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3D printing materials and their use in medical education: a review of current technology and trends for the future

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ABSTRACT

3D printing is a new technology in constant evolution. It has rapidly expanded and is now being used in health education. Patient-specific models with anatomical fidelity created from imaging dataset have the potential to significantly improve the knowledge and skills of a new generation of surgeons. This review outlines five technical steps required to complete a printed model: They include (1) selecting the anatomical area of interest, (2) the creation of the 3D geometry, (3) the optimisation of the file for the printing and the appropriate selection of (4) the 3D printer and (5) materials. All of these steps require time, expertise and money. A thorough understanding of educational needs is therefore essential in order to optimise educational value. At present, most of the available printing materials are rigid and therefore not optimum for flexibility and elasticity unlike biological tissue. We believe that the manipulation and tuning of material properties through the creation of composites and/or blending materials will eventually allow for the creation of patient-specific models which have both anatomical and tissue fidelity.

INTRODUCTION

The rapid development of 3D printing has created a new learning and teaching tool for medical education. The ability to produce patient-specific in silico models from digital imaging and communication in medicine (DICOM) data derived during CT, MRI, or ultrasound scanning has been coupled with new, less expensive 3D printing technology. Depending on the area of interest, these printed models demonstrate anatomical and structural fidelity consistent with the patient's actual disease process.^{1,2} This fidelity has allowed learners to view and understand gross pathology and structural relationships prior to surgical intervention. An improved understanding and visualisation has in turn allowed surgical teams to plan interventions more accurately and guide margins of resection, model appropriate implant dimensions and sometimes create the implant itself using 3D printing technology.^{2,3}

However, the vast majority of printed models are made with hard materials and only a few present some flexibility and elasticity. Although hard materials are sufficient to recreate anatomical fidelity, it has been challenging to recreate models with tissue characteristics similar to the human pathological specimen. Patient-specific practice prior to an intervention could be improved with more representative materials. This will only be possible

with a firm understanding of the tissue characteristics required of the model and the capacity of the printer to blend composite materials to mimic human tissue. The type of print material which can be printed is dependent on the type of printer used. As many groups are using 3D printing technology and many more wish to enter into this expanding field, we feel that a review of the 3D printing process would be an important starting point for medical educators.

As with every educational tool, the appropriate construction and use of these models is guided by educational objectives. Once the need has been established, there are essentially five important and often related steps to the 3D printing process to create patient-specific models which have anatomical and/or tissue fidelity: (1) capture the area of interest, (2) creation of 3D geometry from dataset specific to the area of interest, (3) transformation of the 3D object to a file ready for printing, (4) selection of the appropriate 3D printer, and (5) selection of an appropriate use of materials (figure 1). The main focus of the review is to describe the process required for the creation of 3D patient-specific models and by way of example, we highlight the stepwise 3D printing process by referring to the creation of a thoracic aorta with a root aneurysm throughout the review. We also discuss the available 3D printed materials best suited for various tissue types. Finally, we suggest future directions and areas of research to advance the field of printed materials.

CAPTURE THE AREA OF INTEREST

Understanding the need

The first step in creating a new tool for medical education using 3D printing consists of defining the educational objective. Is the need to teach anatomy, preprocedural planning or technical skills? In addition, which anatomical region is of interest, and how much needs to be included? Understanding the educational need or learning gap you are trying to address is crucial in creating the most educational appropriate and cost-effective model.

In planning the 3D printed model, four essential characteristics of the model should be addressed and aligned with the educational need:

1. Size: How much of the organ or anatomical area is necessary? For example, is the whole ascending aorta required to instruct learners if the purpose is to teach the anatomy of the aortic root?



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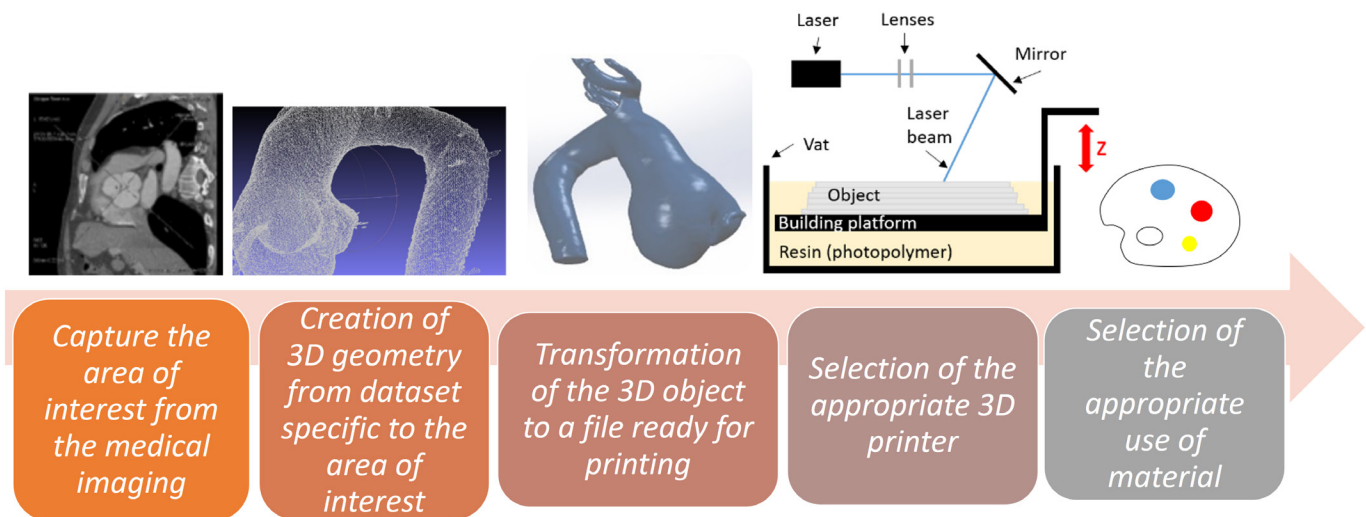


Figure 1 Steps required in the creation of a 3D printed model in healthcare education.

2. Surrounding structures: Are the surrounding structures necessary to describe the relationships of your specific anatomical area of interest? For tumours and invasive cancer, having multiple different structures is crucial to understand relationships to and plan for resection.
3. Surgical manipulation: Do you wish learners to not only view the pathologic anatomy but also perform dissection or resection? In this case, more emphasis will be placed on precise anatomical details including surrounding structures, especially if dealing with potential resection of tumours. The material characteristics of the model will be essential if you require a model which will allow one to cut, resect and suture.
4. Accuracy and resolution of the model: How much granular detail and resolution is required for your teaching and learning? Some models print to a resolution of 1 mm, is this necessary?

These four considerations will have impact on the type of imaging used to capture the area of interest, the resolution required, the nature of materials and composites employed and the type of 3D printer to be used. All of these will have a direct impact on eventual costs for the production of a 3D printed model.

In regard to the thoracic aorta, we wanted to create a 3D printed and anatomically correct model with a root aneurysm

able to teach the geometry of the thoracic aorta to residents in cardiac surgery. We limited the representation of the aorta to the root, the ascending aorta, the arch and the commencing of the descending aorta (figure 2). It also included the three major branches (from proximal to distal: the brachiocephalic artery, left common carotid artery and left subclavian artery) and the commencing of the two coronaries. We kept the real size of the artery but omitted the calcifications of the patient. High accuracy and resolution were required for the model to ensure the representation of important details in the final product.

Selection of the anatomy

Once the need has been defined, discussion of these requirements should be shared with the radiologist whose expertise is to choose the adequate medical imaging process for your specific 3D printed simulator, as well as the precision of the imaging data for an appropriate representation. The concept of the medical imaging process can be seen as a multitude of 2D pictures taken one after the other and which are separated with a controlled thickness determined in advance; thus, the 3D representation is made by simply stacking successive layer of 2D images into a 3D volume. This explains why the accuracy of the 3D geometry diminishes as the thickness between each slice increases (see figure 3). Low resolution will produce large spaces between

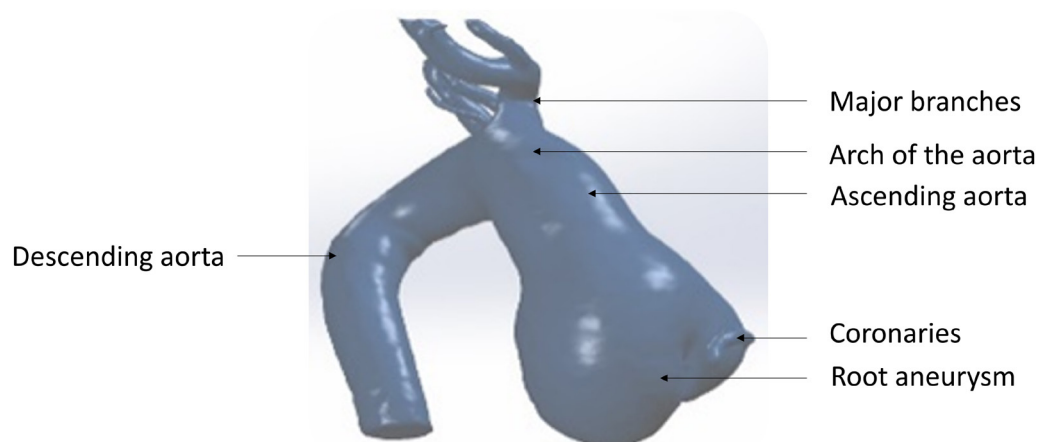


Figure 2 Representation of geometry of the thoracic aortic model for teaching purposes.

