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Research Article

A Method for Producing 3D Printed Models of the Mediastinum

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Abstract

Plastic models are a useful resource for teaching macroscopic anatomy, but have several drawbacks. We present a method for the in-house production of high-fidelity anatomical models using real patient scans, which overcomes many of the limitations associated with traditional models. These models are capable of showcasing real patient anatomy, including any normal or abnormal anatomical variations. The flexibility of this method allows models to be designed according to the producer's needs and could see use in both supplementing the education of surgical trainees and in aiding perioperative planning. The development of open access software and publicly-accessible libraries of model designs should make our technique easily adoptable.

Keywords: 3D printing; Education; Mediastinum; Perioperative planning

Abbreviations: 3D: Three-Dimensional; CT: Computed Tomography; MRI: Magnetic Resonance Imaging; C1: Cervical Vertebrae1, L1: Lumbar Vertebrae1, DICOM: Digital Imaging and Communication in Medicine

Introduction

Human anatomy is taught through a number of different mediums, the most effective of which is generally considered to be the use of human cadavers [1]. This gold standard allows anatomical structures to be examined in situ and easily visualised in three dimensions. However, cadaveric teaching presents serious ethical and logistical problems pertaining to the acquisition and storage of human tissue. The use of cadavers in undergraduate and postgraduate teaching is therefore often relegated to an adjunct of lecture-based teaching. As technology is advancing an increasing number of resources are becoming available to supplement anatomical teaching in universities, such as virtual reality and augmented reality devices that can accurately represent human anatomy [2,3]. However, evidence suggests that teaching with physical specimens remains an important and effective tool that should not be entirely replaced [4]. Three-dimensional plastic models could provide an adequate substitute for real human cadavers [5], but classically have their own issues such as high costs, improper detail and a failure to illustrate anatomical variation [6]. These problems may be resolved by utilising 3D printing, as recent technological advances have decreased costs such that it now represents a viable method of producing physical resources for anatomical teaching [7]. Moreover, 3D printing can draw from computed tomography and magnetic resonance imaging scans taken from real patients in order to accurately generate complex anatomical models that display realistic anatomical variation [8]. Through utilising 3D printing and open-source modelling software individual institutions could generate their own models in a flexible manner with decreased costs. This could extend to producing detailed and complex models to allow surgeons to visualise a patient's real anatomy prior to a surgery. This technique also represents a practical method of emulating cadaver-based learning without presenting serious logistical or ethical concerns. We have previously described how models of the hepatobiliary system [9] and retroperitoneum [10] can be generated from CT and MRI images. In this paper we describe the generation of a model of the mediastinum and its contents.

Methods

This mediastinum and thoracic outlet model was created through a partnership between the University of Oxford and 3D LifePrints. 3D LifePrints is a technology company with a particular interest in applications of 3D printing in medicine. CT dataset segmentation and 3D modelling were utilised to construct the anatomy of the model, which includes

- Spine (C1-L1), ribs (1-12, cut distally), clavicles and sternum
- Anterior, middle and posterior scalenes and diaphragm
- The heart including caval veins (tributaries: axillary, subclavian, internal and external jugular), aorta (branches: brachiocephalic trunk, right common carotid, right subclavian, right axillary, left common carotid, left subclavian, left axillary, left and right vertebral arteries), pulmonary artery with left and right branches, pulmonary veins, left and right coronary arteries, coronary veins and coronary sinus
- Intercostal neurovascular bundles (Right Side)
- Oesophagus, respiratory tract (Larynx, Thyroid Cartilage, Cricoid Cartilage, Trachea to first bronchi division), thyroid gland and thymus gland
- Brachial plexus (roots to 5 terminal branches), vagus nerve, recurrent laryngeal nerve, phrenic nerve and the sympathetic chain.

