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. 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?
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
A. Capture of the area of interest

B. Outlines of the structure in the 2-D images

C. 3-D representation of the structure created from the 2-D images

**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 distance between two slices is generally recommended to be 1 mm or less but Matsumoto *et al* 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. 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 vessels 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 by enhancing the contrasts of the tissues. Temporal bone 3D reconstructions have been created from CT or microCT, 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.

In the field of neurosurgery, CT and MRI have been used to reproduce vascular and brain tissue. 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, as well as a malformed skull, as well as a cortical brain tumour structure through the skin, bone, dura mater and surrounded by normal brain. 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 anatomy and a cerebral aneurysm.

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.

**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 based and therefore it is performed using high contrast between the cortical bone and the surrounding tissues. Temporal bone 3D reconstructions have been created from CT or microCT, 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.
the colour contrast between tissue densities to separate tissue structures into different objects.3 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 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.
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.
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 droplets. 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.

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, 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 use leading up to the most user-friendly process. SLA and PJ can provide high resolution but are also

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.

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 contain the portal vein, the hepatic vein as well as the tumour.
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 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).

Figure 12  Rapid prototyping methods with red arrows indicating the directions of motion (x, y, z axes).
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. Nevertheless, good machines with a high resolution requiring support fibre scaffolds may still fabricate an object with a good surface roughness and definition as the FDM and SLA (table 1).

In addition, powder fineness will impact the quality of the printing by SLS, 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 model, thus, causing fragile structures with a low stiffness in BJ, in opposite to the solid structures created by SLS. In contrast, liquids tend to create more homogeneous material properties that can be hard as well as elastic.

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. 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.

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)](attachment:table_1.png)
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     | Makerbot x2                                    | Cohen and Reyes(20) |
|            |                            |                                              |              | Head and neck | Endoscopic surgery               | Inexpensive model with good haptic and visual aspects | Vantage/Stratasys                      | Mowry et al(21) |
|            |                            |                                              |              | Head and neck | Dissection and drilling          | Durability, accuracy, rigidity, homogeneity     | ZP printer 310/2                          | Chan et al(22) |
|            |                            | Hydroquinone+Binder (cyanoacrylate)          | Cortical and trabecular temporal bones | –          | Anatomical fidelity, cutability, realistic response for drilling | Anatomical fidelity of the internal structure and proper mechanical characteristics (elasticity, hardness, vibrations while drilling) | Z printer 650/3D Systems                  | Hochman et al(23) |
|            |                            | Selective laser sintering (SLS)              | Polyamide+glass beads | Temporal bone | Drilling, burring and suction | Suitable for surgical simulation | –                                      | Suzuki et al(24) |
| Tumour     | BI                        | Plaster (ZP-150)+binder (ZB-63 clear)       | Skull base tumour | –          | Investigation of the usefulness of the tumour by evaluating its visibility | –                                      | Z printer 450/3D systems                  | Kondo et al(25) |
| Semirigid material | Cartilage                | Polyjet (PJ)                                | Rubber-like resin (TangoPlus FLX930) | Trachea | – | Proper mechanical characteristics (compliance) | Objet500/Connex3                        | Walenga et al(26) |
|            | BI                        | Plaster (ZP-15)+binder Infiltration (elastomeric resin, 30min) | Septum, middle and inferior turbinates | –          | Dissection and drilling          | Anatomical fidelity, cutability, realistic response for drilling | Objet500/Connex3                        | Chan et al(27) |
| Flexible material | Artery                   | PJ                                            | Rubber-like resin (TangoPlus FLX930) | Human pulmonary arteries | – | – | Proper mechanical characteristics (distensibility) | Objet500/Connex3                        | Kurumov et al(28) |
|            | BI                        | Model infiltrated with polyurethane         | Ascending aorta | –          | – | – | – | Spectrum Z510/Z corporation | Biglino et al(29) |
| Valve      | PJ                        | Rubber like resin (TangoFLX930 Shore 27 and 35) | Mitral valve | Catheter-based interventions: Mitraclip procedure and plug of a transcatheter device | – | No moving of the MitraClip after pulling and accuracy of the geometry | – | Objet500/Connex3 | Schmauss et al(30) |
| Heart      | BI                        | Plaster (ZP 150)+binder (Z-bond 90) Plaster (ZP 150)+binder (NIA) Infiltration (urethane) | Hepatic segments | – | – | – | Spectrum Z510/Z corporation | – | Noecker et al(31) |
|            |                            | Starch/cellulose+binder (polymer) Infiltration (urethane) | – | – | – | – | Spectrum Z510/Z corporation | – | Smiwi et al(32) |
|            |                            | Starch-based powder elastomer coating       | – | – | – | – | Spectrum Z510/Z corporation | – | Smiwi et al(33) |
| Cerebral aneurysm | PJ                        | Stereolithography                          | Urethane | – | Cutting and suturing              | – | – | Spectrum Z510/Z corporation | Shinaishi et al(34) |
| Soft tissue| PJ                        | Rigid material (NeroBlackPlus RGD875)+Rubber like resin (TangoPlus FLX930) | Cerebral vessel | Clipping the aneurysm | – | Proper mechanical characteristics | – | Objet500/Connex3 | Wang et al(35) |
| Composite material | Skin, bone, dura mater, tumour, brain | Polyjet (PJ) | – | – | Cutting and suturing (skin; perforation and cutting (bone); drilling (cranium) | – | – | Spectrum Z510/Z corporation | – | Smiwi et al(36) |
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, but powders of plaster and hydroquinone were also used by BJ, as well as a mix of polyamide with glass beads by SLS. ABS is the same plastic used in water pipe 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.

