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ORIGINAL ARTICLE

3D printing anatomical models of head bones

M. Bartikian[1] · A. Ferreira[1] · A. Gonçalves-Ferreira[1,2] · L. L. Neto[1,3]

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Abstract

Purpose In many medical schools, the study of Anatomy is becoming increasingly theoretical owing to the difficulty of having human body parts available, rather than offering the students the possibility of a more realistic and practical approach. We developed a project where we use a 3D printer to produce models of the human skull bones, with high quality and quantity to satisfy the needs for Anatomy classes and to be available for request to study at home.

Methods We selected regular and well-shaped bones of the head upon which we based the 3D models. These bones were scanned using a 64-channel Computed Tomography (high-resolution volumetric acquisition) and the resulting images were then processed with a segmentation software to isolate and reconstruct the structures of interest. The final digital three-dimensional objects were converted into a printable file that the 3D printer could read. We used two filament extrusion type 3D printers, the Prusa i3 and the Zortrax M200.

Results We have printed successfully several models of the skull bones, such as the temporal, occipital, and sphenoid. All the models have obtained good anatomical detail, thus demonstrating the practicality of this technology. Key aspects of the CT image post-processing are discussed. The production process is cost-effective and technically accessible.

Conclusions These results confirm the potential of 3D printing to create more complex models (e.g. regional, vascular, nervous system structures) that would allow a similar experience compared with a dissection.

Keywords 3D printing · Anatomy · Skull · Bones · Temporal · Sphenoid · Occipital · Segmentation

Introduction

The teaching of Human Anatomy is a milestone of medical education and requires a hands-on approach to apply and strengthen theoretical knowledge [1–3]. In a global perspective, not all medical schools have access to human cadaver specimens for dissection in part due to financial considerations involved in accessing and maintaining them [4, 5]. Furthermore, the increasing number of students, the reduction of contact hours, the shortage of cadavers, and the excessive time that is required to perform a dissection have diminished this practice [6]. Dissection-based teaching is still subject to social and ethical debate. Nowadays even though there is a necessity to modernize the teaching of Anatomy, it is mostly based on images and plastic models. Specimens conserved in formaldehyde and individual bones are scarce and very fragile, thus limiting their handling and the possibility for the students to study at home. The advantages of the recent 3D virtual dissection tables are well known for the pre- and postgraduate students, not only for revisions in anatomy but also for technical skills training [7]. Despite the availability of these computer devices which allow to interact virtually with human organ models, the current two-dimensional monitors limit the perception and understanding of the spatial relationships of complex surfaces. Additionally, they limit the desirable interaction to study the detailed anatomy directly on a 3D model.

Trying to overcome these restrictions, several projects have been conducted in the Anatomy Department at the Faculty of Medicine, University of Lisbon, in order to create plastinated anatomical models of the brain (data not

✉ M. Bartikian
mickael.bartikian@gmail.com

1 Anatomy Department, Hospital de Santa Maria, Instituto de Anatomia, Faculdade de Medicina da Universidade de Lisboa, Avenida Professor Egas Moniz, 1649-028 Lisbon, Portugal

2 Neurosurgery Department, Hospital de Santa Maria, Centro Hospitalar Lisboa Norte, Lisbon, Portugal

3 Neuroradiology Department, Hospital de Santa Maria, Centro Hospitalar Lisboa Norte, Lisbon, Portugal

published). These models achieved a very positive feedback from the community in our faculty.

The head bones, due to their complexity, are most likely to benefit from the practical study. Ideally, every student should have access to an anatomical model, at least during classes. If one should consider buying a high-quality anatomical model, the current prices are not accessible for many students. In our department there are few skulls available and usually the different head bones are not separated.

Additive manufacturing or 3D printing is often promoted as one of the most significant technological advances in our modern era. In the last couple of years, additive manufacturing, also known as 3D printing, has become more available to makers, researchers, and to different areas of the biomedical industry, allowing the production of physical models quickly and inexpensively [8, 9]. Since 3D models can be generated from medical computed tomography (CT) or magnetic resonance imaging data, it is logically possible to use 3D print outs from common imaging studies to augment the teaching of topographic and applied clinical anatomy [4]. Concerning head bones, one advantage of this technique is that it is possible to print separately the different components of skull base, vault, and face. Being able to show separate bones makes it easier to study the surface details which is rarely feasible with a real skull.