Imaging

To ensure anatomical accuracy, the bony anatomy was segmented from a high-resolution CT scan in the Digital Imaging and Communication in Medicine (DICOM) format. The boundaries of the heart, the lungs and the respiratory tract were also segmented from the CT scan and used as markers for digital sculpting. Images were anonymised to preserve patient confidentiality. To reduce the possible introduction of anatomical inaccuracies in the final 3D geometry, a scan with 0.6mm slice thickness was used. This is because there is an absence of imaging data between the slices and so the final 3D geometry is created by interpolating between the segmentation mask on each slice.

Segmentation of Anatomical Structures

Anonymised DICOM data was uploaded to Simpleware ScanIP (www.simpleware.com/software/scanip/) which semi-automatically classifies anatomical structures into bone, soft tissue, and vascular structures using Hounsfield Units to determine tissue density. This allows for differing anatomical structures to be segmented into separate 3D objects, which ultimately allows individual colour and material properties to be applied to each anatomical structure.Due to the low contrast gradients between some of the cardiac structures on the CT imaging and the inclusion of small structures such as nerves, semi-automatic segmentation was not possible for all anatomical structures. Manual segmentation may have taken a number of weeks, and so it was necessary to use 3D modelling and digital sculpting software to complete the model. (Figure 1) shows the collated 3D models representing the anatomical structures that were segmented on Simpleware ScanIP from the CT dataset. Where appropriate these 3D meshes were digitally optimised using Meshmixer® (version 3.5, http://www.meshmixer.com/). Mesh mixer allows for meshes exported from Simpleware ScanIP to be repaired, modified, and smoothed. This largely consisted of removing surface irregularities and sharp edges that presented as artefacts from the creation of the mesh. This is an important step in improving the resolution and contours of the model (Figure 1).

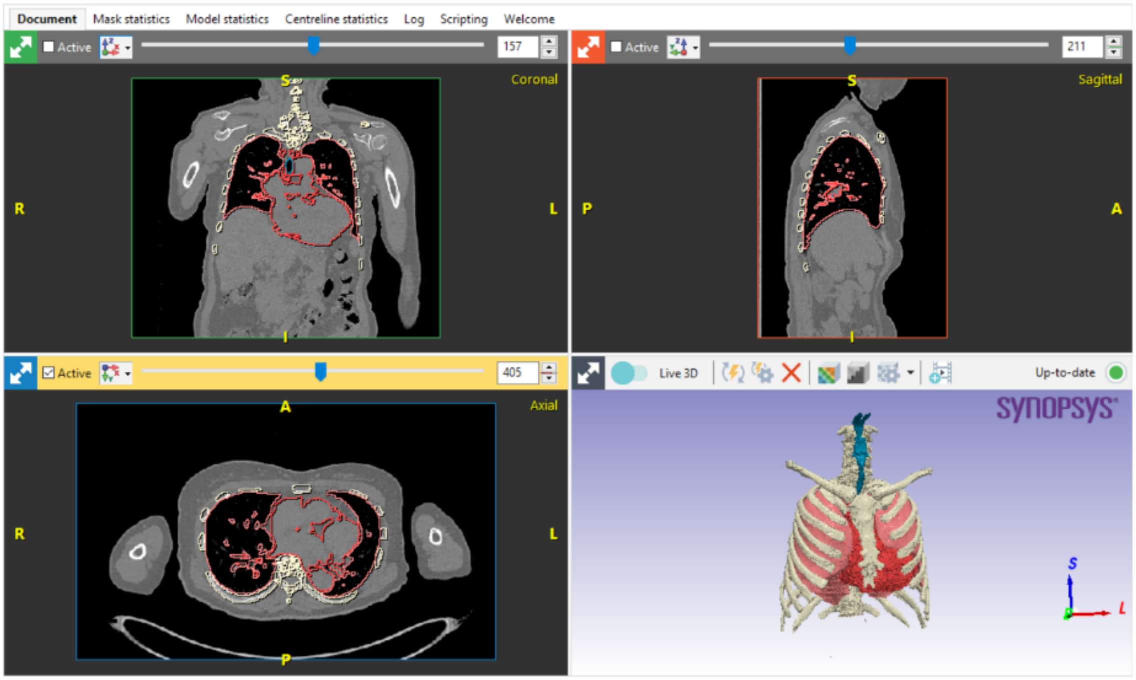

Figure 1: The segmentation process performed with Simpleware ScanIP. The bottom right panel shows the overlayed models of the viscera and bones produced by this process.