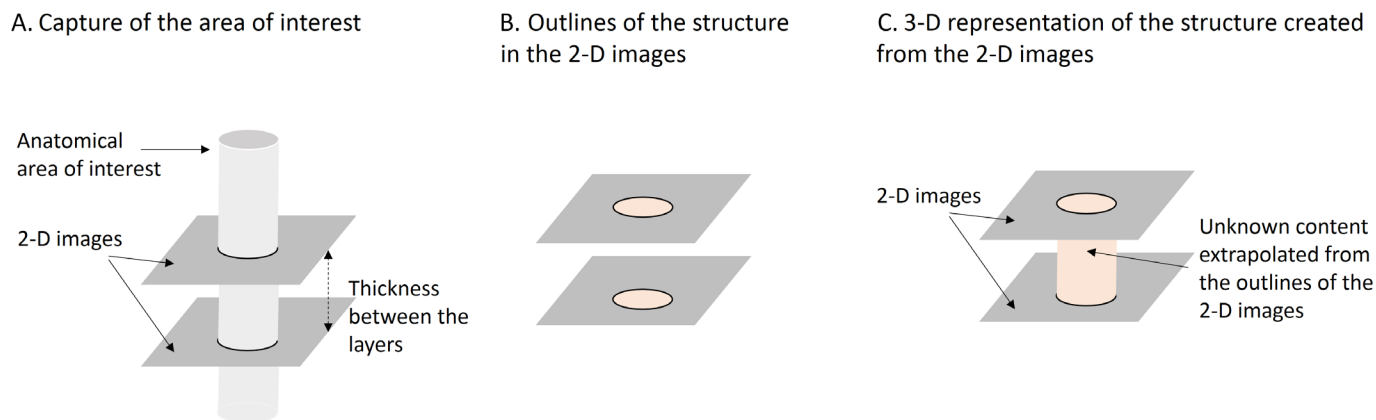


Figure 3 (A) Illustration of the planar 2D images of an area of interest captured by most medical imaging techniques, (B) segmentation of the object cross-section (black circles) extracted, and (C) interpolation required to fill in the missing volume between segments.

the 2D images, losing potentially important anatomical detail. The distance between two slices is generally recommended to be 1 mm or less⁴ but Matsumoto *et al*⁵ found that 1.5–3 mm is an appropriate thickness for the chest and the abdomen and 0.4–0.75 mm for bones and joints. In our lab, we used a slice thickness of 0.625 mm in our reproduction of cardiovascular (thoracic aorta with root aneurysm) and hepatic anatomy.

Several imaging processes are used in radiology to capture 2D images of the human body but the most common technologies remain CT and MRI. For both methods, contrast agents are injected into the patients before each acquisition for a better distinction between the tissues by enhancing the contrasts of the structures of interest. Controlling the noise and resolution of the images also impacts on the quality of the 2D images.⁶ A very high resolution of data imaging is always recommended; however, depending on the needs and the capabilities of the 3D printer selected for the fabrication, high resolution may not be required. As will be reviewed later, only a few printing technologies and apparatus models can reproduce very fine details.

If one is interested in printing structures of the cardiothoracic and vascular systems, the best modalities to visualise arterial and venous vessels⁴ are CT angiography and MRI angiography. CT is the method we chose to capture the geometry of the thoracic aortic model. CT and MRI both require ECG-gated acquisitions to identify the systolic and/or diastolic geometries while reducing body motion⁷ essential to avoid blurry images and thus improving the visibility of aortic valves while capturing the geometry of the aorta for instance. In the literature, CT datasets have also been used for other aortic models⁸ and geometries as hearts with congenital diseases,⁹ aneurysm of the celiac trunk,¹⁰ bronchial tree¹¹ and oesophagus.¹² Similarly, structures of a pulmonary valve,¹³ cardiac tumours¹⁴ and thoracic aortas¹⁵ have been replicated from MRI images. Datasets from multiple imaging sources can be merged for optimal results. Indeed, pulmonary arteries for thoracic surgery training have been created with a mix of conventional CT and CT angiography images.¹⁶ Similarly, models for cardiac surgery and interventional cardiology have been developed with CT and MRI¹⁷ and mitral valve models by CT and transoesophageal echocardiography.¹⁸

Models that replicate soft tissue and the skeleton, such as the assembly of lungs and a thorax are made from CT images¹⁹ and require optimisation of imaging for multiple tissue densities. Friedman *et al*⁴ have used CT with a standard algorithm to capture bone geometries minimising artefacts along the contacts between bone and soft tissues, while using MRI to provide

high contrast between the cortical bone and the surrounding tissues. Temporal bone 3D reconstructions have been created from CT^{20–22} or microCT,²³ while cone beam CT (cone formed by X-rays) and multislice CT (higher number of slices, thus a better resolution) are known to be other appropriate methods in craniomaxillofacial surgery.²⁴

In the field of neurosurgery, CT and MRI have been used to reproduce vascular and brain tissue.^{25–26} CT imaging data has been used in otolaryngology—head and neck surgical training for the creation of endonasal, paranasal sinuses, skull base and mandibular phantoms,²⁷ a malformed skull,²⁸ as well as a cortical brain tumour structure through the skin, bone, dura mater and surrounded by normal brain.²⁹ Nevertheless, single CT datasets can also provide enough information to proceed a geometry extraction from the 2D images, as in the case of phantoms for endovascular aneurysm repair in complex neck anatomy³⁰ and a cerebral aneurysm.³¹

Finally, when metallic elements are involved in CT imaging (eg, prosthesis, plate, screw, etc) the artefacts distorting the geometry of the structure caused by beam hardening or scatter can be well controlled with a dual energy CT giving a second less powerful X-ray after the conventional one for a better image quality.⁴

CREATION OF 3D GEOMETRY FROM DATASET SPECIFIC TO THE AREA OF INTEREST

Once an adequate clinical imaging dataset has been acquired, an *in silico* geometric object needs to be created. As a rule, one 3D object means one component that will be fabricated from one specific material. For instance, if the assembly is composed of two distinct objects such as a bone and ligament, both geometries need to be clearly defined separately before joining them back together as an assembly before the printing for a proper fabrication (see figure 4). Often the two objects will be made of different materials or printed in different colours for clarity.

The thoracic aortic model with root aneurysm did not include any secondary elements, such as calcifications of the aortic wall. Therefore, a single 3D printed material was required to uniformly recreate the walls of the artery.

When different objects are involved, it is best to define them directly from the acquired DICOM image by extracting points along the outline of the anatomical structure and define its geometry. This extracting process is called a segmentation which is often threshold based²⁴ and therefore it is performed using

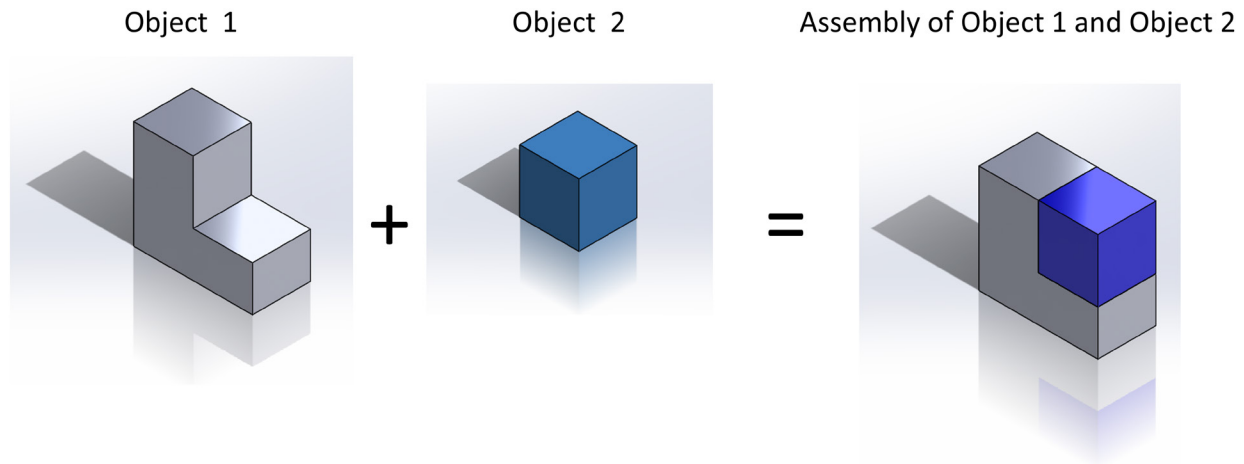


Figure 4 Two distinct objects made of different materials or printed in different colours creating an assembly.

the colour contrast between tissue densities to separate tissue structures into different objects.⁷ Some may prefer defining the geometries afterwards by dividing a bigger structure; however, this can be a complicated task for non-experienced design software users.

