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TECHNICAL NOTE

3D visualization and simulation of frontoorbital advancement in metopic synostosis

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Abstract
Objectives Current multislice computed tomography (CT) technology can be used for diagnosis and surgical planning applying computer-assisted three-dimensional (3D) visualization and surgical simulation. The usefulness of a technique for surgical simulation of frontoorbital advancement is demonstrated here in a child with metopic synostosis.
Materials and methods Postprocessing of multi-slice CT data was performed using the software 3D slicer. 3D models were created for the purpose of surgical simulation. These allow planning the course of the osteotomies and individually placing the different bony fragments by an assigned matrix to simulate the surgical result. Photo documentation was obtained before and after surgery. Surgical simulation of the procedure allowed determination of the osteotomy course and assessment of the positioning of the individual bony fragments.
Conclusions Computer-assisted postprocessing and simulation is a useful tool for surgical planning in craniosynostosis surgery. The time–effort for segmentation currently limits the routine clinical use of this technique.

Keywords Craniosynostosis · Image processing · Computer-assisted · Computer simulation · Craniotomy

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Introduction

Premature ossifications of cranial sutures, referred to as craniosynostosis, cause specific deformations of the skull. They may be associated with bony anomalies of the orbit, increased intracranial pressure, seizures, and neurological impairment [7, 11]. The incidence is reported to be 0.6/1,000 births. The impact of craniosynostosis on intracranial volume has been discussed controversially [18]. The surgical correction of craniosynostosis is complex and presents an interdisciplinary challenge, as the procedure is comparatively rare even at specialized centers [8]. Cosmetic aspects present a major issue when surgery is considered [4, 9, 14]. As early surgery is beneficial, there is a demand for less drastic but effective techniques [4]. Among other issues, surgical time and blood loss are of importance in the small children undergoing surgery [4]. Different surgical techniques, varying in the shape of the osteotomies and fixation of the osteotomy segments, for remodeling have been described and compared for different patient groups; furthermore, alternative approaches including distraction

Fig. 1 Preoperative 3D CT of the skull at 6 months showing the closed metopic suture. The patency of the coronal, sagittal, and lambdoid sutures is shown. Superior view

and other techniques have been reported [1–5, 12, 17]. The specific entity of metopic synostosis causing trigonocephalus is treated by frontoorbital advancement. Aims of the procedure are correction of the nasopterional angle, forward advancement of both pterions and anterolateral parts of the frontal bones, and shortening of the overgrown midline structure [19].

Current computed tomography (CT) technology allows high-resolution imaging of craniosynostosis. Reconstructions can be performed both for diagnosis and surgical planning. Several postprocessing algorithms for three-dimensional (3D) visualization of the skull in craniosynostosis with their specific advantages and disadvantages have been described [4, 13, 14, 16]. Alternative techniques using image data for surgical planning include stereolithographic modeling and computer-assisted surgical planning [8, 11, 15].

In this study, we report on computer-assisted 3D visualization and simulation of frontoorbital advancement in trigonocephalus because of metopic synostosis and discuss its possible future perspectives.

Material and methods

Patient history

A 2-month-old boy was referred to our hospital with an abnormally shaped head which was noted at routine pediatric examination. Pregnancy and birth were unremarkable. Development milestones were normal. In addition to