In this study, we aim to use a consumer type 3D printer to produce models of human skull bones with high quality and anatomical detail. The ultimate goal is to have enough models to satisfy the demands of Anatomy classes and to allow students to take them home to study.

Materials and methods

Materials

We selected a normal human adult skull, without anatomical deformities, from which the bones were individualized. In this work, we used the sphenoid, temporal, and occipital bones for the imaging study.

To produce the anatomical models, we used two different Fused Deposition Modelling (FDM) 3D printers, the Prusa™ i3 model (specifications: nozzle diameter: 0.2 mm, mechanical nominal resolution on the *XY* axis: 0.015 mm, mechanical nominal resolution on the *Z* axis: 0.781 µm, layer height: 100–500 µm) and the Zortrax® M200 (specifications: nozzle diameter: 0.4 mm, mechanical nominal resolution on the *XY* axis: 1.5 µm, mechanical nominal resolution on the *Z* axis: 1.25 µm, layer height: 90–400 µm). The models were printed with poly lactic acid (PLA) filament when using the Prusa™ i3. When printing with the Zortrax® M200, we used Z-ULTRAT, a proprietary filament from Zortrax® based on acrylonitrile butadiene styrene (ABS) polymer.

Methods

Imaging protocol

Each bone was separately scanned with continuous axial volumetric acquisition by CT. Scanner model: Philips® Brilliance™ 64-slice. Acquisition settings: 120 kV, X-ray tube current: 173 mA, exposure: 400 mAs, exposure time: 2312 ms, slice thickness: 0.67 mm, spacing between slices: 0.335 mm.

Image processing

We previously consulted the current literature on medical image segmentation software [10, 11] and determined the most appropriate methodology for our work. The CT images were processed with 3DSlicer™ program. For each bone, the 3D structure was reconstructed as a volume from the DICOM files.

The first step was segmentation, which consists of applying a volumetric filter over the voxels that correspond to the structure of interest. Since only separate bones were scanned each time and these were held with a very radio-transparent cellulose support on the CT scanner, the segmentation was simplified. The filter was applied by manually setting the lower threshold of greyscale values, above which only bone would be selected.

The second step involved the application of a Laplacian smoothing algorithm over the segmented volume. This step is necessary as the reconstruction from the CT images leaves edgy polygons along the three planes because of the slice thickness and the spacing between them. The smoothing operation may be described per-vertex of the polygons as $\bar{x}_i = \frac{1}{n}\sum_{j=1}^{n}\bar{x}_j$, where n is the number of adjacent vertices to the node i, x_j is the position of the j-th adjacent vertex and $\bar{x}_i$ is the new position for the node i [12]. The smoothing factor is manually defined with simultaneous visual feedback by two different observers. The rendered volume is satisfactory when the correct balance between surface smoothness and anatomical detail is established. The final volume is then exported as a stereolithography (STL) format file.

3D printing setup

The STL files were imported into a slicing software (CraftWare™ when printed with the Prusa™ i3 and Z-Suite™ when printed with the Zortrax® M200) that converts the digital 3D object into a G-code toolpath format, compatible with most 3D printers. Structural supports were added and standard printing settings were optimized for each 3D printer and for each model to the highest quality. The bone models were printed with 0.2 mm layer height on the Prusa™ i3 and 0.09 mm on the Zortrax® M200. PLA filament extrusion temperature was set to 200 °C and the print bed was not heated. Z-ULTRAT filament extrusion and print bed temperatures were predefined (256 °C and 50 °C, respectively).

Once the printing was completed, the supports were carefully manually detached and the models were brushed with abrasive tools and clear coated for an optimal finish.

Results and discussion

In this work, we successfully printed several exemplars of three head bones.