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. Similarly, BJ was used for tumours in the context of surgical simulation, arteries to practise transcatheter valve replacements, as well as hepatic segments and hearts 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. Similarly, a cartilaginous trachea was also replicated by PJ providing a rubber-like material mixable with a rigid photopolymer to control the flexibility of the structure, as arteries, soft tissue, mitral valve and cerebral aneurysms. 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 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 created a material made of rigid fibres embedded in a flexible material to control the properties of the printed composite. Chan et al 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 added as well three coats of urethane to simulate the dural membrane of the temporal bone models for a better tissue fidelity.
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, 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. Such models are 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 (figures 15 and 16) and the multi-material head model by Waran et al. (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 diameter 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 learning while significantly ameliorating the knowledge, management and confidence of the trainees regardless of the area of expertise. Physical interaction has been proven to be the key to gaining motor skills needed for surgical intervention improving operating room outcomes. We believe that 3D digital reconstruction of surgical anatomy is complimentary to 3D physical

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

Figure 16  Head model made of a combination of materials to practise the drilling in medical simulation. (with permission Rockwater Inc.)
models. Shah and Ahmed 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 professional doctors.

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. 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 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-merarial composites which are created in the laboratory. Hopefully, this process and research will open the possibility for 3D printing in surgical education.

Acknowledgements  We gratefully thank the Research Institute of the McGill University Health Centre (MUHC) for their assistance in this project and McGill University for the financial support.

Contributors  JG: literature review, data collection, 3D printing, software, materials and manuscript writing. ZLY: literature review, 3D printing, software. RM: materials and software. Richard Leask: supervision, study design, materials and manuscript review. KL: supervision, study design, surgical education, 3D printing, manuscript writing and review.

Funding  McGill Engineering Doctorial Scholarship (JG), NSERC Discovery Grant #261938-13 (RL).  

Competing interests  None declared.

Provenance and peer review  Not commissioned; externally peer reviewed.

Open Access  This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/  

© Article author(s) (or their employer(s) unless otherwise stated in the text of the article) 2018. All rights reserved. No commercial use is permitted unless otherwise expressly granted.