When defining objects from DICOM images, the contrast levels or thresholds of the segmentation are highly dependent on the image. Threshold levels often vary between patient images, and image quality from one slice to another may require altering threshold levels. Therefore, verification that the anatomical structures of interest are properly identified from the imaging data needs to be checked. Once threshold levels have been defined, segmented points can be then extracted from the dataset along the outline(s) of the structure on the 2D images by appropriate segmentation software (figure 5). Each 2D image (or slice) of the 3D imaging dataset are analysed individually and data points are created along the perimeter (or outline) of the structure. The number of data points describing the geometry of the structure for one slice depends on the size of the structure at that specific cross-sectional view. Number of points should increase with the size of the perimeter of the structure to avoid losing details of the geometry. The data points from all slices are collectively called a point cloud as seen in figure 5 representing the aortic model with root aneurysm. We were only able to select the inner lumen of the geometry due to the lack of visibility of the thickness of

the walls. The thickness would have to be determined later after the creation of the 3D geometry of the inner lumen of the aorta.

When stacking successive slices of 2D images to create an object, such as an aorta, each point is represented in the larger point cloud of the aorta. The multiple points of the cloud will be used to create the surface of the object.

Segmentation is necessary as it extracts the points used to create a contour of the structure which will be read and printed by a 3D printer in successive layers. Segmentation can be performed manually or automatically. Manual segmentation is extremely slow but suitable for almost any anatomical structures even with complex geometries and in the presence of artefacts, as the human visual system is still far superior to any algorithms in terms of pattern recognition.³² However, it requires an experienced user with a good 3D appreciation to diminish the risks of potential errors since low contrasts or overlapping tissues may complicate the task.²⁴ Automatic segmentation is much quicker, but can only be used for easily identifiable or high-contrast structures.⁴ Regardless, in any realistic setting, segmentation is always done via a mix of manual and automatic segmentations by leveraging the advantage of both techniques to produce the best results as we did for the thoracic aorta after we verified the dataset for proper gating before any attempt at segmentation. The segmentation procedure of a very clear dataset can be done within a few hours, while a very unclear dataset may

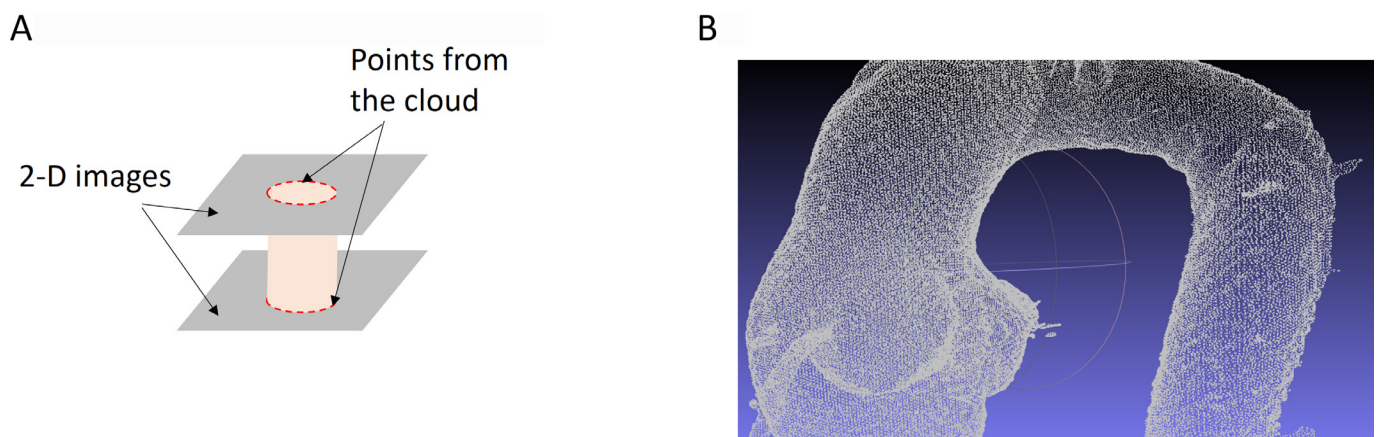


Figure 5 (A) Point cloud created from two 2D images and an example of a (B) point cloud from the inner lumen of an ascending aorta of a patient from the Royal Victoria Hospital (Montreal, Canada) with a 0.625 mm thickness between the slices.

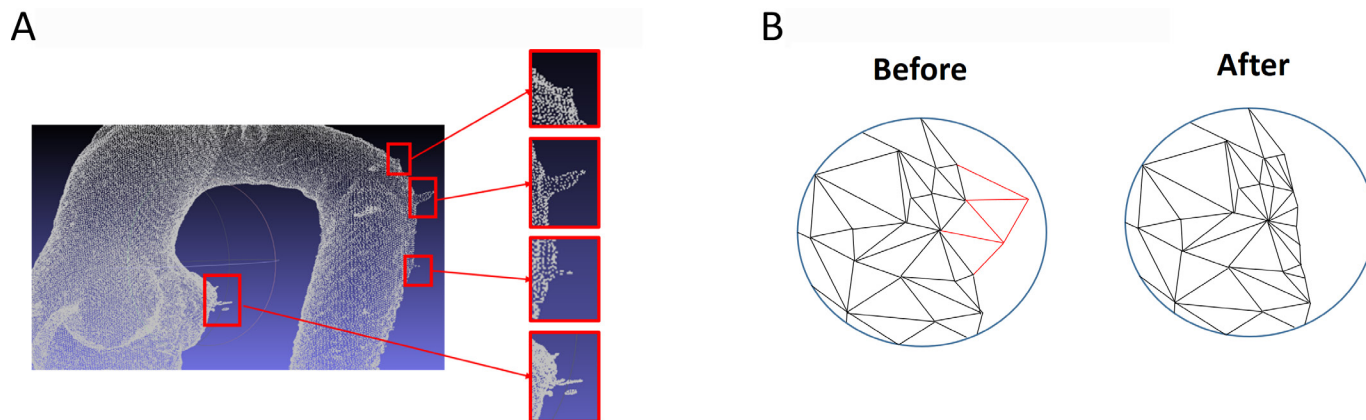


Figure 6 (A) Artefacts from the point cloud of an ascending aorta of a patient from the Royal Victoria Hospital (Montreal, Canada) and an (B) artefact before and after the mesh smoothing.

take up to a week. Only a few slices were segmented at once to optimise between time and quality. Each time a set of images has been segmented, the segmented slices were checked one by one to ensure that the lumen in each slice was given a proper boundary; if not, manual correction was made. 3D visualisation of the segmented section was generated to ensure the quality of segmentation. Special care was given to the aortic root where the shapes of the valves were extrapolated from the images of the blood flow; however, we knew that they were closed as the dataset used were all taken during diastole.

TRANSFORMATION OF THE 3D OBJECT TO A FILE READY FOR PRINTING

The point clouds defining the objects are exported into a mesh-processing software to remove all visible artefacts manually created by selecting unnecessary points. Deformations can create cavities or peaks deforming the original geometry of the structure (figure 6). Once the *in silico* model is optimised, a computational mesh (a surface composed of flat polygonal elements to approximate the geometry) is then created by connecting the points from the cloud as a grid in order to describe the object.

At this stage of the process, the interconnected elements of the model may present new artefacts that should be removed, as well as surface irregularities or sharp edges. Most irregularities can be fixed by simply smoothing the surfaces with algorithms meant to remove details from the object (figure 6). The procedure took less than a half hour for the case of the aorta. However, the user should be aware that excessive smoothing can also deteriorate the resolution of the 3D model. Too little smoothing generally increases the number of elements required to define the object, while too much smoothing has the opposite effect. It is recommended to control the number of elements since file size increases with the number of elements, thus making computer manipulations more difficult. In our lab, we use the open-source meshing software (MeshLab, Italy).

For the thoracic aortic model with root aneurysm, once the point cloud of the inner lumen of the artery was cleaned, we removed the vasa vasorum (small vessels) and other irregularities from the geometry. The mesh was then repaired and the number of elements decreased to simplify the geometry and make it printable.

