THREE-DIMENSIONAL IMAGING IN MEDICINE: SURGICAL PLANNING AND SIMULATION OF CRANIOFACIAL SURGERY

D.E. Altobelli, R. Kikinis[*], J.B. Mulliken
H. Cline[**], W. Lorensen[**], F. Jolesz[*]

Craniofacial Centre, The Children's Hospital
300 Longwood Ave., Boston, MA 02115, (617) 735-6309

ABSTRACT

Interactive visualization of three-dimensional data from CT scans has been applied for quantitative analysis and surgical planning of craniofacial deformities. Approaches to integrate existing two-dimensional normative databases for three-dimensional analysis are discussed. Methods of simulating osteotomies (bone cuts) and repositioning of computer analogs of hard and soft tissue units are presented.

INTRODUCTION

The Problem: The effects of congenital, developmental, and acquired abnormalities of the cranio-maxillofacial skeleton are profound for the patient, their families, and society. The human face serves a structural role for chewing, speech, and breathing while protecting the brain and vital senses. The face is also the primary interface for communication and psychosocial interaction. Ideally, surgical correction of facial deformities could be formulated with a detailed blueprint to optimize morphology, function, and in the developing child, normal growth.

Current correction of craniofacial congenital deformities predominately involves surgical procedures that empirically reposition and augment large segments of the craniofacial skeleton. To determine the extent of the deformity in a quantitative fashion, normative relationships of skeletal and facial surface structures are available from anatomic data bases for comparison. These discrete parameters of distance, angle and proportion are measurements from conventional radiographs[1] and surface landmarks[4] on the face and skull. Unfortunately, original three-dimensional spatial relationships are lost, with the data greatly insufficient to describe the complex surface contours and spatial geometries characteristic of the craniofacial anatomy[3].

Limitations in quantitative description of normal and abnormal anatomy limit the degree of pre-surgical planning possible. Thus, the surgical team is required to evaluate, analyze, react to unanticipated problems, and implement the procedure in a subjective and empiric fashion intraoperatively. This approach is plagued with obvious limitations, including increased surgical time and difficulty, and sub-optimal results. Even if the surgical team had a detailed blueprint of the procedure to transform the deformity to normality, the tools for navigation and measurement intra-operatively are limited to those of our ancestors...rulers, calipers, and primarily artistic ability.

The Approach: Advances in medical imaging and computer graphics provide the opportunity to quantitatively study the detailed structure of normal and abnormal craniofacial anatomy. Computer generated three-dimensional CT and MRI images allow comprehensive and interactive visualization, measurement, and analysis of hard and soft tissues. This new vantage point provides a foundation for converging on the understanding and treatment of craniofacial deformities, including; 1) quantitative morphologic description, 2) pre-surgical planning and simulation, 3) anatomic model and implant fabrication, 4) biomechanical modelling, 5) intraoperative navigation, and 6) the real time coordination of the patient anatomy with the three-dimensional image data. Work presented in this paper will address the first two components listed.

MATERIALS/METHODS

Case 1: A 14 year old female with a diagnosis of Pfeiffer Syndrome will be used to illustrate the methodology. This condition is characterized by forehead and supra-orbital rim retrusion, depression of the nasal bridge, hypertelorbitism, ocular proptosis, mid-face hypoplasia, relative mandibular prognathism with an open-bite deformity.

Interactive Visualization: The CT data in image format on magnetic tape was loaded on to a Sun Sparc 4/370 with Taac Board and a GE custom hardware board. The headers were read to determine resolution and slice thickness. A total of 47 slices were processed. The headers were striped from the image files, and the files were initially reduced from 512 x 512 to a 256 x 256 matrix with a bilinear interpolation scheme. The data was then imported into ANALYZE, a robust software system for biomedical visualization and measurement (Mayo Foundation)[5]. This data was also imported into MR console (GE), a software environment under development for surgical planning and simulation[2]. Interval thresholding and dynamic thresholding with connectivity was used to isolate the soft and hard tissue components. The hard and soft tissues were then reconstructed into three-dimensional images on the computer workstation in surface and volume rendered formats.

A hollow cubic grid was intersected with the skin surface to provide reference for distance and to assess contour

[*] Dept. of Radiology, Brigham and Women's Hospital, Boston, MA 02115
[**] Corporate Research, General Electric, Schenectady, NY 12301

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asymmetries.

