresses at the anatomical structures of the midface and cranial base with different surgical procedures.

Anatomical structure	von-Mises stress (MPa)			
	No surgery	Weakening of zygomaticoalveolar crest	Complete lateral osteotomy	Le Fort I osteotomy
Zygomatic bone	33.8	21.4	14.4	4.7
Zygomaticoalveolar crest	188.8	48.7	62.1	23.3
Zygomaticofrontal suture	150.9	86.4	40.6	15.9
Infra-orbital foramen	42.1	44.5	22.1	6.4
Infra-orbital margin	73.7	70.9	50.1	12.8
Anterior lacrimal crest	174.6	117.1	93.8	10.2
Anterior wall of the maxillary sinus	20.1	180.8	36.7	16.9
Naso-frontal suture	192.3	136.9	25.6	4.3
Supra-orbital margin	57.8	46.8	31.9	7.2
Pterygopalatinal fossa	72.1	61.3	45.3	32.6
Medial lamina of the pterygoid	205.9	179.7	176.9	114.4
Pterygoid fossa	93.5	97.3	55.3	52.1
Lateral lamina of the pterygoid	180.0	178.2	136.5	109.9
Optical foramen	150.9	122.4	50.2	27.3
Superior orbital fissure	111.3	90.6	64.6	35.9
Foramen spinosum	32.8	26.6	19.7	16.3
Foramen ovale	75.1	65.3	57.0	36.9
Foramen lacerum	92.7	73.4	54.9	28.1
Foramen rotundum	31.4	26.7	28.4	25.3
Internal auditory canal	28.4	23.8	16.1	6.8
Frontal crest	72.4	50.1	32.4	6.3
Cribriform plate	157.8	110.3	87.6	15.8
Orbital part of the frontal bones	15.5	13.7	14.7	4.3
Pituitary fossa	50.7	45.1	19.8	14.1
Carotid sulcus	78.0	79.9	62.6	31.7
Spheno-occipital synchondrosis	12.8	12.9	8.9	3.8
Petrosal part of the temporal bone	25.1	26.4	20.4	9.2
Squamosal part of the temporal bone	63.5	42.8	17.1	3.7
Jugular foramen	48.6	33.4	18.9	6.2
Occipital crest	2.7	1.5	1.4	1.2

osteotomy from the piriform aperture to the pterygopalatal junction (Table 2).

The distribution of the stresses at the cranial base, in almost all simulations, i.e. the optical foramen, the supra-orbital fissure, the cribriform plate, and the foramen lacerum showed the highest stresses, while the foramen rotundum, the foramen spinosum, and the spheno-occipital synchondrosis showed lower values in comparison (Table 2). In the midface, the highest relative values were measured at the naso-frontal suture, the zygomaticofrontal suture, the zygomaticoalveolar crest, and the pterygoid plates, while the zygomatic bone and the area around the infra-orbital foramen showed relatively low measurement values (Table 2 and Figures 3 and 4). The von-Mises stress measured at the optical foramen of the cranial base during simulation without surgical weakening was 150.9 MPa, while with weakening of the zygomaticoalveolar crest the value was 122.4 MPa. A complete lateral osteotomy from the piriform aperture to the pterygopalatal junction resulted in an even greater decrease at this measurement point to 50.2 MPa, while the lowest value was seen after a Le Fort I osteotomy (27.3 MPa). At the superior orbital fissure, weakening of the zygomaticoalveolar crest caused a reduction in stress from 111.3 (simulation without surgical weakening) to 90.6 MPa, while after a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction the stress was 64.6 MPa, and after a Le Fort I osteotomy 35.9 MPa. In the midface, von-Mises stress at the naso-frontal suture was 192 MPa without the surgical osteotomy, 136.9 MPa with weakening of the zygomaticoalveolar crest, 25.6 MPa with a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction, but only 4.3 MPa after a Le Fort I osteotomy (Table 2 and Figures 3 and 4).

Discussion

Publications on FEM-based simulations of RME in the field of orthodontics (Iseri *et al.*, 1998; Jafari *et al.*, 2003; Holberg, 2005) have been restricted until now to RME carried out without surgical assistance. Simulations with measurements of the stress-reducing effect of different surgical procedures in adulthood have not been reported previously in the literature. In this study, an improvement in the anatomical differentiation of these skull models compared with earlier simulations (Iseri *et al.*, 1998; Jafari

