FOLIA MEDICA CRACOVIENSIA
Vol. LVI, 2, 2016: 45–52
PL ISSN 0015-5616

Three-dimensional model of the skull and the cranial bones reconstructed from CT scans designed for rapid prototyping process

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Abstract: This paper presents the effects of building mesh models of the human skull and the cranial bones from a series of CT-scans. With the aid of computer software, 3D reconstructions of the whole skull and segmented cranial bones were performed and visualized by surface rendering techniques. The article briefly discusses clinical and educational applications of 3D cranial models created using stereolitographic reproduction.

Key words: mesh models, 3D-printing, cranial bones, plastic surgery.

Introduction

In recent decades the technical advances of computer graphics conjugated with medical imaging techniques have improved imaging quality and provided a wide spectrum of possibilities to perform accurate 3D reconstructions of anatomical structures. Progressively developed algorithms used for visualization of data obtained from CT scanners and other diagnostic devices allow for perfect, non-destructive insight into the human body. Detailed and reliable imaging of body structures is a necessity in contemporary surgery, which is based on knowledge of organ topography and anatomy. Spatial orientation within the interior of the human body is required from the operator during endoscopic surgery or implant fixation [1]. Therefore, virtual 3D reconstructions of organs have been used for teaching anatomy as well as for training surgical procedures and planning surgical operations [2–4]. Virtual anatomical models and 3D reconstructions have become indispensable in plastic surgery because they allow visualization of post-operative effects. So far, medical technologies have significantly improved the ability to minimize invasive surgery, decreased the risk of failure in surgical procedures, and reduced post-operative patient discomfort, particularly by producing individually modified implants or prostheses.

The current study briefly discusses the idea of creating computer 3D models from serial CT scans and reveals their potential role in reconstructive surgery and anatomical education. Products of three-dimensional reconstructions of the human skull and selected cranial bones intended for rapid prototyping were presented in a pictorial way using multiplanar views.

Materials and methods

Contemporary possibilities of three-dimensional imaging and creating virtual models from computed tomography were tested using a serial sequence of CT scans of the human skull of an adult individual. The skull was well preserved and all cranial bones presented normal anatomy and therefore could serve as reference objects to be modeled.

CT data was acquired using a CT scanner (Somatom Sensation 16, Siemens). The parameters of the CT study were the following: matrix — 512; exposure factors — 120 kV, 208 mA; slice thickness — 0.8 mm. Three-dimensional reconstructions of the whole skull and separated cranial bones were obtained by means of the InVesalius open source computer software developed at CTI (Renato Archer Information Technology Center) and dedicated to processing CT data [5] (http://www.cti.gov.br/invesalius). The software uses slices captured by CT-scanners as DICOM images in order to generate virtual 3D models corresponding to anatomical parts of the human body by allowing the conversion of a stack of DICOM files into a stereolithography file.

Three-dimensional models of the skull and the cranial bones were processed with MeshLab software to improve model quality by denoising, smoothing, and decimation procedures. The 3D model of the skull was displayed on a computer screen and compared with the volume rendered skull for assessing the quality of the model and, if needed, for performing reoptimization. Further, the graphical information of the model stored in the stereolithography file was processed with Meshmixer software which allows for virtual sectioning of the rendered model intended for 3D printing.

The MeshLab and the Meshmixer softwares are freely available from the web (http://meshlab.sourceforge.net/ and http://www.meshmixer.com/). Both softwares are designed for processing triangular meshes and provide a set of useful tools for editing, cleaning, healing, inspecting, rendering and converting mesh models. For final graphical presentation of the recreated models we used MeshMagic 3D modelling software (http://www.nchsoftware.com/meshmagic3d/). This software allows for perspective viewing of the model simultaneously with XZ-plane, XY-plane, and YZ-plane projections seen in separate windows.

Results

From the sequential series of CT-scans of the human skull, the computer software generated a detailed 3D model of the skull whose parameters were stored in the stereolitography file format. Anatomical details of the cranial bones were easily recognized, therefore the quality of the created model appeared to be satisfactory both from scientific and utilitarian points of view. Virtually dissecting the skull presented realistic surface topography of cranial fossae and the endocranial surfaces of each cranial bone revealed a complete spectrum of anatomical details (Fig. 1).