REFERENCES

1. Negi S, Dhiman S, Kumar Sharma R. Basics and applications of rapid prototyping medical models. Rapid Prototyp J. 2014;20:256–67.
2. Rengier T, Mehndiratta A, von Tengg-Kobligk H, et al. 3D printing based on imaging data review of medical applications. Int J Comput Assist Radiol Surg 2010;5:335–41.
3. Malik HH, Darwood AR, Shaunak S, et al. Three-dimensional printing in surgery: a review of current surgical applications. J Surg Res 2015;199:512–22.
4. Friedman T, Michalski M, Goodman TR, et al. 3D printing from diagnostic images: a radiologist’s primer with an emphasis on musculoskeletal imaging—putting the 3D printing of pathology into the hands of every physician. Skeletal Radiol 2016;45:307–21.
5. Matsumoto JS, Morris JM, Foley TA, et al. Three-dimensional physical modeling: applications and experience at mayo clinic. Radiographics 2015;35:1989–2006.
6. Ogden KM, Aslan C, Ordway N, et al. Factors affecting dimensional accuracy of 3-D printed anatomical structures derived from CT data. J Digit Imaging 2015;28:654–63.
7. Ripley B, Kelll T, Cheezum MK, et al. 3D printing based on cardiac CT assists anatomic visualization prior to transcatheter aortic valve replacement. J Cardiovasc Comput Tomogr 2016;10:28–36.
8. Schmauss D, Schmitz C, Bigdeli AK, et al. Three-dimensional printing of models for preoperative planning and simulation of transcatheter valve replacement. Ann Thorac Surg 2012;93:e31–e33.
9. Shitashi I, Yamagishi M, Hamaoka K, et al. Simulative operation on congenital heart disease using rubber-like ultrasonic stereolithographic biomodels based on 3D datasets of multislice computed tomography. Eur J Cardiovasc Surg 2010;37:302–6.
10. Salloum C, Lim C, Fuentes L, et al. Fusion of information from 3D printing and surgical robot: an innovative minimal technique illustrated by the resection of a large celiac trunk aneurysm. World J Surg 2016;40:245–7.
11. Deferm S, Meyns B, Vlasselaers D, et al. Individualizing management of complex esophageal pathology using three-dimensional printed models. Ann Thorac Surg 2015;100:692–7.
12. Dickson KJ, Matsumoto J, Cassivi SD, et al. Individualizing management of complex esophageal pathology using three-dimensional printed models. Ann Thorac Surg 2015;100:692–7.
13. Armillotta A, Bonhoeffer P, Dubini G, et al. Use of rapid prototyping models in the planning of percutaneous pulmonary valved stent implantation. Proc Inst Mech Eng H 2007;221:1407–16.
14. Schmauss D, Gerber N, Sodian R. Three-dimensional printing of models for surgical planning in patients with primary cardiac tumors. J Thorac Cardiovasc Surg 2013;145:1407–8.
15. Marlit M, Schumacher R, Kiffer J, et al. Rapid vessel prototyping: vascular modelling using 3t magnetic resonance angiography and rapid prototyping technology. MAGMA 2005;18:288–95.
16. Kurenov SN, Ionița C, Sammons D, et al. Three-dimensional printing to facilitate anatomic study, device development, simulation, and planning in thoracic surgery. J Thorac Cardiovasc Surg 2015;149:973–9.
Review

17 Schmauss D, Haeberle S, Hagi C, et al. Three-dimensional printing in cardiac surgery and interventional cardiology: a single-centre experience. Eur J Cardiothorac Surg 2015;47:1042–52.

18 Vukicevic M, Puperi DS, Grande-Allen KJ, et al. Erratum to: 3D printed modeling of the mitral valve for catheter-based structural interventions. Ann Biomed Eng 2014;42:3432–12.

19 Gillaspie EA, Matsumoto JS, Morris ET, et al. From 3-dimensional printing to 5-dimensional printing: enhancing thoracic surgical planning and resection of complex tumors. Ann Thorac Surg 2016;101:1958–62.

20 Cohen J, Reyes SA. Creation of a 3D printed temporal bone model from clinical CT data. Am J Otolaryngol 2015;36:619–24.

21 Hochman JB, Kraut J, Kazemir K, et al. Generation of a 3D printed temporal bone model with internal fidelity and validation of the mechanical construct. Otolaryngol Head Neck Surg 2014;150:448–54.

22 Suzuki M, Ogawa Y, Kawano A, et al. Rapid prototyping of temporal bone for surgical training and medical education. Acta Otolaryngol 2004;124:400–2.

23 Hochman JB, Rhodes C, Wong D, et al. Comparison of cadaveric and isomorphic three-dimensional printed models in temporal bone education. Laryngoscope 2015;125:2335–7.

24 Hulstalainen E, Jaaninen R, Valälä K, et al. Inaccuracies in additive manufactured medical skull models caused by the DICOM to STL conversion process. J Cranio-maxillofac Surg 2014;42:259–62.

25 Ploeh CC, Manci S, Jayamohan J, et al. Using 3D Printing to create personalized brain models for neurosurgical training and preoperative planning. World Neurosurg 2016;90:668–74.

26 Kondo K, Harada N, Masuda H, et al. A neurosurgical simulation of skull base tumors using a 3D printed rapid prototyping model containing mesh structures. Acta Neurochir 2016;158:1213–9.

27 Chan HH, Sieversdor JH, Vescan A, et al. 3D rapid prototyping for otolaryngology-head and neck surgery: applications in image-guidance, surgical simulation and patient-specific modeling. PLoS One 2015;10:e0136370.

28 Levi D, Rampa F, Barbieri C, et al. True 3D reconstruction for planning of surgery on malformed skulls. Childs Nerv Syst 2002;18:705–6.

29 Waran V, Narayanan V, Karuppaiah R, et al. Utility of multimaterial 3D printers in creating models with pathological entities to enhance the training experience of neurosurgeons. J Neurosurg 2014;120:489–92.

30 Tam MD, Laycock SD, Brown JR, et al. 3D printing of an aortic aneurysm to facilitate decision making and device selection for endovascular aneurysm repair in complex neck anatomy. J Endovasc Ther 2013;20:863–7.