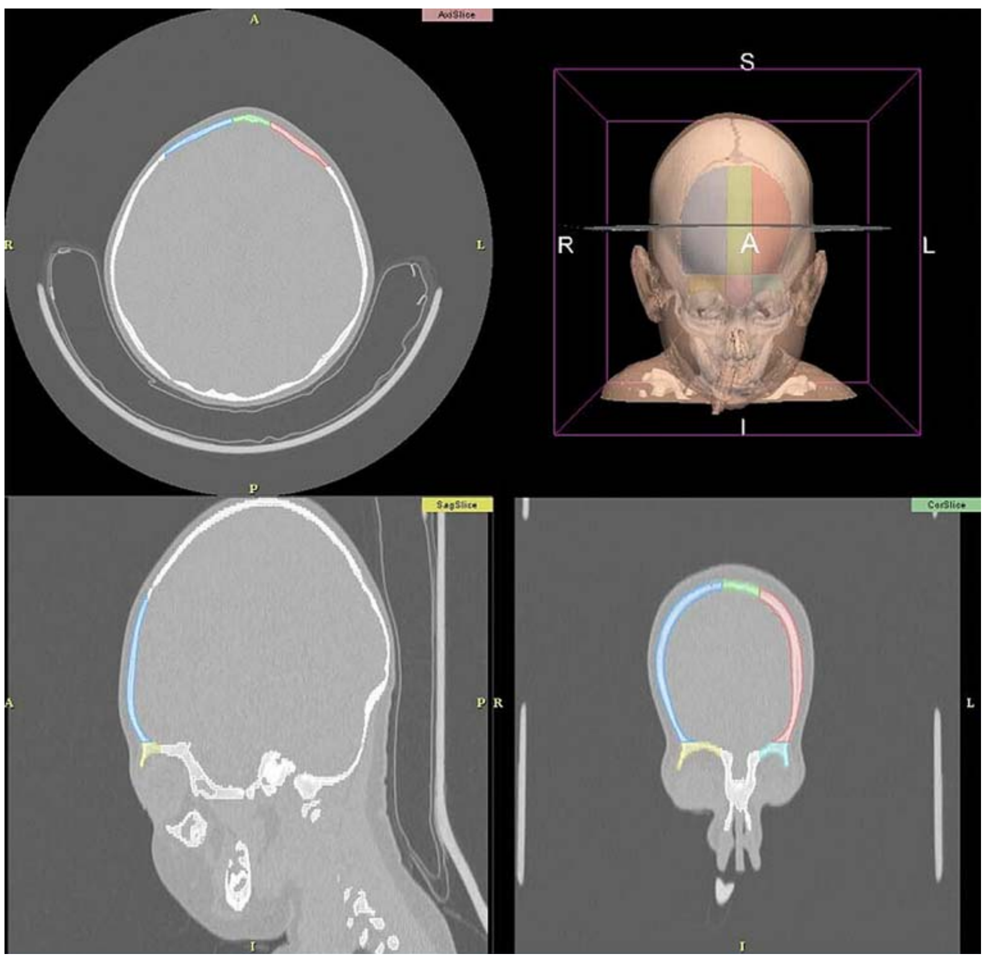

Fig. 2 Postprocessing of the preoperative CT data. The skull was segmented using a threshold; the individual osteotomy segments were separated using manual segmentation. Of each segmented structure, an individual 3D model was generated. The software 3D slicer allowed reformation of the segmented data (*lower left image*, *lower right image*) and correlation of the 3D models to the cross-sectional images (*top right image*)

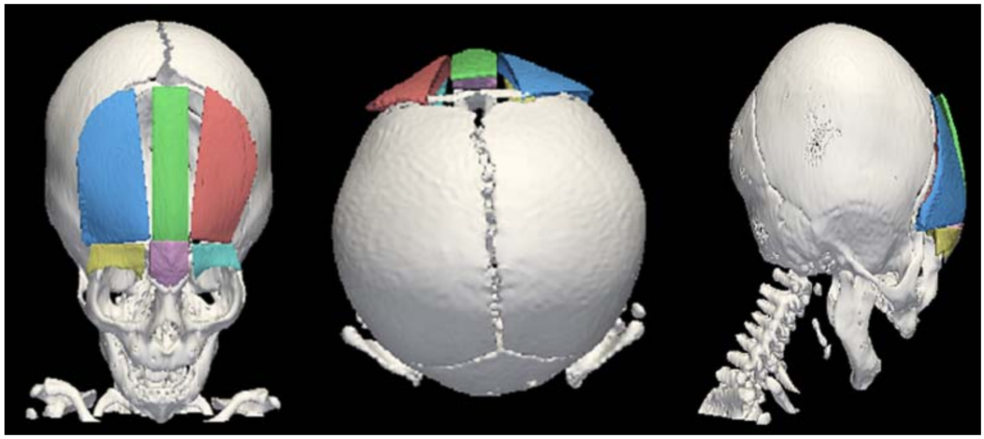

Fig. 3 Preoperative CT data. Anterior, superior, and right view of 3D models of the skull and the planned osteotomy segments after simulation of the frontoorbital advancement

the wedge-shaped deformity of the forehead, bony abnormalities of the orbits were present. Examination detected an obliterated metopic suture, while the sagittal suture was patent. The frontooccipital circumference was 38 cm (within the 25 percentile). 3D-computed tomography confirmed premature metopic synostosis and demonstrated subsequent trigonocephalus. No other anomalies were found.