All natural foramina and fissures of the cranial base were well visible on the model. Also, the outline of the cranial sutures could be traced on the skull surface, including variable morphology of sutural interdigitation and degree of its patency. For instance, interdigitation of the occipital squama incorporated into the lambdoid suture was reconstructed in detail. The internal surface of the occipital squama shows well modeled grooves for dural sinuses and depressions for the cerebral and cerebellar lobes (Fig. 2, Fig. 3).

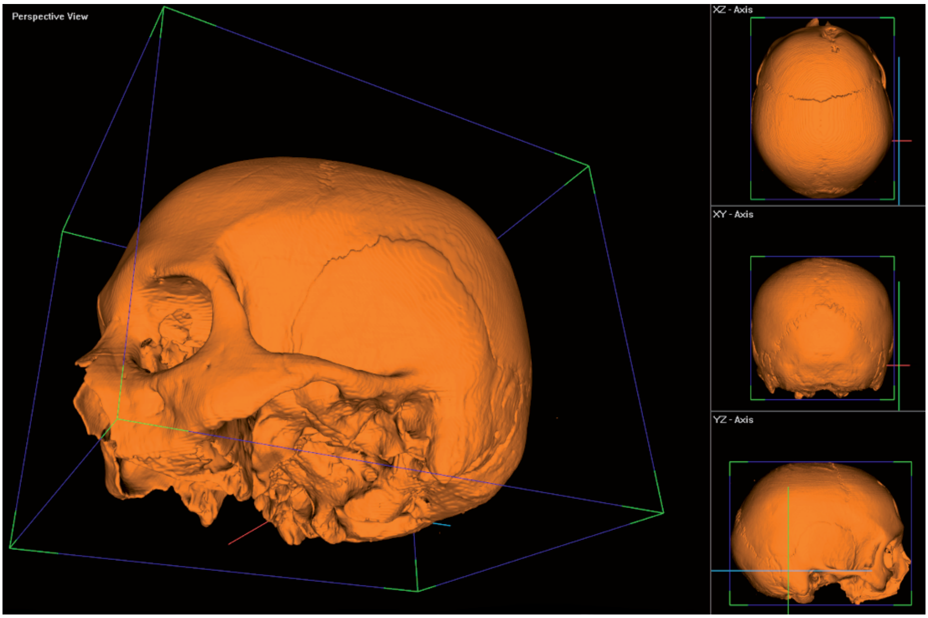

Fig. 1. Rendered model of the whole skull presented in perspective view (left) and three standard projections (superior, posterior, lateral). The mandible was removed for better observation of anatomical details of the cranial base.