Computer Aided Design

1. The modified 3D meshes that were exported from Mesh mixer were imported in to Z-brush (https://www.maxon.net/en/zbrush) and these provided anatomically accurate boundaries and landmarks for use in digitally sculpting anatomy that could not be segmented or needed significant refinement. Anatomical structures that were newly added included the musculature, vessels, nerves, glands and cartilage. The heart was created by using the segmented mask from the CT as a template and guide to build new, optimised geometry. Primitives and Z-spheres were used to create basic geometry, which could then be digitally sculpted using a variety of brushes. This was carried out by a biomedical engineer with experience in anatomical 3D modelling under the guidance of the Director of Anatomy.

2. Once all the anatomical structures were generated and reviewed by the Director of Anatomy, the model was optimised for 3D printing. Small positional changes were made and connectors were added to the model in regions of possible instability or weakness. A small detachable part of the model was created to allow for better visual inspection of the internal thoracic cavity, this part included the sternum, costal cartilage, clavicles and thymus gland.

3. To create a more realistic look, Z-brush was also used to digitally paint the model. This allows a texture map for each anatomical structure to be created by UV unwrapping each object and baking the texture, or paint, on to the resultant map. The texture map can then be exported and used by the 3D printer to colour the model.

4. Once the digital 3D model was completed, the file was exported as an OBJ file, which contains the texture map data as an accompanying MTL file and JPG, this can be uploaded to the 3D printer software GrabCAD (https://grabcad.com/) for production.

Material Selection

The model was printed on the Stratasys J850 printer to allow the model to be coloured using the texture map. The core of the model was printed using VeroWhite and the outer coloured shell is created by the mixing of 6 base colours of polymer resin. The detachable part of the model was printed using a connex3 object 260 which allows for three polymers to be simultaneously 3D printed. The materials chosen were VeroMagenta, Agilus30Clear and VeroWhite.

Printing Process

GrabCAD calculates the most economical print orientation while considering the need to support overhanging 3D parts of the model with a removable support polymer (FullCure705 support). After this calculation the printing process took 81 hours and the model was printed in two parts. The model used 5.94Kg of plastic material, comprising 3.6 Kg of VeroWhite, 0.62 Kg of VeroMagenta, 0.39 Kg of VeroBlack, 0.45 Kg of VeroCyan 0.37 Kg of VeroClear, 0.34 Kg of VeroYellow and 0.17Kg of Agilus30Clear. The removable support required 7.25 Kg of FullCure705 support. The cost of the raw plastic materials alone was £3263.20. After printing was complete, post-processing involved use of a chemical solution to remove the support polymer, and joining of the separate sections. For added stability and better surface finish, the model was then spray coated with 5 coats of acrylic matt gloss paint, after which it was mounted in a case (Figure 2).

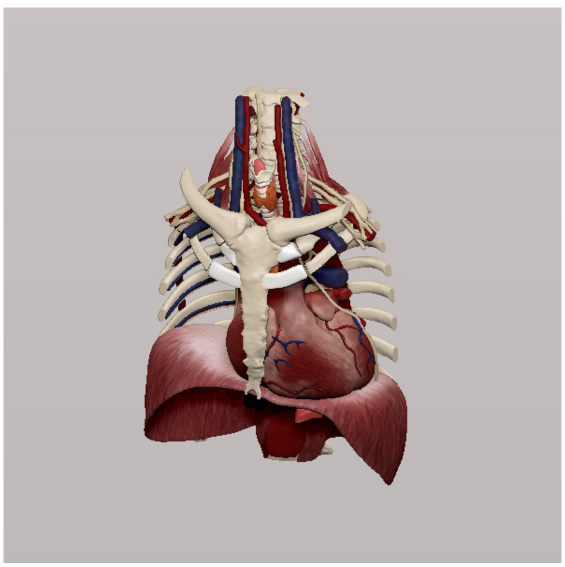

Figure 2: The final design of the model used for printing.