Manipulations of meshed anatomical geometries require powerful computers with good processors (Intel i7 with 3.2 GHz or better), memory (8 GB or better) and a good graphics card (with dedicated memory). Gaming computers and engineering

workstations generally has the capacity to handle most 3D models; however, with particular large files, custom-made workstation may be required. An optimisation of the model with a proper degree of smoothness and a reduction of the element numbers describing the shape of the structure can diminish the processing time for visualisation and editing.

Sometimes, images obtained from the radiology may have poor resolution with no distinct boundaries; thus, sections of the structure may not be fully defined. This lack of information can be replaced with a manual reconstruction by computer-aided design, 3D graphics software and even some mesh-processing programmes that can make very basic modifications of the geometry. For example, we have previously used simple spherical segments to replace and approximate aortic valve leaflets missing from CT images, see figure 7.

Such software is also useful to make modification of objects if the printed model is made of several materials. As mentioned in the previous section, the geometry of each object of the model has to be defined individually; hence, the easiest model would be made of only one object/material. To define the shape of the objects, it is recommended to use Boolean operations which are mathematical operations for volumes such as the addition (also called union) and subtraction, both most frequently used in medical simulation (figure 8). For instance, if the user wants to print a liver containing a vein, the former will be removed from the liver with a subtraction giving two distinct objects (one for the vein and one for the hollowed liver without the vein) which will be finally printed together as an assembly. This step is crucial to avoid any volume overlapping (figure 8) that would produce printing errors. Similarly, if a ball-shaped object made of the same material as the rest of the structure needs to be added to the geometry to simulate an aneurysm or a tumour, a union operation is required to create a unique object.

To finalise the model, repair algorithms can highlight and correct all potential errors in your meshes which are not easy to see by eye, such as holes from non-connecting triangles or bad edges, overlapping triangles and small triangles that you may have missed and which are not part of the main geometry, for instance (figure 9). The software netfabb (Autodesk, California, USA) is open access and can perform these tasks for very simple geometries. For more complicated models, such as the patient-specific aorta of figure 6, a professional paid version is required.

To create hollow objects, a thickness can be added to the mesh surface, otherwise the whole model will be automatically filled

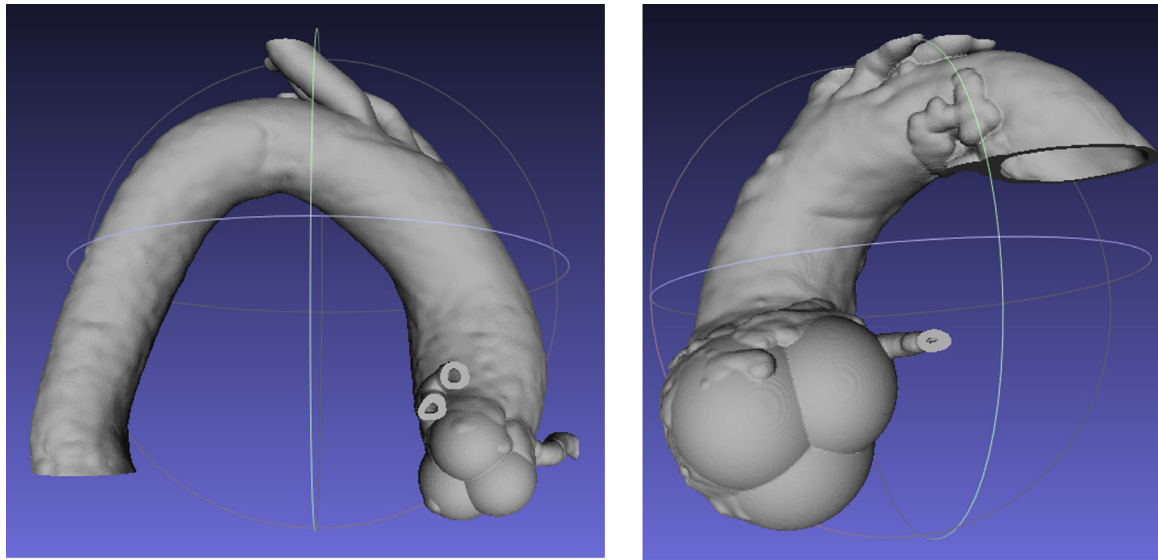


Figure 7 Spheres created to approximate the shape of a patient-specific aortic root, open source Meshlab (MeshLab, Italy).

and made of solid unless it is clearly specified in the geometry. This is the method we used to create an aortic wall of 2 mm from the 3D object of the inner lumen in order to create a 3D printed model with the geometry of the *in vivo* artery.

The aforementioned steps are important steps but also probably the most difficult in the creation of 3D printed models. Once again, if your mesh contains error(s), the printer might not be able to fabricate the object at all or mistakes would occur during the printing. Sometimes, it may be easier to remove and replace an entire surface instead of trying to fix the original object. Knowledge in 3D computer-aided design is a significant asset.

Once the 3D *in silico* solid model is finalised, the file can be then exported to the stl (stereolithography) standardised format for 3D printing before being uploaded to the 3D printer for fabrication. These files contain information related to the generated mesh, as well as orientation and position of the structure. Once again, only one object/material/colour can be assigned to one file. If several objects/materials/colours are required for the final 3D model, each object should be saved as a different file (see figure 10) and all have to be uploaded simultaneously to the printer as an assembly. Material/colour is then attributed to each object with the 3D printer software.

SELECTION OF THE APPROPRIATE 3D PRINTER

Selecting the appropriate 3D printer to fabricate a patient-specific model can be a challenge. It is most helpful to have clarified

the educational needs and the intended use of the model prior to the printing process. This will help guide the selection and requirement for the 3D printer. Herein, we describe the most suitable methods for printing which are currently available and will discuss the pros and cons for each of them.

Description of the 3D printing methods

The general concept of 3D printing is the fabrication of objects as a succession of layers (see figure 11). Each layer of an object (or an assembly of objects) has the same thickness and the thickness depends on the accuracy of the method and the machine chosen. Moreover, 3D printers are not necessarily limited to one material, for instance, material (A) can be used for one object composed of layers 1, 2 and 3, while a second object (layer 4) can be fabricated with the material (B). This information has to have been previously defined by the geometrical files converted in stl that you have created for each distinct object. Some machines are even able to mix materials for one (or more) layer(s) in order to obtain specific colours or material properties.

Materials used in 3D printing are transformed during the fabrication of a model by changing their consistency. This process, commonly called the cure, can take the form of (1) a melting of hard filaments to give the desired form of the model by material distortion, (2) a liquid solidification for the construction of a solid structure and (3) a powder solidification.

1. Melting of hard filaments: Filaments are melted in fused deposition modelling (FDM) then injected through a nozzle.

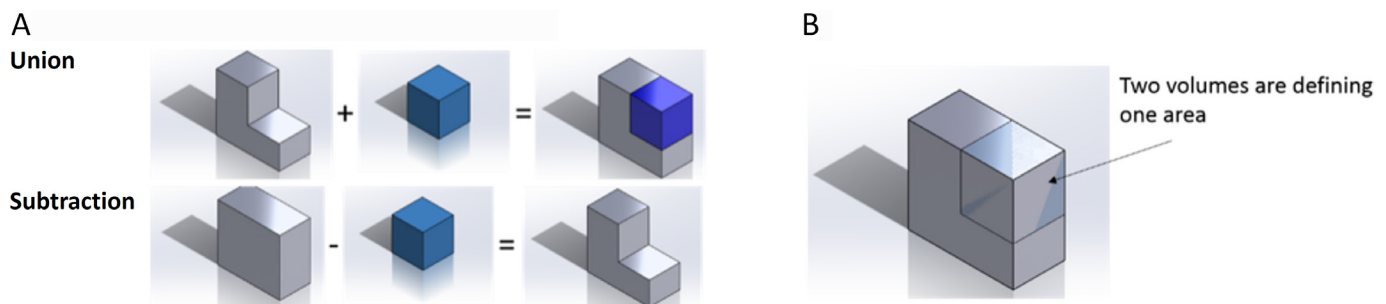


Figure 8 (A) Most frequent Boolean operations to create objects (union and subtraction of volumes) and (B) volume overlapping that should be avoided in any circumstances.