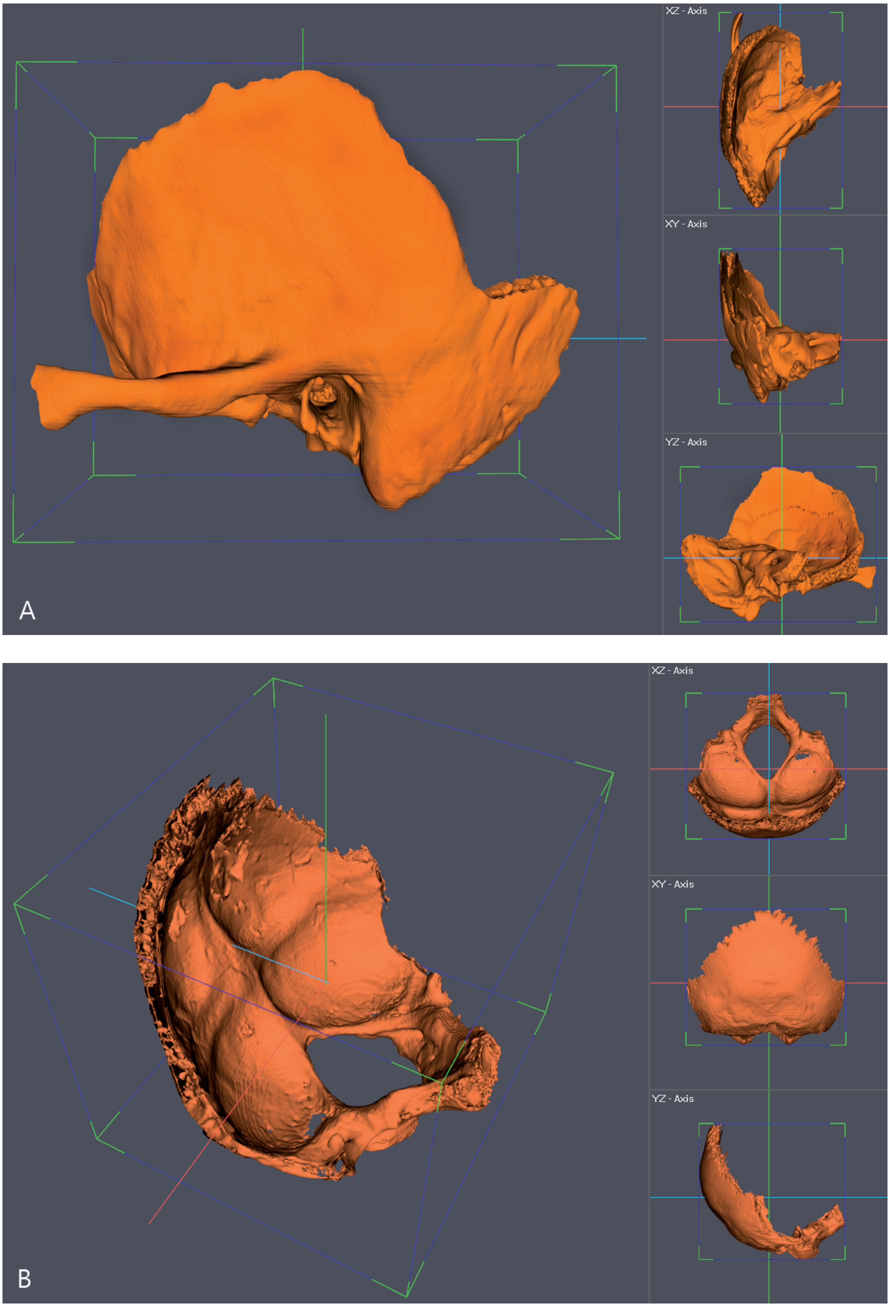

Fig. 2. Examples of rendered models of the temporal and occipital bone extruded from the skull. Lateral projection of the temporal bone (A) — the squama, the tympanic part and the mastoid part are visible. Perspective view of the endocranial surface of the occipital squama (B) — the cruciate eminence and the grooves for the dural venous sinuses are visible.

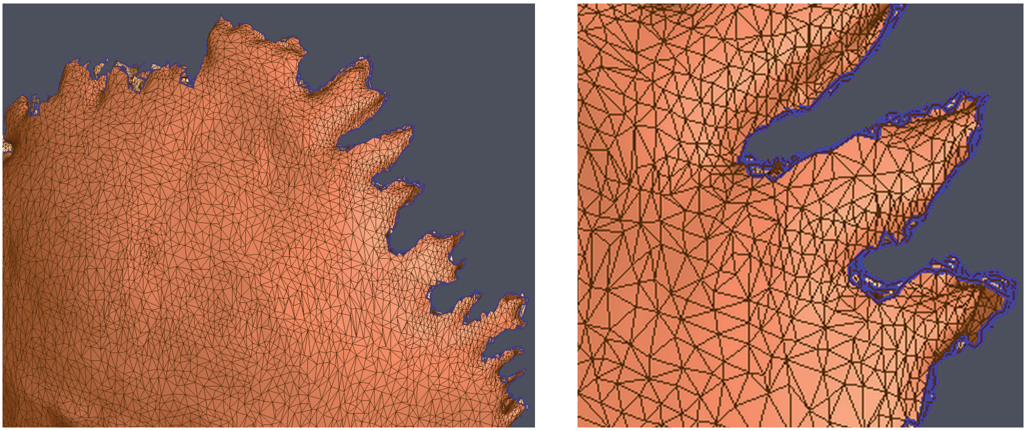

Fig. 3. Close-up of the edge of the occipital squama shows accurately modeled osseous projections of the lambdoid suture. On the external surface of the occipital squama is visible a mesh composed of tiny triangular faces whose gaps are filled with a texture to illustrate the idea of creating a mesh model.

