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REVIEW ARTICLE

Craniofacial Computed Tomography Imaging: A Review

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ABSTRACT
Imaging is a keystone for the understanding and delivery of craniofacial health care and recent developments have led to many diverse technologies and approaches. This paper reviews new developments in three-dimensional imaging, as well as three-dimensional facial image acquisition. Visualization and convergence of the data from these technologies are also described for construction of patient-specific models.

Key words: computed tomography, three-dimensional imaging, facial image acquisition

INTRODUCTION

Computed Tomography (CT) has its roots in the early part of this century. In 1917, the Austrian mathematician, Johann Radon (1887-1956) described a mathematically rigorous inversion formula for reconstruction of an object from its projections. Although Radon's work fell into obscurity after the First World War, the problems of image reconstruction were tackled by Ronald N. Bracewell (1956) in the field of astronomy and William H. Oldendorf (1961), an American neurologist frustrated by the inadequacy of X-ray images, devised an electronic apparatus designed to overcome existing technical and computational difficulties (Robb, 1995). In the late 1950s, Allen McLeod Cormack (a physicist) proposed that if sufficient X-ray views were taken at different angles, a cross-sectional matrix of mathematical coefficients could be calculated. These coefficients could then each be given a value of intensity on a grey scale from which an image of the internal structure or anatomy of the object or body being studied could be constructed. His early studies led to a mathematically accurate way of quantitatively reconstructing cross-sectional images from x-ray projections (Romm, 1984).

In the late 1960s, the British scientist Godfrey Hounsfield was independently developing his ideas that mathematical techniques could be used to reconstruct the internal structure of the body from a number of x-ray measurements. He concluded that quantitative tomographic techniques could produce up to 100 times more accurate measurements than conventional radiographic methods. This realization motivated the construction and testing of several prototype scanners in the Central Research Laboratories of Elector-Musical Instruments Ltd. (EMI).

These efforts eventually resulted in the construction of the first clinical X-ray CT scanner of the head, called the EMI brain scanner, which was installed at Atkinson Morleys Hospital, Wimbledon, England, in 1971. With the successful introduction of the EMI brain scanner into the clinical arena, an explosive development and marketing of CT scanners started with an increasing accumulation of published data in the early 1980s. The potential utilization of 3D imaging in biomedical in biomedical research is now being explored. The realisation that this tool may be useful in basic biological investigations has been precipitated by continually improving the capability of 3D imaging for quantitative tissue characterisation and by the promise of dynamic scanning for measurement of functional parameters.

APPLICATION OF 3D IMAGING TO THE STUDY OF CRANIOFACIAL DYSMORPHOLOGY

Assessment of craniofacial deformities

Medical imaging of the craniofacial area was limited to the mid-sagittal plane, primarily using cephalometric methodology, until the introduction of 3D surface reconstructions from CT scans. The ability to remove the cranial vault made the endocranial base visible; the ability to disarticulate the mandible exposed the entire exocranial base. The resultant 3D images are useful for longitudinal measurement of cranial length, width, and height, as well as assessment of symmetry of the calvaria about the midsagittal plane and the paired components of the three endocranial fossae. (Marsh *et al.*, 1986; Marsh and Vannier., 1987). Reformatted CT data, displayed both as 2-D slices and 3D images, provide the simulator with the information necessary for comprehension of the relevant anatomy (Lo *et al.*, 1994).

Ono *et al.* (1992) studied deformities in patients with congenital facial anomalies, such as cleft lip and palate and hemifacial microsomia, using 3D CT images. Using this system, they prepared a wire frame model called a 'skeletogram', for detailed morphological analysis. This study allowed detection of severe and complex deformities (e.g. cranial deformation and mandibular displacement) and severe facial asymmetry.

Sakurai *et al.* (1998) developed an hypothesis about the mechanisms by which the craniofacial bones are deformed in plagiocephaly (unilateral premature synostosis of the coronal suture). Three-dimensional CT data were obtained from two patients with plagiocephaly and three-dimensional skeletal replicas were made to analyse the deformities of the cranium, facial bones and mandible. From this analysis it was concluded that the asymmetric deformation of the facial bones in these patients was caused by a combined rotation of the calvaria and facial bones, and the displacement of the temporo-mandibular joint on the affected side.

3D CT morphometric analysis of craniofacial deformity

The most recent approaches to the study of growth in three dimensions have come from the field of morphometrics, a field that joins biology and geometry (Ohman and Richtsmeier, 1994; Richtsmeier *et al.,* 2002). Morphometric techniques use the location of particular biological loci called 'landmarks' (for example, foramina, sutural intersections, or bony prominences) to define form. Forms are quantitatively compared on the basis on these data.

For example, a CT examination of a patient usually consists of a set of parallel images, and 3D coordinates of landmarks located within this set of CT images can be used as input for morphometric analysis. Because a CT image is actually a matrix of pixels (picture elements) organised in rows and columns, the coordinates of landmarks within an image can be expressed by row, or x coordinates, and column, or y coordinates, and the direction perpendicular to the parallel image planes is the z direction. If landmark coordinate data such as these are collected from a form at one point in time (from CT examination) and then collected from the same form later in time (a subsequent CT examination), the changes in the relative location of these landmarks provide a 3D description of growth, based on landmark data.