Discussion

Comparison of 3D Printed Models, Plastic Models and Cadavers

Cadavers, plastic models and 3D printed models differ in a number of factors that determine their use as anatomical teaching aids.

Realism: The extent to which the medium actually represents human anatomy is greatest for fresh cadaveric specimens, and least for plastic models which generally lack detail and realistic textures. Plastic models also often omit key structures like nerves, for example, and even if they do include them they tend to poorly represent their true anatomical course. On the other hand, using real patient scans to print models ensures that every major anatomical structure is accurately recreated. Furthermore, the flexibility of design that comes with 3D printed models means that they can convey very specific details for instance, a model of the liver could exhibit the nodular appearance classically seen in cirrhosis.

Accessibility: Plastic models are by far the most accessible teaching medium. Cadavers are difficult to obtain, requiring bodies to be donated, and considerable ethical concerns are generated regarding both their acquisition and use [11]. 3D printed models require a considerable amount of time and skill to produce, as well as an initial setup of a printer and modelling software. Disregarding the costs resulting from this setup, 3D printed models may be cheaper to produce than plastic models are to purchase.

Applications: The ability to view anatomy in a 3-dimensional space is invaluable, for example in aiding understanding of complex positional relationships of anatomical structures, or for interpreting imaging scans that may not necessarily be intuitive to the learner. A prominent feature of 3D printed models is that they can be highly variable, capable of being designed to illustrate surgical landmarks or anatomical variation, for example. Cadaveric specimens may lack such features; however, they do represent viable mediums for teaching practical skills such as suturing. While arguably not as effective in this regard, plastic and printed models may have some utility for the teaching of practical skills. For instance printed models can be designed for simulating intraoperative navigation [12].

Upkeep: A major issue with cadaveric specimens is that they require a large amount of time, skill and money to be kept in a good condition. Even then, they are liable to degrade over time as they are used. Plastic and 3D printed models are very durable and no upkeep is required to maintain them.

Practicality of Model Production

The aim of this paper was to outline a method for generating high quality anatomical models that other groups could follow for their own purposes. While simple in principle, our methods do present some logistical hurdles that should be considered before attempting to replicate the process. For instance, the design of a model from multiplanar images takes a considerable amount of time and skill, so a suitably trained individual must be available to produce these designs. To help overcome this issue we are aiming to develop an online, free-to-access library containing this, and other, model designs. This will make our method much easier to adopt by greatly cutting down the time and skill required for production. An important consideration is the cost of producing 3D printed models compared to purchasing commercially-available models. Production of detailed models requires expensive state-of-the-art printers and licensed software, which could mean significant start-up costs. Once this infrastructure has been established further costs may come from the purchasing of plastic materials, maintaining the 3D printer and employing in-house developers. For instance, a single copy of the full-scale model described in this paper cost £3263 to produce. By comparison, an equivalent anatomical model from Adam Rouilly could be purchased for £1010 (excluding postage and VAT) at the time of writing; a model of the human torso could similarly be purchased for £3426 [13]. It is worth considering that the cost given above is for a full size model. A smaller scale model may be perfectly adequate for teaching undergraduate anatomy and could be printed for a fraction of the price. It may also be possible to produce a model with interchangeable parts such that it has the functionality of several different models in one (see section 3.3). Furthermore, start-up costs are likely to decrease over time. Improvements in technology are continually pushing down the cost of 3D printer [7,14]; likewise, the development of open-source software may provide a cost-free alternative for model design [15] (Figures 3,4).

Figure 3: Anterior views of the finished mediastinum model with the removable section attached (left) and detached (right).