The left temporal bone (Fig. 1) took 3 h and 38 min to print each one of the 4 exemplars. A single occipital bone (Fig. 2) took 4 h and 20 min and was printed twice. These were printed using the Prusa™ i3. The sphenoid bone (Fig. 3) was printed with the Zortrax® M200 and took 23 h and 10 min for each of the 8 exemplars. All the models that we produced with our methodology presented a high detail and replicability, thus demonstrating the feasibility of this technology in the production of head bone models with anatomical accuracy.

When comparing the two printers, the Prusa™ i3 was faster but less reliable and many failures occurred. However, its open source design allowed experimenting with different parameters and materials. The Zortrax® M200 was much slower but very reliable. Its 0.09 mm layer height gave structural strength and a quality surface appearance to the model.

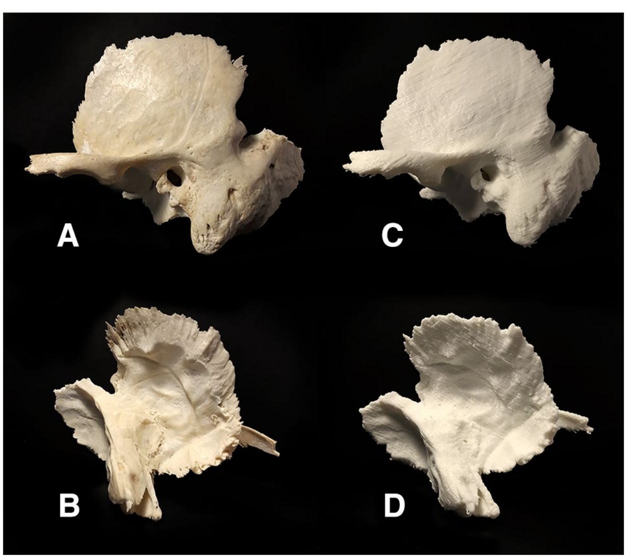

Fig. 1 Left temporal bone: lateral (**a**) and medial (**b**) views of the real bone. Lateral (**c**) and medial (**d**) views of its 3D printed copy made of PLA

Fig. 2 Occipital bone: 3D printed copy made of PLA

The final result depends on the quality of the image acquisition method, which itself depends on the thickness and intervals of the CT slices and on the amount of radiation that was used. Individual ex-vivo bone CT protocols are not described in the literature. Therefore, we elaborated our

Fig. 3 Sphenoid bone: different angles of the real bone (on the left) and its 3D printed copy (on the right) made of ABS

imaging protocol on the principle of dimensional accuracy with thin slices and by minimizing image noise by setting high current values [13]. Image voxel size and reconstruction kernels should be selected according to model requirements. Small voxel size and sharp kernels are appropriate for capturing fine image detail but due to noise may require more manual segmentation and post-processing to smooth the model. With regard to scan acquisition settings, where high-quality 3D printing is required, it is better to increase X-ray tube current to ensure noise is minimized [14].

The result also depends on the quality of the 3D printer. There are many kinds of machines which use diverse types of technology. They have varying properties, orders of magnitude, and range in price. Current examples of those types are FDM, powder bed fusion, binder jetting, material jetting, and vat polymerization or stereolithographic (SLA) printing [15]. To the exception of FDM and SLA technology, the other types of 3D printers generally have an industrial application and are not the best choice for educational or medical purposes. SLA printers allow resolutions of an order of magnitude of 10 µm, which is an interesting feature for low-volume production and high-quality demand. The choice of FDM printers in our work was based on cost-effectiveness. While SLA printers would achieve extremely fine detail, the material cost did not justify such an improvement for the purpose of producing anatomical models.

Segmentation is one of the steps that is most subjected to error because it is user dependent. It may involve manually drawing contours or different thresholds on each image or drawing contours or thresholds on non-contiguous images and interpolating between these contours, which can then be smoothed to form a 3D object [16]. In this step, we manually defined the 3D volume segmentation parameters, such as the threshold value on the greyscale of the CT images to isolate the voxels that represent bone matter. An extremely high value resulted in a loss of information (Fig. 4a), while low threshold value meant the inclusion of image noise in the volume (Fig. 4b).