The orbital contents were displayed and the anterior position of the globe was determined in relation to the orbital rims. Lateral, inferior and superior vantage points demonstrated the exorbitism. Anterior globe position was measured with respect to orbital rim position.

The skeletal structures were visualized both as surface rendered models and as combinations of volume rendered and multiplaner reconstructions. The deficiency of the orbital bone was notable with lack of structure in the supra-lateral, lateral, and inferior orbital regions. The orbital aperture was laterally rotated. The midface was deficient in anterior projection, with no anterior occlusal contacts between the maxilla and mandible. The mandible had a relatively normal appearance, but was prevented from complete rotation to closure secondary to posterior maxillary excess.

2D AND 3D MORPHOMETRIC DATABASES

Conventional Approaches: Cephalometric analysis for maxillary and mandibular position was within normal limits in spite of the obvious clinical deformity. Anterior cranial base length was 65 mm (nl 72 mm) decreased. This inconsistency in the cephalometric analysis and clinical impression was due to the retruded position of nasion. When nasion was moved to a normalized position using the Bolton Standard referenced to the posterior cranial base and the skull base, analysis demonstrated the retruded bimaxillary position.

Anthropometric measurements confirmed the clinical impression of hypertelorbitism [IOD 62 mm (nl 56mm), ICD 40 mm (nl 31)], exorbitism[globe projection 24mm (nl 13-22), and increased lower facial height (63%, (nl-53-57%).

Three-dimensional Mensuration: Our attention was then turned to the 3-D data in the computer workstation. Interactive analysis of the 3-D data set was made possible with multi-planer reconstruction and volumetric reconstructions. Both linear and curvilinear distances were obtained between significant anatomic locations, primarily in the orbital region. The superior, lateral, and inferior orbital rims were quite deficient with the aperture of the orbit angularly displaced posteriorly.

Measurements for anterior cranial base length, cranial width, and cranial length were determined and compared to norms. From this evaluation, it was clear that the patient would require advancement of the forehead, orbital osteotomies with medial displacement, as well as anterior movement of the entire mid-face.

SURGICAL SIMULATION

Planning was initially based on globe position with respect to the orbital rims. Optimal position for nasion was initially established by superposition of the age matched Bolton Standard on the posterior skull base and posterior cranium. The new position from nasion was consistent for normal anterior cranial base length (N-S).

Using a commercial orthognathic surgery planning software (Orthognathic Treatment Planner) surgery of the lower facial structures was simulated. Lefort I osteotomy with advanced movement of 9 mm and positive rotation of 9 degrees was planned. This allowed autorotation of the mandible, with closure of the open bite deformity and reduction of the increased lower facial height.

THREE-DIMENSIONAL PLANNING

The data was then loaded into a custom hardware board on the Sun Workstation for further processing. Custom design software was then applied to simulate the planned sites of osteotomies. The osteotomy segments, including a frontal craniotomy, bilateral 270 degree orbital osteotomies with the medial region intact, and advancement of the mid-face in a Lefort III type of pattern was modelled. In addition, the overlying skin segments were isolated, and moved with their corresponding skeletal segments. In addition, the orbital contents were also segmented, and were used as the central point for planning the surgery.

Initially, the globes were medially rotated together to a more normal inter-pupillary distance of 55mm. The 3-D computer model was then rotated first from a superior vantage point to position the supra-orbital rim, and then the lateral and inferior vantage points as well. To allow correct positioning of the globe with respect to the bony orbits, the orbital segments were medially displaced 4mm, and then advanced anteriorly 8mm. At this point, center rotation was determined on the medial aspect of the orbital osteotomy, and a 6 degree rotation of the orbital segment was obtained. This allowed good position of the globe with respect to the bony orbit bilaterally. Next, osteotomy of the mid-face was simulated. This was a modified Lefort III osteotomy including the maxilla and zygomas. An anterior movement of 9mm was planned with a clockwise rotation about the sagittal plane of 5 degrees. The mandible could then be autorotated 7 degrees in a counterclockwise fashion to bring the dentition into occlusion. Adjustments of the skin over the bone in the lower face was simulated using proportions used for orthognathic prediction tracing. In the upper face, 1-1 movements of skin with relation to the bone were initially modelled.

CONCLUSION

From our initial experience using three-dimensional visualization for surgical planning, subjectively we feel this approach is advantageous and warrants further development.

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