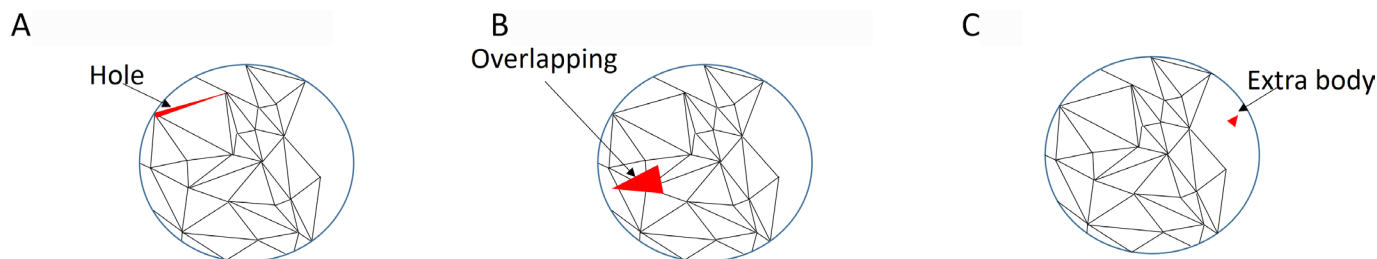


Figure 9 Mesh errors of (A) non-connecting triangle, (B) overlapping triangles and with an (C) extra body that is not part of the main geometry.

zle to a bed while cooling and solidifying during extrusion (figure 12). These printers are inexpensive and fast, but are limited to rigid material. FDM needs a scaffold or bed to support the object during the printing.

2. Liquid solidification: Liquid solidification is used in stereolithography (SLA) and polyjet (PJ) technology. SLA is the oldest method which contains liquid in a vat solidified with an ultraviolet (UV) laser controlled by lenses and mirror reflection, while a building platform is moved down for a layer-by-layer fabrication (figure 12). A lattice structure is created to support the object. In contrast, PJ uses jets of liquid to build up thin layers of liquid before UV curing by sliding the head in the x and y axes then a moving platform for the z axis to build up successive layers (figure 12). PJ is suitable for a wide range of coloured materials with specific properties (eg, rubber-like material).^{33–36}
3. Powder solidification: Finally, powder materials can be solidified by selective laser sintering (SLS) and binder jetting (BJ). SLS uses a laser to create the surface of an object by sintering a powder. When a layer is done, the build plate is stepping down and covered with a new layer of powder using rollers to keep a constant thickness (figure 12). At the end of the process, all powder is removed with compressed air and recycled.³⁷ A wide range of materials are provided for SLS and no scaffold or support material is required since the unsintered powder provides support of the object during the 3D printing. Similar to the SLS, BJ has a platform covered with powder which is moved down while being solidified with a selective spraying of liquid binder; thus, no support material

is needed for the fabrication of the object (figure 12). This technology offers a wide range of materials as far as a powder can be combined with a liquid with enough viscosity to form droplets³⁸. In addition, mechanical properties of the structures obtained by BJ in medical simulation are generally tuned by postprocessing techniques, such as drying and/or heating. Both have an impact on the mechanical properties of the materials (eg, hardness); however, none can be precisely replicated for each fabrication resulting in variations or the characteristics from a model to another.²¹

Support material

Material cannot be deposited on empty space, and thus models with overhangs, as figure 13, often require filler or support material in lattice (or scaffold) forms. Moreover, the filling material is meant to strengthen the structure during the printing, thus avoiding distortion of the model while the material is being cured.

With filaments (FDM) or liquids (SLA), support materials provide lattices which can be easily removable by hand with a cutting tool; however, they often leave undesired impressions on the surface requiring an additional polishing for a good finish. This step of the process is extremely delicate due to the risk of damaging the model by losing details of the geometry. A few support materials can also be easily removed when the model is complete by dissolution, as with water soluble PVA in FDM.

In PJ, volumes of cured waxy support material are used to fill the overhangs. For the soluble ones, sculpting tools are generally used to clean the models, as well as water jets. Otherwise, bath of solutions can remove on its own the filling necessary for the printing.

If your 3D printer is fabricating models from powders (BJ, SLS), the overhangs will be filled with uncured material playing the role as support. This is also very easy to clean up.

It is important to note that models printed with insoluble lattices or waxy support material can be extremely complicated to clean up especially when hollows are not easily accessible by hand or with tools.

Costs of the printing: 3D printer, material and technical support

The easiest, most accessible and cost-effective technology is the FDM,³⁷ which is also the least expensive technology, see table 1. Price generally increases from BJ to SLA and finally the SLS and PJ.

Regarding the material costs, FDM filaments are once again the least expensive material of all 3D printer type and should be considered for large print volume where material property and high print resolution are not the main concern. Moreover, they are easy to store and use¹³ leading up to the most user-friendly process. SLA and PJ can provide high resolution but are also

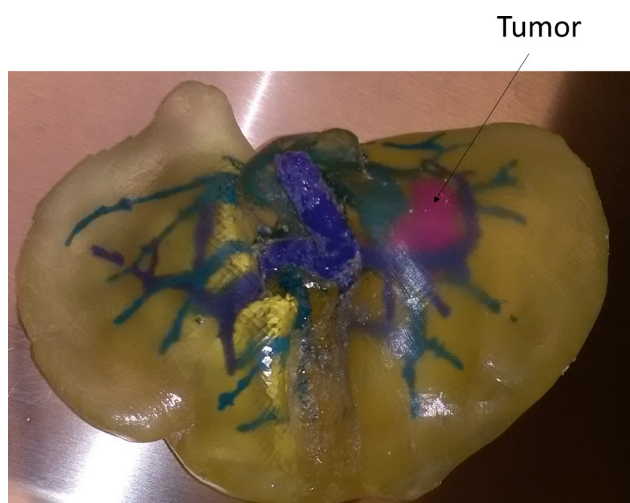


Figure 10 Multicolor 3D printed liver with a tumour (pink) of a patient from the Royal Victoria Hospital (Montreal, Canada) for surgical planning of a diseased liver. The print contains the portal vein, the hepatic vein as well as the tumour.

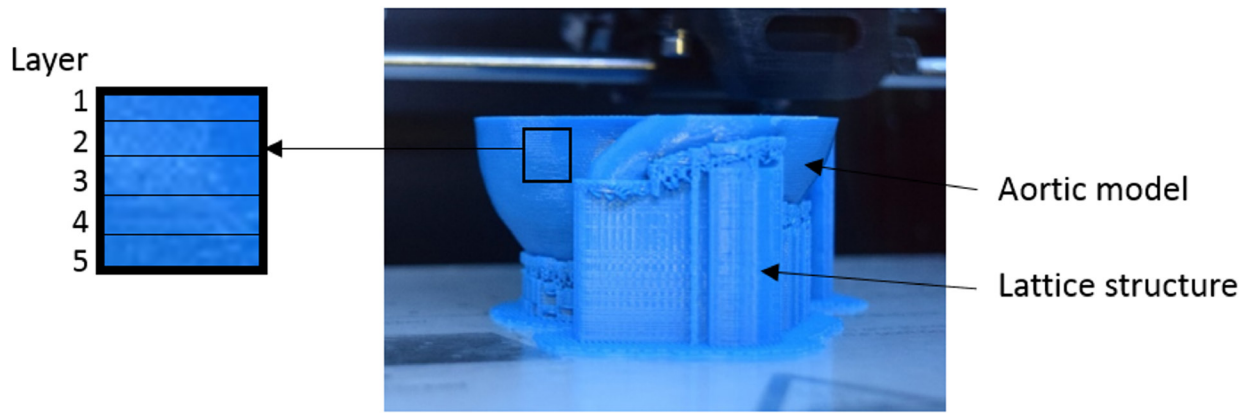


Figure 11 Aortic model in process for being printed on a fused deposition modelling 3D printer by successive layers of acrylonitrile butadiene styrene plastic (0.3 mm thickness).

much more expensive. SLA has the highest resolution of all types of 3D printer, while PJ printers allow the use and mixing of more than one material in a single print. BJ is also cost-effective and the overall cost of the printing low. The powders are somewhat more expensive than the filaments for FDM, nevertheless, they have the advantage of being reusable when uncured but used as support for previous printings. Therefore, there is very little waste of material in comparison to liquid and filament methods. Moreover, BJ printers are fast, easy to use and maintain. Main consumable components are inexpensive and easily replaceable.

BJ models are, however, more fragile than FDM prints when untreated.