The most difficult to 3D model appeared to be the temporal bone. Although its external morphology was properly captured by the mesh model, the internal structure of this bone was not satisfactory for anatomical and morphometrical studies. The reasons for this were relatively low resolution of images delivered by clinical CT scanners and relatively small size of inner components of the temporal bone.

Presented 3D models of the human skull and extruded cranial bones can be visually inspected from any point of view and measured using computer software to perform quantitative analysis. Such models can also be used to create a computer animation and can be interactively explored by virtual sectioning of the object using different cutting tools or trimming by appropriate adjustment of the clipping planes. This is particularly applicable to the temporal bone because of the complex internal morphology and intricate spatial orientation of the osseous structures building the middle and inner ear.

Discussion

Three-dimensional imaging of human organs has been a field of focus of the second half of the 20th century. Since then, 3D imaging techniques have been implemented in numerous medical procedures and helped understand complex topographical relationships within human organs as well as between them. Thus, precise three-dimensional representation of human organs can enhance teaching of anatomy and improve perception of their spatial configuration. Realistic 3D imaging and modeling have become helpful in diagnosis and utilized in computer-aided surgery. Such 3D models can be generated from images obtained from computed tomography or magnetic resonance [6–8]. In this process, rendering of 3D anatomical models is based on creation of a polygonal mesh which represents geometrical properties of the object. In other words, 3D shape is defined by a polygonal mesh which is frequently a triangle mesh consisting of vertices, edges, and faces.

In the current study we created 3D cranial models which may serve for teaching anatomy by visual inspection in the virtual space or by being manufactured from polymeric substances. The same models may become an example of the use of computer techniques in reconstructive surgery and may illustrate the essential stages for designing implants or prostheses [9]. Computer generated models stored in stereolithography files can be further used in rapid prototyping processes (eg. 3D-printing) in which models are built layer-by-layer according to 3-dimensional datasets [10–12].

Novel computer algorithms allow rendering and display of mesh surfaces in a relatively short time and therefore quality of the model can be quickly verified by visual assessment before it is printed [13]. However, creation and manufacturing of medical models from CT-scans or laser scanning systems also has some limitations which are described in literature [14, 15]. Invention of 3D-printers has allowed for rapid prototyping of three-dimensional objects from polymers or biomaterials. All these circumstances — virtual modeling, 3D printing and development of polymer engineering, biomaterials — have provided new perspectives in plastic and reconstructive surgery [16]. Thanks to this, regional disruptions of the skull can be fixed using biomaterials which can substitute living tissue and still preserve the protective role of the cranial bones toward the underlying brain. This is particularly useful for people who suffer from cancerous diseases of the bone or head trauma and need replacement of cranial bones [17]. The 3D-printed skull implants have a huge advantage because their shape can be easily customized for the patient's requirements [18, 19]. Custom-made implants were even used to replace large parts of the damaged skull and filled the gaps safely. Contemporary manufacturing techniques are capable of producing replacement parts which encourage the growth of natural tissue. A recent overview of materials used for cranioplasty, including autografts, allografts, and synthetic biomaterials has been presented by Song *et al.* [20].

Conclusions

The mesh-based modeling technique appeared satisfactory for creating an accurate three-dimensional model of the human skull which can be virtually explored on the computer screen. The rendered model of the skull can be decomposed into separate cranial bones using standard tools for mesh editing and manipulating. Hence, such a virtual model can be materialized through a rapid prototyping process.

Conflicts of interest

None declared.

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