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3D printed replica of the human temporal bone intended for teaching gross anatomy

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Abstract: The anatomy of the human temporal bone is complex and, therefore, poses unique challenges for students. Furthermore, temporal bones are frequently damaged from handling in educational settings due to their inherent fragility. This report details the production of a durable physical replica of the adult human temporal bone, manufactured using 3D printing technology. The physical replica was printed from a highly accurate virtual 3D model generated from CT scans of an isolated temporal bone. Both the virtual and physical 3D models accurately reproduced the surface anatomy of the temporal bone. Therefore, virtual and physical 3D models of the temporal bone can be used for educational purposes in order to supplant the use of damaged or otherwise fragile human temporal bones.

Key words: anatomy, temporal bone, mesh model, 3D printing.

Introduction

In recent years, 3D printing technology has been a subject of interest because of its numerous applications in the field of medicine. The possibility of manufacturing accurate three-dimensional models has attracted the attention of anatomists and clinicians who have perceived benefits from utilizing replicas in medical education, surgical planning, and training approaches to particularly complex anatomical structures such as, for example, the bones of the cranium [1–4].

The temporal bone is one of the cranial bones which has particularly complex anatomy and its subsequent components have relevance to neurosurgical approaches. Its peculiar position in the skull, both in the cranial base and in the lateral wall of the cranial vault, necessitates that visual inspection of the subsequent anatomical parts of the temporal bone and their topographical relationships must be performed from various directions [5]. Therefore, the most effective way of observing the entirety of temporal bone is from a disarticulated bone. However, removing of the intact temporal bone from the dry skull is not a trivial task and may cause destruction of other cranial bones. Moreover, independent temporal bones are fragile and have structures that are inherently at risk for damage (e.g., styloid and zygomatic processes), particularly in the setting educational environments. Therefore, manufacturing of artificial replicas of the temporal bones may serve as a solution to solve this problem, with the capacity to produce numerous durable models.

An accurate simulation of the cranial bone anatomy can be attained if the three-dimensional models are prepared from the image data captured with high spatial resolution. Thereby, high resolution computed tomography or micro-tomography have the potential to disclose complete morphology of the anatomical structures and deliver relevant digital images for creating virtual and printing three-dimensional models. An extensive review of methods and applications of 3D printed models created from medical imaging data has been performed by Marro *et al.* [6].

The intention of this study was to prepare a printable 3D model of the human temporal bone from CT scans, and evaluate to what extent clinical CT data are useful for creating replicas which can demonstrate external anatomy of the temporal bone.

Materials and Methods

For creating a representative 3D model of the temporal bone we used a single temporal bone of an adult female, selected from the osteological collection of the Department of Anatomy of the Jagiellonian University Medical College. The selected temporal bone was well preserved, did not show traces of pathology, and revealed normal anatomy characteristic for all its regions: squamous, petrous, mastoid and tympanic. Therefore, the sample was deemed appropriate for creating a 3D model demonstrating anatomy of the temporal bone.

In order to create a replica, the temporal bone was scanned using GE Medical Systems Optima CT 660 using following parameters of examination: X-ray tube current 100 mA, 140 kVp, slice thickness 0.625 mm, pixel spacing 0.355\0.355.

Serial CT scans were used to create a virtual model of temporal bone with the aid of InVesalius software, designed for reconstruction of computed tomography and magnetic resonance images, and supporting 3D printing technology. The software was used to generate a mesh of triangles which approximated the surface of the temporal. Further, the 3D mesh model was processed with MeshLab software in order to eliminate geometrical errors from the mesh and smooth its surface to obtain a virtual model appropriate for 3D printing. The software packages: InVesalius and MeshLab are freely available from the web (https://invesalius.github.io/ and http://meshlab.sourceforge.net).

A detailed survey regarding the preparation of data for 3D printing can be found in the article "3D Printing of Preclinical X-ray Computed Tomographic Data Sets" by Doney *et al.* [7]. Hereby, the authors give a detailed description of method for printing plastic models of the bones and other structures derived from X-ray CT scans utilizing various computer software, including the MeshLab system which was employed in our project.

Images from the computed tomography were combined into a stereolitography file containing data indispensable for materializing virtual model of the temporal bone by means of rapid prototyping technology. The final 3D mesh model consisted of 235,645 triangles that approximated the surface anatomy of the temporal bone. For the purpose of materializing the 3D model, we used fused filament fabrication dual extruder 3D printer Ultimaker 3 with Cura 4.0 software (Geldermalsen, The Netherlands). Both extruders had the nozzle diameter of 0.4 mm, but two different filaments were used: polylactic acid filament (PLA Ultimaker Green filament diameter = 2.85 ± 0.10 mm) for manufacturing the replica of the temporal bone and polyvinyl alcohol filament (PVA Ultimaker Natural filament diameter = 2.85 ± 0.10 mm) for generating water soluble supports of the replica. The layer height of the print was 0.15 mm. The used polylactic acid filament was selected because it provides good surface quality of the printed objects and what is beneficial for creating accurate replicas of the anatomical structures.