In terms of technical requirements, risks of malfunction of the printer in FDM are rare and easy to solve. Common issues can be summarised as a melting or sliding problem of the material through the nozzles provoking a clogging, or when a part does not attach properly on an inadequately heated print bed. Most failures in FDM printer trend to be caused by the design of the 3D model rather than any issues with the machine itself. The technology requiring the most extensive technical support is the

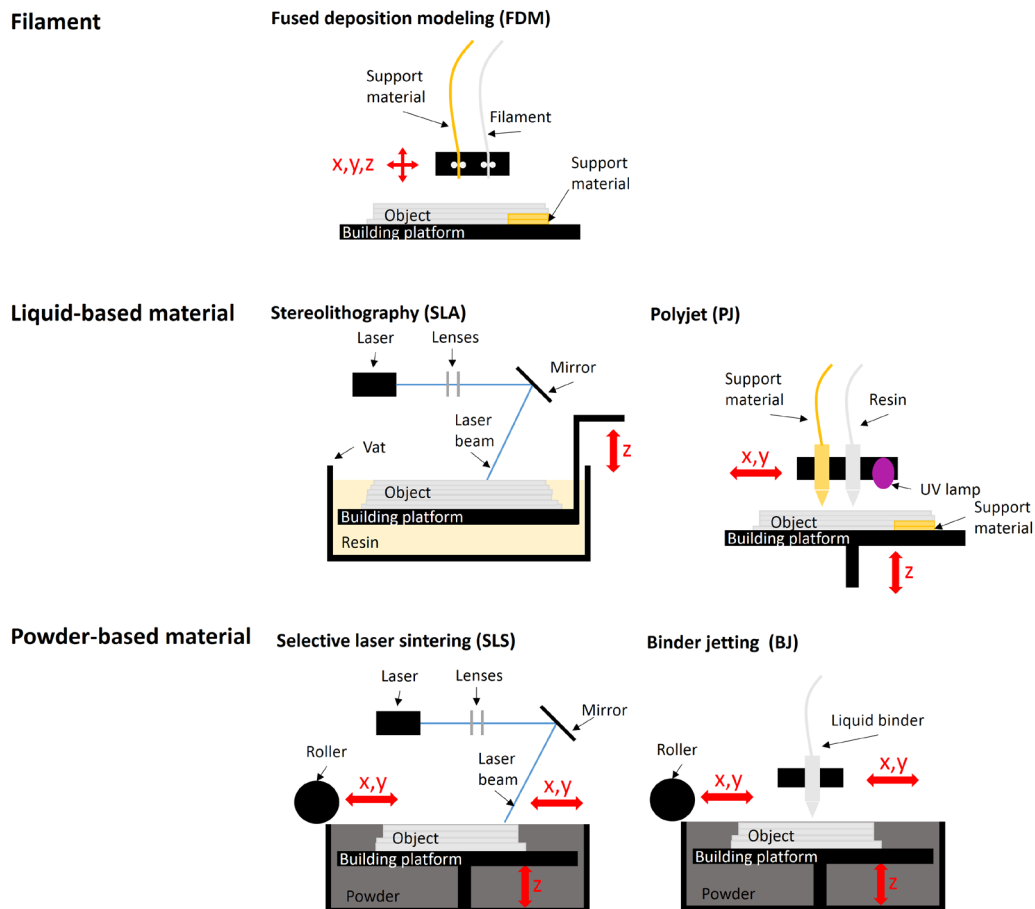


Figure 12 Rapid prototyping methods with red arrows indicating the directions of motion (x, y, z axes).

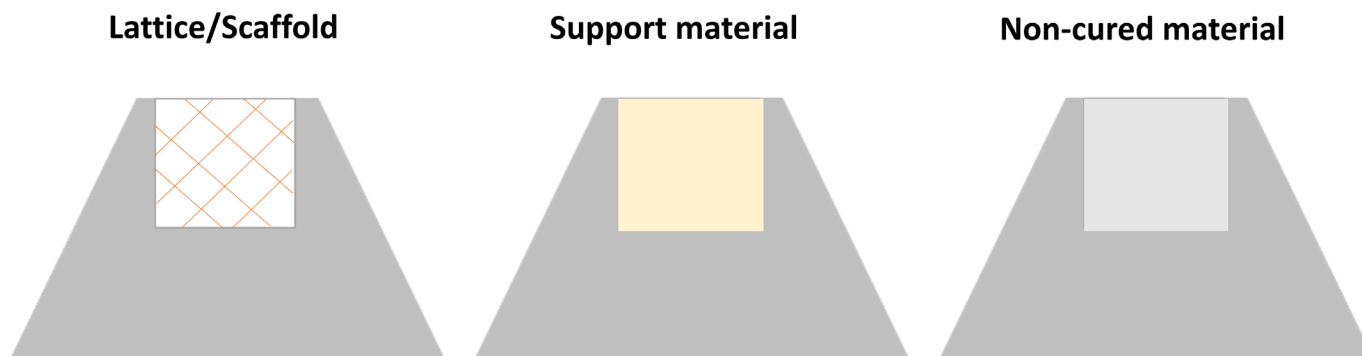


Figure 13 Structure with an overhang filled with a lattice structure, support material or non-cured material.

PJ. In order to avoid any clogging with a potential solidification of the liquid in the nozzles, a technician should run a weekly maintenance by using all loaded materials (if there is no scheduled printing) to provide a continuous flow of materials in the printer. Moreover, multiple pieces of the machine need to be frequently cleaned using very specific techniques, and mistakes can easily damage the equipment. Furthermore, the 3D printer should be kept in a specific environment with a ventilation system, and the materials protected from light. PJ machines also should not be turned off unless there is a long period of time (months) without printing. This involves a large waste of material by removing the liquid to empty the nozzles; thus, maintenance costs become higher if you are using PJ sporadically than if you are continuously printing. Liquids for SLA also need to be kept away from light but the machines do not require weekly maintenance, such as SLS and BJ. They can be used whenever the user wants to print an object and all are easy to use. The most complicated part of the process may be the material removal after the printing. For BJ printers, excess material as well as the build area has to be manually vacuumed to remove unbound powder. For SLA printers, the print tank must be carefully inspected to ensure no cured material remains in the tank, for it may interfere with the curing process of future prints.

Building speed, accuracy and quality of the fabrication

The liquid-based technologies (SLA, PJ) provide the best accuracy and the powder-based (SLS, BJ) printers have the fastest build speed. This is the reason why we chose PJ process to create the thoracic aorta with root aneurysm for teaching purposes to ensure a high-quality printing that can replicate details in the geometry of the artery. We wanted indeed our 3D printed model to be as accurate as possible to show the *in vivo* geometry of a diseased aorta to the non-experienced surgeons. Methods using

a support fibre lattice may degrade surface quality and may require hand finishing to remove the undesired impressions on the surface as explained above.³⁷ Nevertheless, good machines with a high resolution requiring support fibre scaffolds may still fabricate an object with a good surface roughness and definition³⁹ as the FDM and SLA (table 1).

In addition, powder fineness will impact the quality of the printing by SLS,⁴⁰ as well as the quality of the laser. This is the case for any printer using UV for solidification (SLA, PJ) and sintering (SLS). Powder sintering can also create pores/voids in the model³⁸, thus, causing fragile structures with a low stiffness³⁹ in BJ, in opposite to the solid structures created by SLS.³⁷ In contrast, liquids tend to create more homogeneous material properties^{37,39} that can be hard as well as elastic.⁴¹

Finally, good design and positioning of the object are required for an optimal fabrication regardless the technology itself. Mechanical property variations may be observed on the model depending on the method and parameters chosen, such as an anisotropic behaviour corresponding to a higher resistance to deformation of the layer direction directly related to the building direction.⁴² Stiffness reductions can also be seen on the side of the object in contact with the support material which will be less exposed to the UV radiation cure during a polymerisation.⁴¹

Selecting the right printer To Create a Model

3D printing technology can be aligned with the predefined educational need, as listed below.

1. Teaching anatomy, patient education: To teach the anatomy and explain pathology, models constructed of hard materials are often sufficient. The low cost and most accessible method FDM is most certainly the best choice if there is no need for fine printing definition and if the size of the model is large, otherwise we would recommend SLA. Models obtained by

Table 1 Main characteristics of the rapid prototyping methods: stereolithography (SLA), polyJet (PJ), fused deposition modelling (FDM), selective laser sintering (SLS), binder jetting (BJ)

Material based type		Liquid	Liquid	Filament	Powder	
Method		Liquid solidification	Liquid solidification	Material melted and solidified by cooling	Material sintered by laser	Material solidified with liquid binder
Process		SLA	PJ	FDM	SLS	BJ
General building speed (slow/intermediate/fast)		Intermediate	Intermediate	Slow ³⁹	Fast ³⁹	Very fast ³⁹
Printing quality	Accuracy (low/intermediate/high)	High ^{2,39}	High ³⁷	Low ^{2,37}	Intermediate ²	Low ³⁹
	Resolution of a typical machine (µm)	5–25	15–30	100	125	100
Costs	Machine (\$/\$/\$/\$/\$)	\$\$	\$\$\$	\$	\$\$\$	\$\$\$
	Material (\$/\$/\$/\$/\$)	\$\$	\$\$\$	\$	\$\$	\$\$
	Overall cost for printing an object all costs included (low/intermediate/high)	Medium ²	High ³⁹	Low ^{2,37}	High ²	Very low ³⁹

Table 2 3D printing technologies and materials involved in the fabrication of models for surgical training, their simulated body parts, purposes, requirements and the machines used