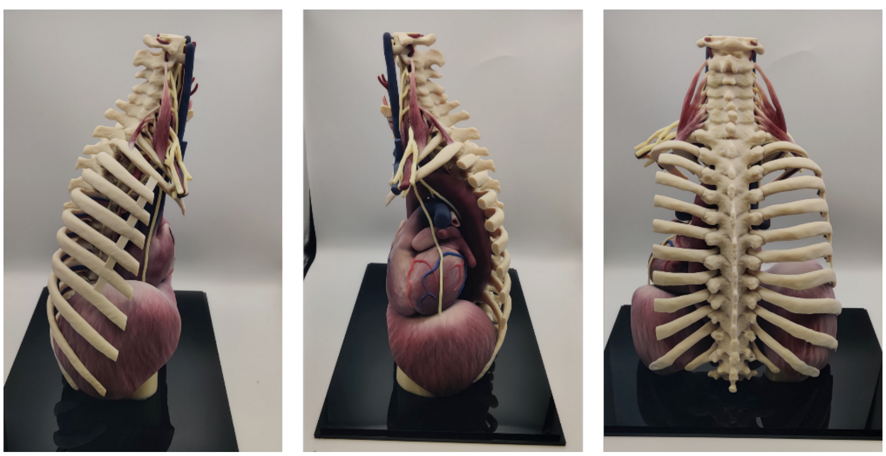

Figure 4: Alternative views of the finished model.

Versatility of Model Production

Once the infrastructure needed to support the model design and production has been established, a group can produce anatomical models at their own discretion in order to best meet their personal needs. This should be an appealing alternative to purchasing commercial 3D plastic models, which are often expensive and may not provide the specific set of details that are desired. For example, surgical trainees may benefit most from models that showcase important surgical landmarks. The ability to produce custom designs therefore means that models could be tailored to specific groups, such as undergraduates or postgraduates, in order to enhance their effectiveness. This could mean life-sized models to be used alongside imaging scans in order to help surgical residents with visualising intraoperative navigation, or multiple small scale models to help an undergraduate class understand the basic anatomy. Furthermore, an

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inherent advantage of designing models from real patient scans is that it allows for anatomical variations to be replicated. These are important to consider during surgery but are rarely demonstrated in commercially available models [16]. Similarly, anatomical changes that accompany pathologies could be demonstrated with this technique, for example by producing models of healthy and cirrhotic livers for comparison. Taken one step further, a single design with multiple interchangeable parts could be produced, allowing one model to demonstrate normal and pathological anatomy, and normal anatomical variants, thus greatly reducing material costs. This flexibility in model design goes far beyond what could be acquired from traditional plastic models.

This model was produced with state-of-the-art equipment and used materials of differing colours and textures. However, it still fails to emulate the rigidity and texture of real anatomical structures, a shortcoming not seen with fresh, well-preserved cadavers [17]. This is an important consideration as it makes the model unviable as a tool for practicing suturing or dissection, important surgical techniques that can be performed on high-quality cadavers. It may be practical, therefore, to make printed models a primary resource for undergraduate teaching, so that cadaveric specimens may be reserved for surgical trainees. This could increase the availability of cadavers for those who would benefit from them the most, while providing a useful substitute for students undertaking primarily theoretical studies. Alternatively, advances in bioprinting may make it possible to produce models with more realistic textures [18].

Future Perspectives

This study is part of a series documenting the recently formed Oxford Library of Anatomy. It is intended that upon completion this library will serve as a repository of anatomical structures from the entire human body. As the library is expanded and 3D printing becomes increasingly accessible, it is hoped that teaching institutions and even individual students will be able to download models from the library and print them as they require. Furthermore, in the future we aim to develop a new generation of 3D models that incorporate haptic technology. These will provide audio-visual information to students as they lay their hands on the models.

Conclusion

We have described a method of producing high-fidelity anatomical models by combining 3D printing, modelling software and in vivo patient data, and have presented one such model of the mediastinum. These printed models are highly customisable, giving them advantages over traditional plastic models, and may serve as useful adjuncts or alternatives to cadavers in anatomical education, as well as offering significant promise as tools in surgical planning. We hope that the collaborative development of publicly-accessible, online libraries of model designs will make it easy for others to adopt this technique.

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