Results

The virtual and physical 3D models of the temporal bone demonstrated correctly external anatomy of all bony parts: squamous, tympanic, petrous and mastoid. The overall appearance of the printed replica of the temporal bone possessed a moderately distinct surface texture (roughness) and an altogether distinctive color compared to the original bone. Though, the polymer color can be altered for mimicking the appearance of natural bone.

The natural sharp protrusions and tubercles of the original bone gained a more rounded and smoothed appearance, referring mainly to the articular tubercle, convexity of the mastoid process, irregularities along the edge of the temporal squama, and vascular grooves which looked more shallow than on the original bone.

The printed replica of the temporal bone revealed most of the anatomical details visible on the surface of the original bone (Figs. 1 and 2). The outer surface of the printed temporal bone exhibited remarkable anatomical landmarks and morphological details characteristic for the temporal squama, tympano-mastoid regions and the zygomatic process. However, the groove for the middle temporal artery visible on the original bone was not present on the replica.

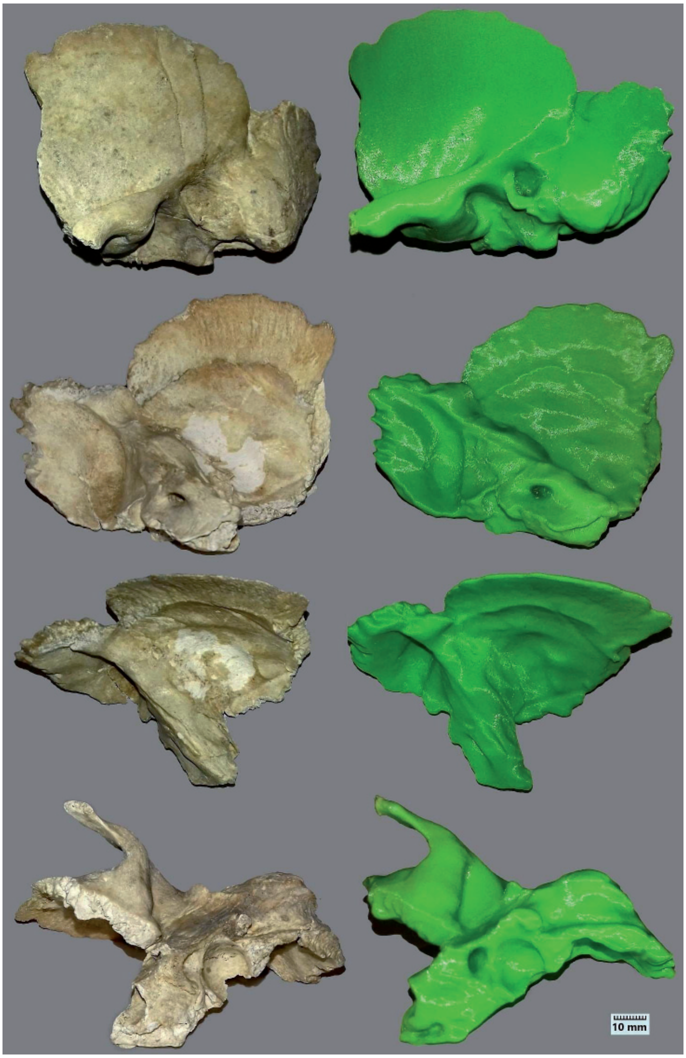

Fig. 1. Original temporal bone (left) and printed polymer replica (right) seen in various orientations.

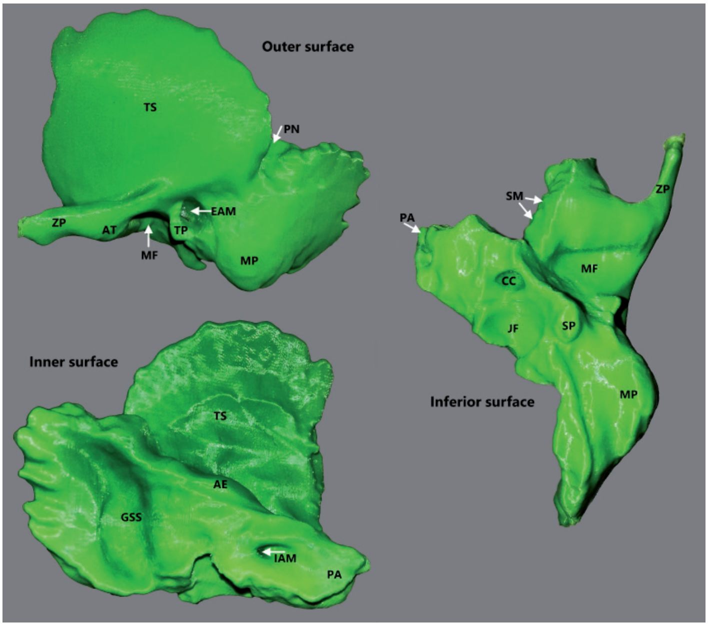

Fig. 2. Anatomical structures noticeable on the printed replica of the temporal bone: TS — temporal squama, ZP — zygomatic process, AT — articular tubercle, MF — mandibular fossa, TP — tympanic part, EAM — external acoustic meatus, MP — mastoid process, PN — parietal notch, PA — petrous apex, CC — carotid canal, JF — jagular fossa, SP — styloid process, SM — sphenoid margin, GSS — groove for the sigmoid sinus, AE — arcuate eminence, IAM — internal acoustic meatus.