Simulation	Technology	Material	Reproduction	Purpose	Requirement	Machine/manufacturer	Reference
Rigid material							
Bone	Fused deposition modelling	Acrylonitrile butadiene styrene	Temporal bone	Drilling	Quick and inexpensive fabrication Inexpensive model with good haptic and visual aspects	Makerbot x2	Cohen and Reyes ²⁰ Mowry et al ⁴³
	Binder jetting (BJ)	Plaster (ZP-130)+binder (CA101 cyanoacrylate) Hydroquinone+binder (cyanoacrylate)	Head and neck Head and neck Cortical and trabecular temporal bones	Endoscopic surgery Dissection and drilling –	Durability, accuracy, rigidity, homogeneity Anatomical fidelity, cutability, realistic response for drilling Anatomical fidelity of the internal structure and proper mechanical characteristics (elasticity, hardness, vibrations while drilling)	Vantage/Stratasys ZP printer 310/Z corporation Z printer 650/3D Systems	Chan et al ²⁷ Chan et al ²⁷ Hochman et al ²³
Tumour	Selective laser sintering (SLS) BJ	Polyamide+glass beads Plaster (ZP-150)+binder (ZB-63 clear) Wax coating	Temporal bone Skull base tumour	Drilling, burring and suction Investigation of the usefulness of the tumour by evaluating its visibility	Suitable for surgical simulation Tumour with mesh structure suitable for surgical simulation	– Z printer 450/3D systems	Suzuki et al ²² Kondo et al ²⁶
Semirigid material							
Cartilage	Polyjet (PJ)	Rubber-like resin (TangoPlus FLX930)	Trachea	–	Proper mechanical characteristics (compliance)	Objets500/Connex3	Walenga et al ²²
Artery	BJ	Plaster (ZP-15)+binder infiltration (elastomeric resin, 30 min) Rubber-like resin (TangoPlus FLX930)	Septum, middle and inferior turbinates Human pulmonary arteries Arteries	Dissection and drilling –	Anatomical fidelity, cutability, realistic response for drilling –	– Objets500/Connex3	Chan et al ²⁷ Kurenov et al ⁶ Biglino et al ²⁶
Valve	PJ	Model infiltrated with polyurethane Rubber like resin (TangoPlus FLX930 Shore 27 and 35)	Ascending aorta Mitral valve	Transcatheter valve replacement Catheter-based interventions: Mitraclip procedure and plugin of a transcatheter device	– No moving of the MitraClip after pulling and accuracy of the geometry	Spectrum Z510/Z corporation Objets500/Connex3	Schmauss et al ¹⁷ Vukicevic et al ¹⁸
Heart	BJ	Plaster (ZP 150)+binder (Z-bond 90) Plaster (ZP 150)+binder (NA) Starch/cellulose+binder (polymer) infiltration (urethane) Starch-based powder elastomer coating	Hepatic segments – –	– – –	Realism of anatomical conditions, quality, colour and facility – –	Spectrum Z510/Z corporation Spectrum Z510/Z corporation	Kong et al ²⁰ Schmauss et al ¹⁷
Cerebral aneurysm	Stereolithography PJ	Urethane Rubber-like resin	– Cerebral vessel	Cutting and suturing Clipping the aneurysm	– –	– Objets500/Connex3 Connex350	Noecker et al ⁵¹ Shiraishi et al ⁸ Wurm et al ³¹ Wang et al ²⁴
Soft tissue	PJ	Rigid material (VeroBlackPlus RGD875)+Rubber like resin (Tangoplus FLX930)	–	–	Proper mechanical characteristics	–	–
Composite material	PJ	–	–	Cutting and suturing (skin); perforation and cutting (bone); drilling (cranium)	Phantom providing the haptic of a surgery with layers made of different materials	Objets500/Connex3	Waran et al ²⁹



Figure 14 Model of the aorta with root aneurysm for teaching purposes.

SLA present more detail thus would be better for small printing models (eg, coronary arteries). However, in the case of the thoracic aortic model with root aneurysm we put the emphasis on the realism of the geometry by representing as much as details as possible which is why we needed to use one of the most accurate 3D printing method: PJ. It also allowed us to change easily the colours of the 3D printed model if desired.

2. Surgical planning and review of procedure: Surgical planning and review of procedure do not necessarily require materials to have the same mechanical properties of the biological tissues. Hard material model can be well representative of the anatomical structure and once again, FDM and SLA might be your best options.
3. Preprocedural planning: preprocedural planning models are more complicated to fabricate since they require materials mechanically representative to the biological tissues. Discussions on the matter are provided in the following section where all printing methods are eventually used.

SELECTION OF MATERIALS FOR 3D PRINTING

The selection of the material is directly linked to the selection of the 3D printing process and printer, as well as the needs of the model. All information developed in the following paragraphs are summarised and reorganised in [table 2](#).

Rigid materials

Human bones are the easiest biological tissues to reproduce by 3D printing as the majority of the materials are rigid. The most common option remains acrylonitrile butadiene styrene (ABS) by FDM^{20 27 43} but powders of plaster²⁷ and hydroquinone²³ were also used by BJ, as well as a mix of polyamide with glass beads by SLS.²² ABS is the same plastic used in water pipe of most home and is the most affordable material in 3D printing. It has proved to be an appropriate bone substitute with good visual and haptic renderings for practising the drilling with minimised cost, despite the softness of the material.²⁰ Cohen and Reyes²⁰ believed that the benefits of the training will be felt even if the mechanical properties did not match exactly the bone. This study

is a perfect example showing that the tissue fidelity does not necessarily need to be completely realistic and that the purposes and the requirements of the models are absolutely essential in the choice of the proper materials.

Rigid materials may also be adequate in the context of preprocedural planning which has already proven its ability to improve the way surgeons think, interpret, evaluate a procedure and face a complex situation by simulating all steps in advance.^{2 19 44} A lack of imaging¹⁴ and anatomical consistency (eg, Charcot foot syndrome),⁴⁵ as well as the hard visualisation of a 3D geometry through a 2D monitor,¹⁰ might all complicate surgical strategies that can be fulfilled with 3D printed models. The same rigid model can afterwards be used intraoperatively for orientation purposes.⁴⁶ Moreover, Levi *et al*²⁸ have highlighted the importance for the residents to see an operation several times to memorise phases of the procedures.

On the other hand, the physical and graspable models help the trainees to familiarise themselves with the human anatomy and unlimited pathologies for a superior understanding,^{11 47} tactile and visual 3D appreciations.^{2 3} Therefore, the accuracy of the procedure will be higher and the diagnostic quality facilitated while the operating time is diminishing up to two-thirds,⁴⁸ as well as the risks of complications and traumas of the patients.² Models can also be designed with removable structures for a better understanding and visualisations of multitude situations.⁴⁹

Flexible materials

Most of the 3D printing materials present a lack of realism to mimic adequately a soft human biological tissue; thus, post-processing might be required to soften printed structures. For instance, cartilaginous tissues for dissection and drilling needed a liquid coating to increase the physical strength of a structure created by BJ in contrast to the infiltrations of elastomeric resins meant to increase its flexibility.²⁷ Similarly, BJ was used for tumours in the context of surgical simulation,²⁶ arteries to practise transcatheter valve replacements,¹⁷ as well as hepatic segments⁵⁰ and hearts^{17 51} to teach human anatomy.

By contrast, SLA had the capability to fabricate flexible hearts made in urethane suitable for cutting and suturing practices without postprocessing.⁹ Similarly, a cartilaginous trachea was also replicated by PJ⁵² providing a rubber-like material mixable with a rigid photopolymer to control the flexibility of the structure, as arteries,^{16 36} soft tissue,⁵³ mitral valve¹⁸ and cerebral aneurysms.³¹ The trachea, arteries and soft tissues were created to be as realistic as possible, while the mitral valve was used to learn catheter-based interventions and to evaluate a surgical device; moreover, the aneurysm was to learn how to clip an artery.

Printing with multiple materials

Depending on the needs, several materials (colours, properties, textures) may be required to create a proper phantom. Waran *et al*²⁹ opted for the use of a multimaterial PJ machine for a layer-based model made of rigid and soft tissues (bone, dura mater, tumour, normal brain). Similarly, Wang *et al*⁵⁴ created a material made of rigid fibres embedded in a flexible material to control the properties of the printed composite. Chan *et al*²⁷ manufactured separately the hard structure of the bone and the softer cartilaginous tissues with different materials and processes for a final realistic assembly of a replicated head and neck. Finally, Hochman *et al*²³ added as well three coats of urethane to simulate the dural membrane of the temporal bone models for a better tissue fidelity.