The boy was referred for surgery at the age of 6 months. Before surgery, a low-dose CT and 3D reconstruction using surface rendering was obtained (see Fig. 1).

Data acquisition

CT was performed with a multislice helical CT (GE CT LightSpeed QX/i) applying a low-dose protocol. Tube voltage was 100 kV and tube current was 50 mA. Pitch was 3 and the collimation was 1.25 mm. A 180° linear interpolation image reconstruction was performed, field of view was 23 cm, and reconstruction interval was 1 mm.

Image processing

Processing of the image data was performed retrospectively using the software 3D slicer (http://www.slicer.org). Initial segmentation of CT data was obtained by threshold segmentation. 3D models of the skin and the skull were generated. Using manual multiplanar segmentation and operators such as dilation and erosion, the individual osteotomy segments were separated, according to the planned osteotomy courses in the axial, coronal, and

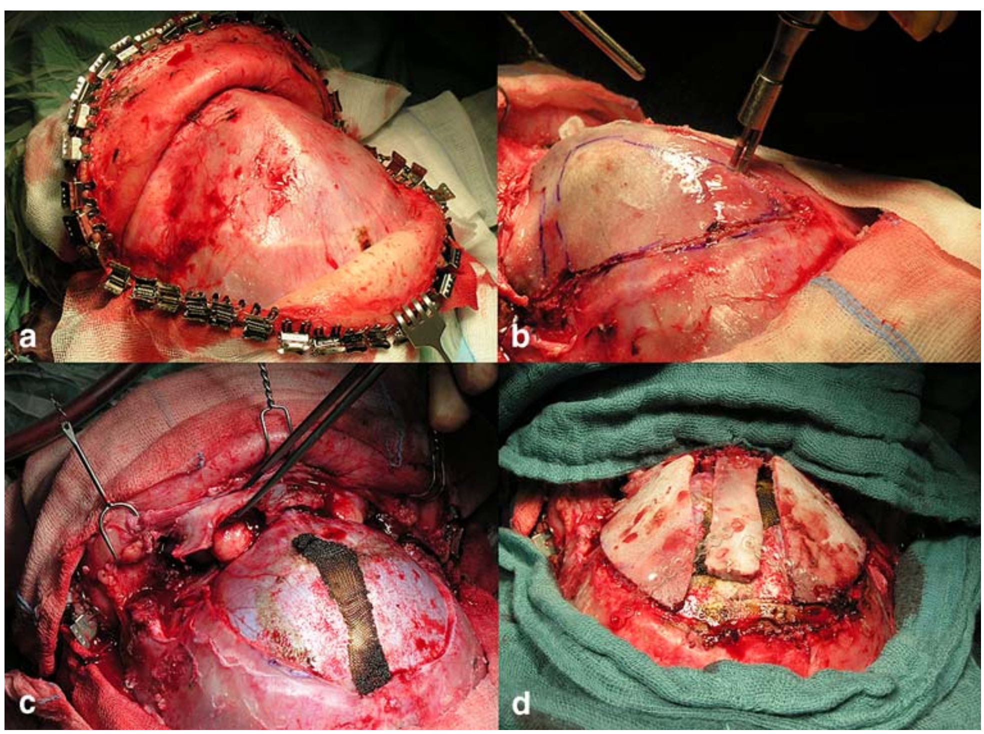

Fig. 4 Intraoperative procedure. **a** After the skin incision and mobilization of the skin, the prominent closed metopic suture can be seen. **b** The individual osteotomy segments are cut from the skull. **c** Orbital advancement. Using the forceps, the superior orbital rim is positioned. The superior sagittal sinus is covered under the tissue strip. **d** Fixation of the individual osteotomy segments using absorbable screws and plates

sagittal images. For each osteotomy segment, an individual 3D model was generated applying surface rendering (see Fig. 2). Then, an individual matrix was assigned to each 3D model. Each 3D model could then be moved using translation along and rotation around the *x*, *y*, and *z* axes (see Fig. 3). The specific features of the software to present the 3D models including changes of the transparency of the models and correlation of the 3D models to the cross-sectional images were used.

Surgery

Frontoorbital advancement was performed in supine position with the head being elevated. A coronal skin incision was made and the borders of the osteotomy segments were drawn on the calvaria. Frontal craniotomies were performed ensuring that the sagittal sinus was conserved. Thereafter, orbitotomies were made by the facial surgeon. The osteotomy segments were rearranged and fixed with absorbable screws and plates (see Fig. 4) [21, 22]. The postoperative course was unremarkable. At follow-up, 6 weeks after surgery, another low-dose CT and 3D reconstruction were obtained (see Fig. 5).