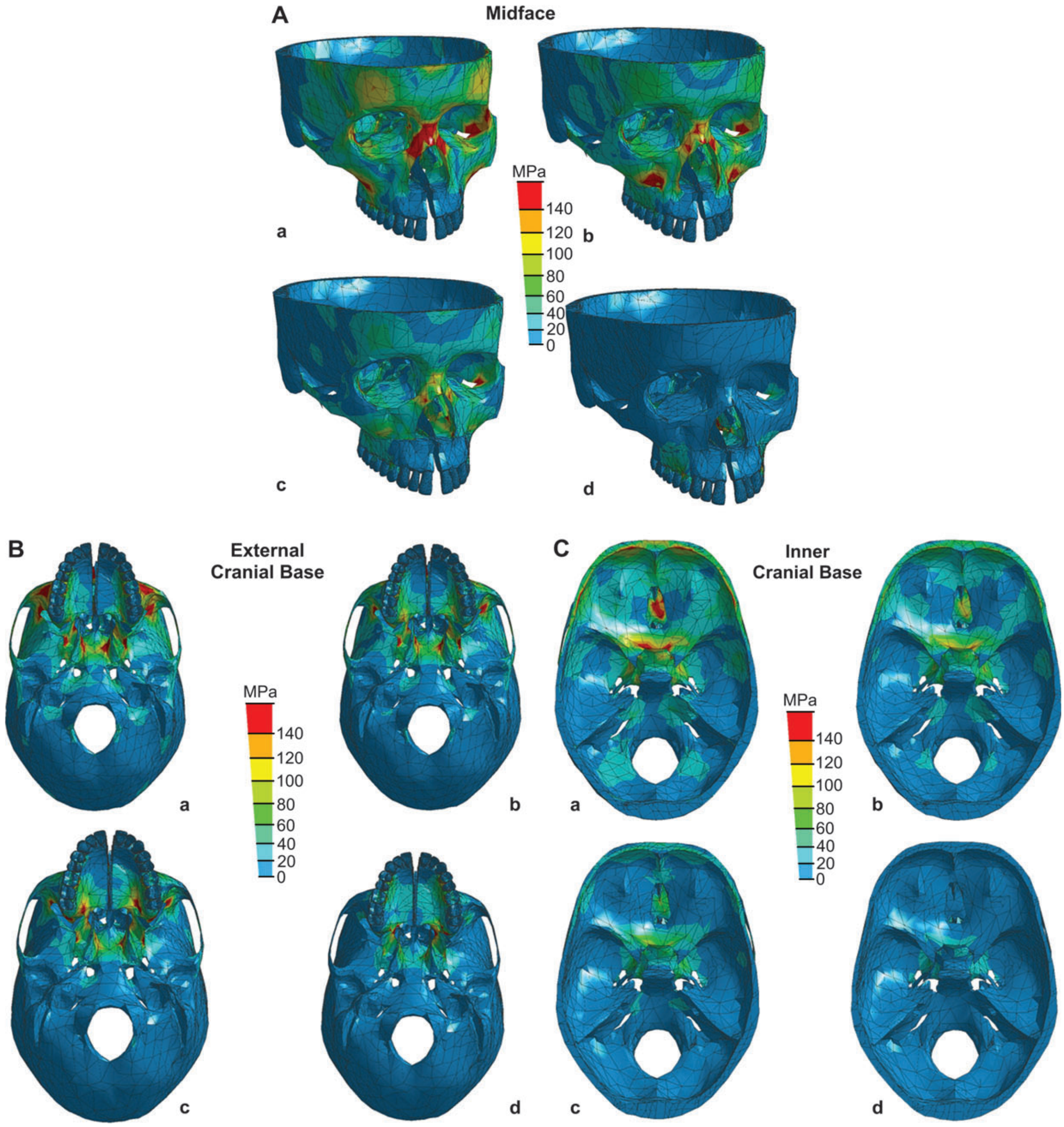

Figure 3 Distribution patterns of von-Mises stresses in the midface (A), the external cranial base (B), and the inner cranial base (C) with different types of surgical relief (a: no surgery, b: weakening of the zygomaticoalveolar crest, c: complete lateral osteotomy from the piriform aperture to the pterygopalatal junction, d: additional osteotomy of the medial maxillary sinus wall).

et al., 2003) was possible, and for the first time, various surgical osteotomies could be considered in the simulations. While this improved differentiation of the FE model allowed direct comparison of the effect of various surgical osteotomies, the simulations represent only an idealization of reality (Tanne *et al.*, 1989), since both the skull geometry employed and the elemental properties and boundary conditions were based on idealized procedures. Furthermore, in the isotropic FE models, the individual varying material properties of the skull bones could not be included, resulting in a method error. Nevertheless, the four simulations allowed a satisfactory, fundamental comparison of the effectiveness of various surgical procedures since all models employed were identical, apart from the extent and localization of the virtual osteotomies.