As an example of this approach, Richtsmeier *et al.* (1991) used longitudinal data to study growth of the cranial base in patients with various types of craniosynostoses. The 3D coordinate set of landmarks located on the cranial base was identified on the preoperative, perioperative, and postoperative CT scans for a set of patients. Quantitative comparison of the relative location of the set of landmarks on the preoperative scans compared with the perioperative scans was interpreted as preoperative growth, whereas the comparison on the landmark location in the perioperative scans versus the postoperative scans was interpreted as postoperative growth.

Comparisons were made using two different morphometric methods: Euclidean Distance Matrix Analysis (EDMA) (Lele and Richtsmeier, 1991) and finite element scaling analysis (FESA) (Richtsmeier and Cheverud, 1986). EDMA uses landmark coordinate data to calculate all possible linear distances between landmarks. A FESA can be used to display developmental transformations in terms of allometry (size-related shape-change) and anisotropy (directionality of shape-change) (Singh *et al.*, 2004). It compares forms in order to determine the amount of change required to produce a target (older) morphology from an original (younger) morphology. Both of these methods enable the localization of form difference between two objects or two samples of objects. This particular study concluded that growth patterns of the cranial base in children with craniosynostosis differ according to which sutures are affected.

Kreiborg *et al.* (1993) did a study to describe and analyze Apert and Crouzon syndromes skulls from 3D reconstructions of CT scans. Their results showed that Apert and Crouzon syndromes are very different in cranial development and their dysmorphology is highly age dependent. They suggested that cartilage abnormalities, especially in the cranial base, play a primary role in cranial development in the Apert syndrome from very early intrauterine life. Thus adult craniofacial morphology in Apert syndrome is a combined result of the primary malformation together with subsequent dysmorphic and compensatory growth changes, probably compounded by early cranial deformation.

The primary abnormality in Crouzon syndrome appears to be early fusion of the sutures and synchondroses. Based on the findings at birth and early infancy, it would appear that sutural fusions occur relatively late in fetal life. The adult cranial form is explainable by the resultant dysmorphic and compensatory growth changes.

Zumpano *et al.* (1999) did a study to quantify the morphological differences in three dimensions among individuals with untreated isolated metopic synostosis (trigonocephaly). Comparisons between the metopic age groups found that trigonocephalic phenotype worsens with time.

Intra-cranial volume

Another promising application using CT or magnetic resonance (MR) examinations, or both, is the evaluation of cranial volume. One of the objectives of surgery in patients afflicted with craniosynostosis is to relieve intra-cranial pressure due to the diminished volume or the altered shape of the intra-cranial cavity, or both.

Previous studies have indicated the important of the relationship between intracranial volume (ICV) and intracranial pressure in patients with craniosynostosis. A few studies suggested that the constricted effect of untreated craniosynostosis on an otherwise normal brain would cause elevation of intracranial pressure during periods of rapid brain growth. This could consequently produce brain damage. Therefore, surgical decompression was advocated to release the prematurely fused metopic or sagittal suture in the hope that spontaneous brain reshaping would occur and prevent brain damage.

As the 3D software has become more advanced, intracranial volume measurements can be calculated non-invasively from standard CT scans. In 1995, Posnick et al. measured ICV in craniosynostosis patients before and after surgery. Using a 3D software package – CT Pak – all the holes in the skulls (i.e., foramina and fontanelles) could be blocked off using the mouse. The computer then counted the number of voxels within the cranial cavity and calculated its volume. Their findings suggested that premature closure of either the sagittal or metopic suture did not result in diminished intracranial volume.

In 2000, Abbott *et al.* measured ICV for normal populations of children using *Persona* 3D software package. *Persona* automatically contours the bone in each slice and saves them into separate files that are processed by a procedure called contour triangulation to produce a triangular mesh. The ICV is calculated by summing the cross-sectional areas that intersect the region of interest and multiplying by slice separation (referred as the Cavalieri estimator).

Stereolithography (STL)

The fabrication of models of the craniofacial complex depends on adequate information about the size and shape of the object to be constructed. CT data have been used to provide a triangular surface description of the craniofacial bones for this purpose. STL is a computer-mediated method to create anatomically correct three-dimensional models based on CT. A variety of methods such as STL and laser sintering are used to accurately reproduce both the internal and external anatomy of craniofacial structures for pre-operative planning of craniofacial, orthognathic and maxillofacial surgery (Lambrecht and Brix, 1990; Abbott *et al.*, 1997; Sailer *et al.*, 1998; Onishi and Maruyama 2001). Dolz *et al.* (2000) have indicated the potential application of STL in the field medicine. The authors suggest that the production of 3D models could be useful in court to demonstrate injuries and convey information to jurors that would be more useful than standard photographs and diagrams.

CONCLUSION

Computer assisted medical imaging technologies provide new tools for the study of congenital craniofacial deformities. The post-processing of CT scan data to produce 3D surface reconstructions has facilitated the comprehension and quantitation of such data by non-radiologists. While 3D reconstructions were applied initially to assist clinical management of patients with craniofacial deformities, these images are now finding utility in the study of unique anomalies, the definition of group characteristics for dysmorphic heads, the differentiation of similar phenotypes, and the documentation of the effects of craniofacial surgery on craniofacial growth. These findings should assist the formation and evaluation of hypotheses regarding mechanisms of congenital malformation and deformation.

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