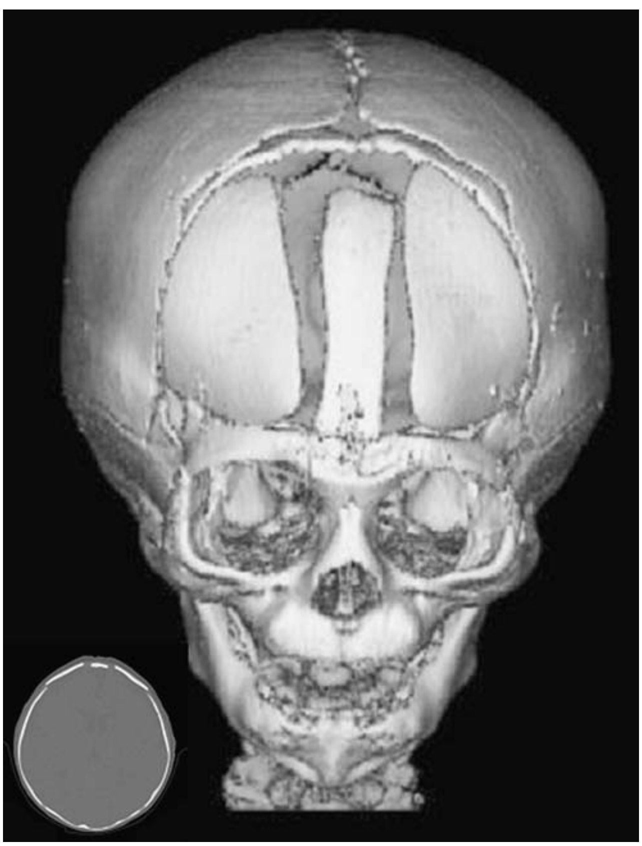

Fig. 5 Postoperative CT data. 3D CT showing the actual osteotomy segments

Results

3D visualization provided complementary information to the axial low-dose CT images demonstrating the obliterated suture more clearly and displaying the spatial anatomy of the cranial structures preoperatively. Surgical simulation of the procedure allowed determination of the osteotomy course. This was possible after a complex manual segmentation process. Positioning of the individual osteotomy segments was achieved by assignment of an individual matrix to each of the osteotomy segments. Rotation and translation of the 3D model of the osteotomy segments was easy to handle. Postprocessing took 6 h, the major part of the time was needed for the complex manual segmentation process of the osteotomy segments.

Discussion

We think that surgical simulation, although time-intensive, is a useful tool for cranial reconstruction procedures in craniosynostosis. Various strategies for surgical simulation in craniosynostosis are available and the opportunity to tailor the procedure to the deformity has been reported as beneficial [6, 10, 13, 20]. Depending on the type of craniosynostosis, different algorithms were used. Because of the complexity of the simulation, several studies focused on a single simulation aspect.

Computer-assisted biomechanical simulation is possible using advanced techniques such as the finite element method and could be used to calculate the effect of forces applied to anatomical structures, e.g., the forces used to bend a bone segment during surgery or even the impact of a developing brain on the postoperative bony situation [10]. Further ways to optimize the surgical plan would be defining aims, e.g., a smooth surface contour of the osteotomy segments, and using computer algorithms to position the osteotomy segments following a predefined bend.

Surgical navigation may also be used to transfer the surgical simulation and plan into the real surgical setting [20]. This may also be implemented into standard navigation techniques using a pointing device and defining landmarks for predefined points of each osteotomy segment.

As mentioned above, the time needed for postprocessing is a crucial issue as it currently limits the routine clinical application of the described technique. This time will decrease with the availability of more sophisticated segmentation routines and cutting tools, as the main time is usually spent on segmentation of the osteotomy segments. Semiautomated or even automated segmentation routines applying various techniques such as edge detection and others have been reported to allow more precise and faster segmentation.

In conclusion, surgical simulation of frontoorbital advancement in children with trigonocephalus is a useful tool. The routine clinical use is currently limited by technical issues concerning segmentation of the osteotomy segments, which might be overcome by further technical developments. The use of this method could further be accelerated by advanced planning routines and the opportunity to simulate the postoperative biomechanic characteristics using the finite element method.

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