There is general agreement on the need for surgically assisted measures during adulthood (Glassman *et al.*, 1984; Byloff and Mossaz, 2004) when carrying out RME if a conventional procedure is complicated by increasing ossification of the median palatal suture or decreasing

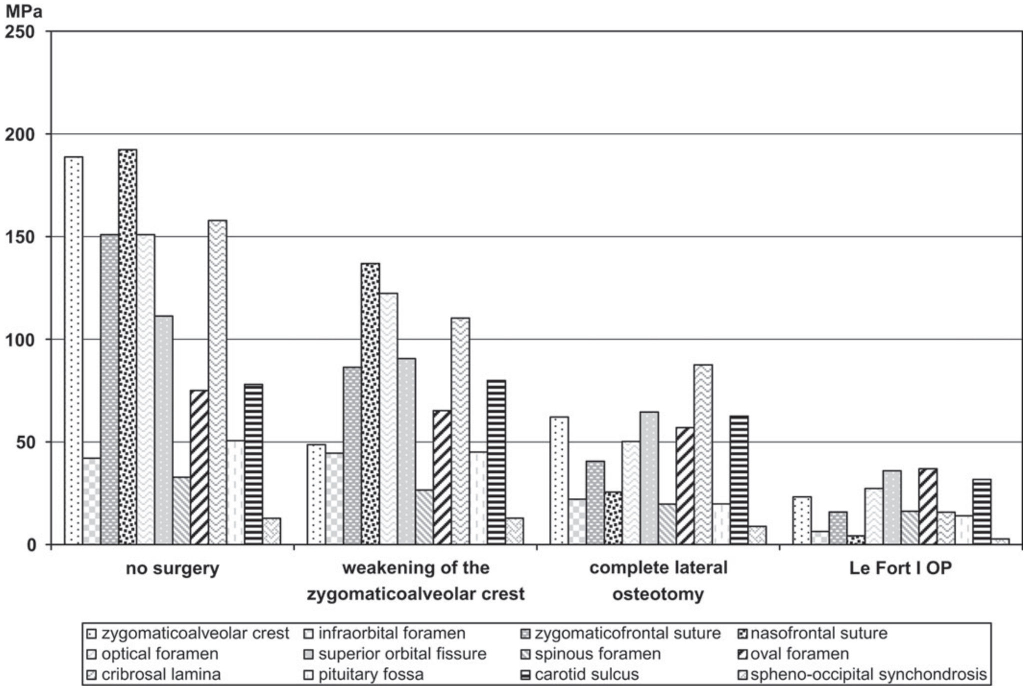

Figure 4 The von-Mises stresses at the anatomical structures depending on the extent of surgical weakening.

bone elasticity (Basdra *et al.*, 1995; Knaup *et al.*, 2004). However, there is little agreement on the extent of the surgical weakening required. The median or paramedian separation of the hard palate is preferred by most authors (Shetty *et al.*, 1994; Basdra *et al.*, 1995; Byloff and Mossaz, 2004) as surgical relief for RME in adults. When implementing a lateral osteotomy, considerable differences exist regarding the degree of extension. While some researchers recommend only weakening of the zygomaticoalveolar crest (Zöller and Ullrich, 1991; Basdra *et al.*, 1995), others favour a complete lateral osteotomy from the piriform aperture up to the pterygopalatal junction (Glassman *et al.*, 1984; Feller *et al.*, 1998; Schimming *et al.*, 2000). The results of the presented research indicate that in adult patients the realization of RME without surgical assistance might lead to considerable stresses developing at the bony structures of the cranial base and the midface so that even with spontaneous opening of the median palatal sutures microfractures at these structures with the risk of injury to vessels and nerves cannot be excluded (Holberg, 2005).

All surgical osteotomies in adult patients apparently lead, to a varying extent, in reductions in these stresses. The measurements in this research revealed considerable differences in the effectiveness of these surgical measures. While surgical weakening of the zygomaticoalveolar crest apparently only produces a minor reduction of the induced stresses, a complete lateral osteotomy from the piriform aperture to the pterygopalatal junction is far more effective. The Le Fort I osteotomy demonstrated the greatest protective effect for the cranial base and the midface, but is more invasive than a conventional lateral osteotomy. The greater and more extensive the surgery, the greater apparently is the protective effect. This is consistent with the view of Anttila *et al.* (2004), that the extent of surgical relief during RME in adults should be more invasive in older patients. However, this should be weighed against the fact that with increasing invasiveness of surgery, the risk of complications also increases (Li *et al.*, 1995; Mehra *et al.*, 1999). Very conservative surgical relief, however, entails the risk of inadequate protection of the cranial base and midface with increased risk of consequent complications (Lanigan and Mintz, 2002).

Conclusions

During RME in adults, considerable stresses are induced in the midface and at the cranial base that can lead to complications such as microfractures. Surgical osteotomies before RME in adults serve not only to facilitate expansion but also to reduce the level of stresses induced at the cranial base and midface. Surgical measures therefore exert a protective effect for these anatomical structures. A complete lateral osteotomy from the piriform aperture up to the pterygopalatine fossa contributes more effectively to a decrease in stress than local weakening of the zygomaticoalveolar crest.

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