The rendering of the 3D volume involves the application of a smoothing algorithm. Without this, the volume will present an edgy surface because of the way CT slices are stacked together. If this smoothing factor is too low, it will not solve the problem (Fig. 4c), and, reversibly, if the factor is too high, there will be loss of detail (Fig. 4d).

These models can be printed as many times as needed without great expense of material and energy, thus revealing the efficiency of this method of manufacturing. The only associated disadvantage is the long printing time, which certainly should be overcome in the future with the advances of 3D printing technology.

The models of human head bones that we have produced so far with our own process are applicable to the teaching of Anatomy, allowing a greater and better three-dimensional knowledge of the skull, thus contributing to a better medical education. Although it was not part of the objectives of this work, these conclusions would be consolidated by conducting a study hereafter to compare the test results of students who have studied using 3D printed models against those who have studied with books and images only, similarly to a randomized control trial comparing 3D prints versus cadaveric materials [17].

An overview of all the different competing technologies, besides 3D-printing, that claim to modernize the tools for teaching and learning anatomy, indicates that they all share a common principle: the ability to visualize an organ in all of its three dimensions. Virtual dissection tables [7] and interactive anatomy software offer that ability typically in a user-friendly format and have the potential of becoming

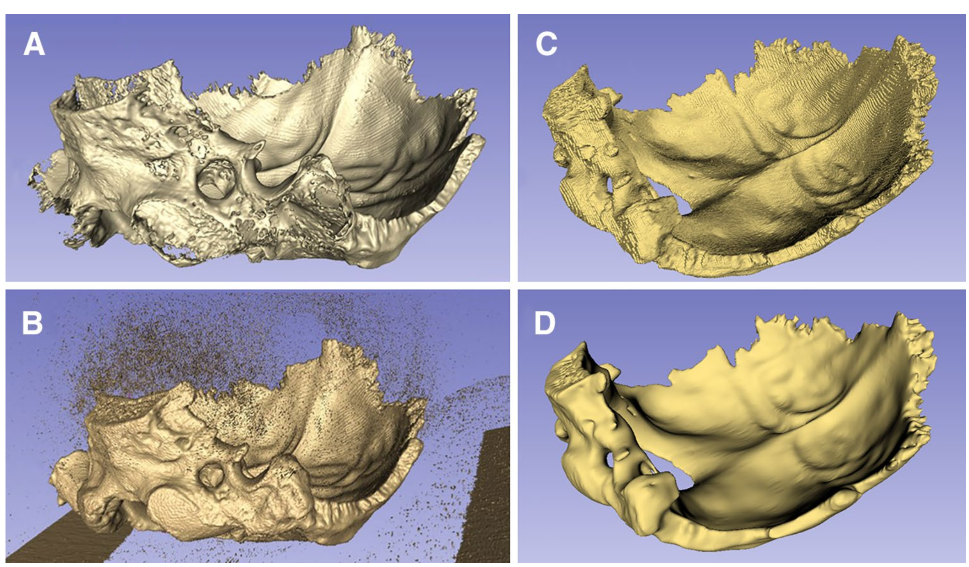

Fig. 4 Occipital bone: post-processing. With a very high segmentation threshold, some parts of the bone are lost (**a**). A very low segmentation threshold results in the inclusion of signal noise in regions corresponding to air (**b**). No smoothing algorithm was applied resulting in a very edgy surface (**c**). With a very high smoothing factor some details are lost (**d**)

a "fun" way for students to study anatomy. Another format is the 360° photography of organs and anatomical structures [18], as it provides a high-definition visual experience and accurately preserves colors and textures. However, the limitation of these technologies is their dependency of a bi-dimensional screen, whether it is a computer monitor or a tablet. Regarding that limitation, we believe that 3D-printed models offer a tangible aspect which adds an extra dimension to the visual information.

The present work also reveals the potential of 3D printing technology for the creation of more complex anatomical models, such as regional, vascular, and nervous system models, that can ultimately provide a similar experience to a dissection and that can be used for postgraduate surgical and interventional procedures.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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