The endocranial surface of the temporal squama viewed on the replica revealed high accordance in appearance relative to the original bone; the conformation of the cerebral surface, and the shapes of the parietal and sphenoid margins were almost the same. In this aspect, we could easily recognize impressions for the gyri of the temporal lobe and grooves for the divisions of middle meningeal vessels.

The petrosquamous fissure and parietal notch were well demarcated, as well the grooves for the superior and inferior petrosal sinuses, and the sigmoid sinus. Anatomical details of the petrous part including the trigeminal impression, internal acoustic meatus, arcuate eminence, tegmen tympani had satisfactory appearance for demonstrating them on the printed replica of the temporal bone. The subarcuate fossa and the external aperture of the vestibular aqueduct were hardly visible on the replica of the temporal bone; however, their location can be identified. Similarly, the orifice of the musculotubal canal was visible, but not the lumen of this canal.

The inferior surface of the printed temporal bone presented relatively big structures: the mandibular fossa, jugular fossa, opening of carotid canal, whereas: the tympanic canaliculus, depression for inferior ganglion of glossopharyngeal nerve and the opening of the cochlear canaliculus were not visible. Diameters of these structures were too small to be replicated from CT image data acquired according to the standard protocols apply for medical examination of the head. Also, tiny foramina like: the mastoid foramen and stylomastoid foramen were not well reproduced on the printed replica of the temporal bone. They were pronounced as shallow depressions.

The styloid process did not exist as a complete unit on the original bone, thereby only small portion emerging from the base of the skull was noticeable. Nonetheless, the fragmentary styloid process was seen on the printed replica of the temporal bone.

In spite of aforementioned imperfections in appearance of the printed model and noticeable discrepancies in morphological details comparing to the original bone, we regard that the anatomy of the temporal bone can be explained quite well using the 3D printed replica.

Discussion

Three-dimensional models of the temporal bone, manufactured by rapid prototyping technology, have been regarded as useful by various scholars who have used them for medical education and surgical simulations. Further, printed 3D models of the temporal bone can be prepared in a multicolor way in order to highlight intrinsic components that facilitate understanding of three-dimensional anatomy [8–12].

The models recreated from CT-scans show surface structures of the temporal bone accurately. Bakhos *et al.*, compared measurements taken from cadaveric temporal bones versus their prototypes obtained by means of stereolithography, and did not find significant difference between them. They concluded that such prototypes were reliable anatomic models which can be dedicated for surgical training (e.g.: antrotomy or tympanotomy) and simulating insertion of prostheses in the middle ear [13]. Also, Cohen and Reyes presented 3D printed models of the temporal bone created from clinical CT scans of resolution 0.227 mm × 0.227 mm × 0.5 mm. They found that macroscopic size and visible structures resembled an actual temporal bone. Besides the gross anatomical structures characteristic for the temporal bone they were able to identify on the models the middle ear structures: the auditory ossicles, oval window, round window, promontory, Eustachian tube, mastoid air cells, and other structures like the facial nerve canal and horizontal semicircular canal seen in a simulated transmastoid approach [14].

Hochman *et al.* found that the printed model of the temporal bone is comparable to the cadaveric temporal bone and can be considered as a valuable training tool with both realistic mechanical and visual character. The material used for manufacturing the replicas of the temporal bone may simulate physical properties of the real bone (e.g., its hardness), therefore, they can be dissected and drilled as real bone [15–16]. Therefore, 3D printing technology has been also used to build an artificial functioning model of the human middle ear and reproduce its essential elements with high accuracy [17]. Abovementioned remarks echo those of other reports and, thus, collectively deliver convincing evidence indicating the benefits of utilization of 3D printed models in medical education, particularly in cases of limited access to the original specimens and in the necessity of preparing a patient-specific model for pre-operative simulation [18–20].

The printed model of the temporal bone in this report was not a perfect resemblance; nonetheless, there was no hindrance in the demonstration of the overall morphology including anatomical structures which serve as the landmarks in surgical interventions. Anatomical inaccuracies, noticeable on the printed replica of the temporal bone, were an effect of spatial resolution of the applied CT scanner and other imaging parameters defined according to the protocol and dedicated for CT imaging of the head in clinical examination. Other factors influencing 3D model quality are related to the thresholding algorithm used for image segmentation prior creating the mesh model as well as the algorithms applied for final refinement of the mesh model. Also, technical parameters of the 3D printer and the way of prototyping may effect the appearance of the manufactured model.

Conclusions

A virtually rendered temporal bone can be easily transposed from the mesh model into reality by a rapid prototyping process. A 3D printed model created from CT data may be satisfactory for demonstrating the external anatomy of the temporal bone, but detailed internal anatomy should be presented on the 3D models created from micro-CT data.

Conflict of interest

None of the authors have any conflict of interest nor any financial interest.

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