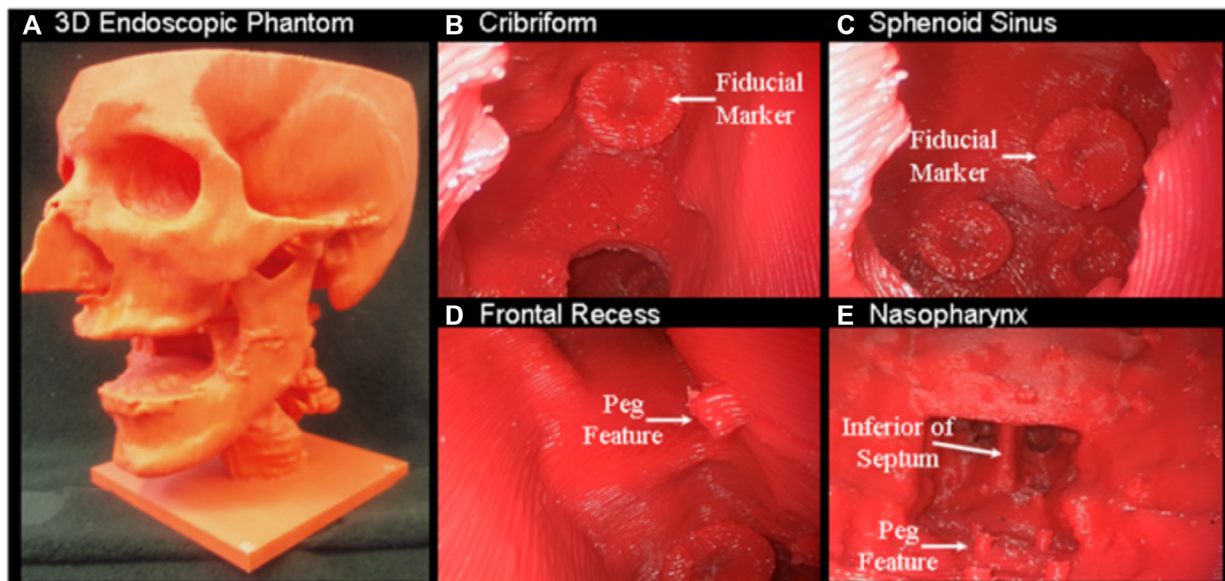


Figure 15 Head model made of one material to practise the drilling in medical simulation.²⁷

Multimaterial composites may be the future of 3D printed models since none of the current available materials can mimic elastic and biological tissues. Hence, printing materials containing fibres to control adequately the mechanical behaviour of the model are being explored. Mechanical testing can be performed to analyse the biomechanical response of the human tissue by cutting, compressing or tearing apart the material. In this way, multi-material composites may be created based on the capacity of selected materials to mimic the mechanical properties of human tissue. Recently, our group has been focused on mechanically testing human aortic tissue,⁵⁵ which provides the necessary data to create and test materials which will eventually have tissue fidelity.

DISCUSSION

We have described the main steps of a general and straightforward method to follow for the creation of 3D printed patient-specific models for medical education. a (figure 14). Such models are

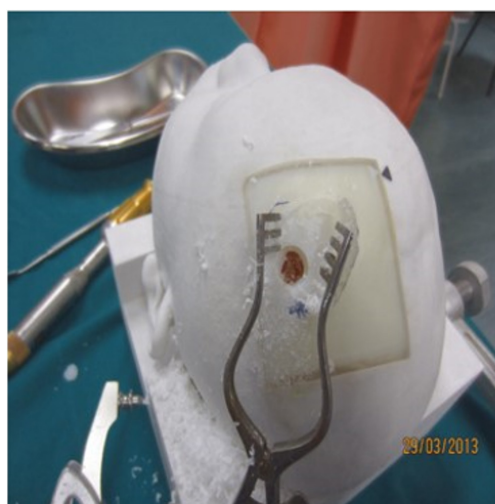


Figure 16 Head model made of a combination of materials to practise the drilling in medical simulation.²⁹ (with permission Rockwater Inc.)

being used in teaching anatomy, planning surgery or practising procedures and medical manipulations, as demonstrated by the one material skull model by Chan *et al*²⁷ (figures 15 and 16) and the multi-material head model by Waran *et al*.²⁹ (figure 16). We started by listing the most appropriate choice of imaging technology to visualise the geometry depending on the tissues and explained how to convert the information to a stl 3D geometrical object for fabrication.

Medical imaging provides good anatomical spatial resolution but still needs to be improved in some areas such as the aortic valves. In addition, the automatic segmentation is not optimal, cannot be entirely trusted (artefacts may not be detected or good part of the geometry may be identified as undesired) and is not good as manual segmentation. Creating a 3D geometrical model requires a high level of anatomical knowledge and coordination between surgeon, radiologist and engineer. It is a relatively simple concept but does require specific multidisciplinary expertise. There is not a 'one size fits' all in this growing field and educational goals, technical expertise, and cost are important considerations when starting a 3D printing programme. However, a good understanding of the 3D printing process will greatly help you meet your educational goals. A recent study has shown the possibility to fabricate very accurate 3D aortic models (cf intimal flap) with a 1 mm of error in the mean difference in luminal diameter⁵⁶ which would allow an efficiency improvement by its use in medical simulation (see figure 17).

3D printing is an attractive, powerful, versatile technology which has the potential to be very accessible to anyone who would happen to be interested. It is gaining popularity mostly in orthopaedics, dentistry and plastic surgery where bones are easier to replicate, even though much work is needed in this area.

3D printed specific-patient models have demonstrated that they can increase performance and foster rapid learning⁵⁷ while significantly ameliorating the knowledge, management and confidence of the trainees regardless of the area of expertise.⁵⁸ Physical interaction has been proven to be the key to gaining motor skills needed for surgical intervention improving operating room outcomes.^{13 22 59 60} We believe that 3D digital reconstruction of surgical anatomy is complementary to 3D physical

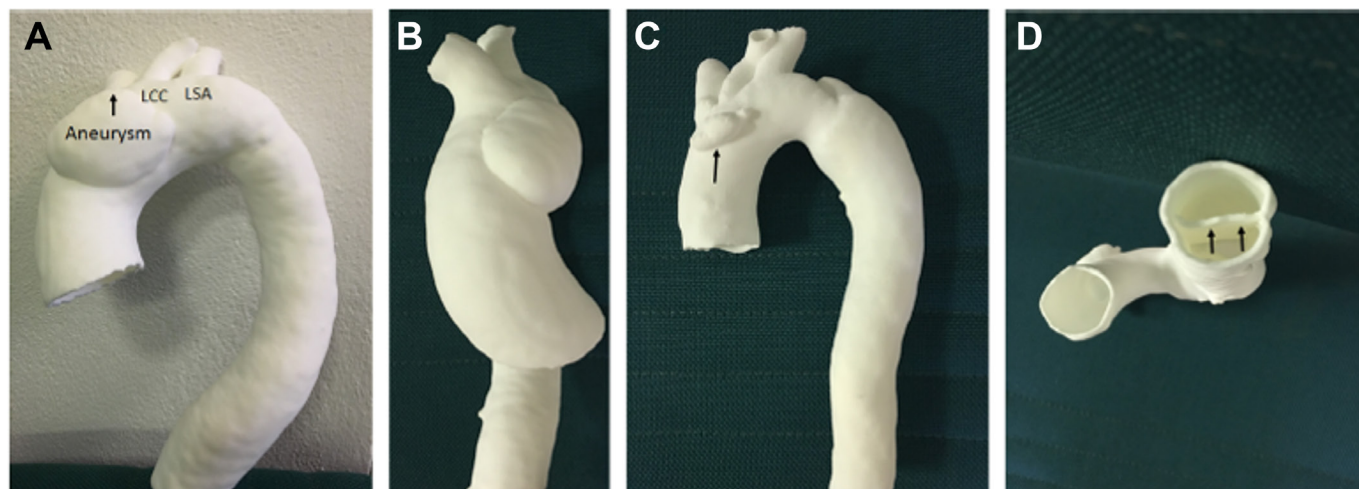


Figure 17 Accurate 3D model of an aortic aneurysm captured from CT imaging.⁵⁶

models. Shah and Ahmed⁶¹ studied the importance of the variation in teaching for undergraduate dental education and found that the majority of students had a preference for kinesthetic learning (ie, tactile learning). Those physical interactions or activities are the reasons why 3D printed models are essential in the training of medical professionals.

Nevertheless, very few materials currently present elastic properties which mimic human tissue and which would therefore be ideal for surgical training models and allow for realistic dissection, cutting, and suturing. This is the current main limitation that companies and researchers are trying to solve. Although soft and elastic materials such as silicone may already be successfully printed they are not suitable for complex geometries.³⁴ In the near future, we believe that the most representative printed materials to mimic soft tissues would have to be made of several components. Manipulating the materials themselves as an area of research and innovation will widen the possibilities and thus improve the mechanical responses of the printed models and provide better teaching tool for surgical education. A combination of materials in 3D printing have recently been explored by Waran *et al*²⁹ as well as in our lab where we have been trying to replicate the natural structure of the biological aortic tissue and mimic as far as possible its biomechanical properties. Mechanical testing allows one to compare engineering properties between human tissue and multi-material composites which are created in the laboratory. Hopefully, this process and research will open a new future for 3D printing. One which will not only include anatomical fidelity but tissue fidelity as well.

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