31 Wumm G, Lehnert M, Tomancok B, et al. Cerebrovascular biomodeling for aneurysm surgery: simulation-based training by means of rapid prototyping technologies. Surg Innov 2011;18:294–306.

32 von Ahn L, Maurer B, McMillen C, et al. reCAPTCHA: human-based character recognition via Web security measures. Science 2008;321:1465–8.

33 Cloonan AJ, Shahrimirad D, Li RX, et al. 3D-Printed tissue-mimicking phantoms for medical imaging and computational validation applications. 3D Print Addit Manuf 2014;1:4–23.

34 Osman N, Tsai E, Fristenberg M. Digital anisotropy: a variable elasticity rapid prototyping platform. Virtual Phys Prototyp 2012;7:261–74.

35 Reiter M, Major J. A combined experimental and simulation approach for modelling the mechanical behaviour of heterogeneous materials using rapid prototyped microcyl. Virtual Phys Prototyp 2011;6:111–20.

36 Biglino G, Verschueren P, Ziegels R, et al. Rapid prototyping compliant arterial phantoms for in-vitro studies and device testing. J Cardiovasc Magn Reson 2013;15:2–7.

37 Wong KV, Hernandez A. A review of additive manufacturing. ISRN Mech Eng 2012;2012:1–10.

38 Guo N, Leu MC. Additive manufacturing: technology, applications and research needs. Front Mech Eng 2013;8:215–43.

39 Kim GD, Oh YT. A benchmark study on rapid prototyping processes and machines: quantitative comparisons of mechanical properties, accuracy, roughness, speed, and material cost. Proc Inst Mech Eng B J Eng Manuf 2008;222:201–15.

40 Ventola CL. Medical applications for 3D printing: current and projected uses. P T 2014;39:704.

41 Blanco D, Fernandez P, Noriega A. Nonisotropic experimental characterization of the relaxation modulus for Polyjet manufactured parts. J Mater Res 2014;29:1876–82.

42 Kim MS, Hansgen AR, Carroll JD. Use of rapid prototyping in the care of patients with structural heart disease. Trends Cardiovasc Med 2008;18:210–6.

43 Mowry SE, Jammal H, Myer C, et al. A Novel temporal bone simulation model using 3D printing techniques. Otal Neurot 2015;36:1562–5.

44 Chua CK, Chou SM, Lin SC, et al. Rapid prototyping assisted surgery planning. Int J Adv Manuf Technol 1998;14:624–30.

45 Giovinco NA, Dunn SP, Dowling L, et al. A novel combination of printed 3-dimensional anatomic templates and computer-assisted surgical simulation for virtual preoperative planning in Charcot foot reconstruction. J Foot Ankle Surg 2012;51:387–93.

46 Spottiswoode BS, van den Heever DJ, Chang Y, et al. Preoperative three-dimensional model creation of magnetic resonance brain images as a tool to assist neurosurgical planning. Stereotact Funct Neurosurg 2013;91:162–9.

47 Chae MP, Rozen WM, McMenamin PG, et al. Emerging applications of bedside 3D printing in plastic surgery. Front Surg 2015;2:225.

48 Singhal AJ, Shetty V, Bhagavatan KR, et al. Improved surgery planning using 3-D printing: a case study. Indian J Surg 2016;78:100–4.

49 Soares PV, de Almeida Millo G, Pereira FA, et al. Rapid prototyping and 3D-virtual models for operative dentistry education in Brazil. J Dent Educ 2013;77:358–63.

50 Kong X, Nie L, Zhang H, et al. Do 3D Printing models improve anatomical teaching about hepatic segments to medical students? A randomized controlled study. World J Surg 2016;40:1969–76.

51 Noecker AM, Chen JF, Zhou Q, et al. Development of patient-specific three-dimensional pediatric cardiac models. ASAIO J 2006;52:349–53.

52 Walenga RL, Longest PW, Sundaresan G. Creation of an in vitro biomechanical model of the trachea using rapid prototyping. J Biomech 2014;47:1861–8.

53 Wang K, Zhao Y, Chang YH, et al. Controlling the mechanical behavior of dual-material 3D printed meta-materials for patient-specific tissue-mimicking phantoms. Mater Des 2016;90:704–12.

54 Wang K, Wu C, Qian Z, et al. Dual-material 3D printed meta materials with tunable mechanical properties for patient-specific tissue-mimicking phantoms. Addit Manuf 2016;12:31–7.

55 Emmott A, Garcia J, Chung L, et al. Biomechanics of the ascending thoracic aorta: a clinical perspective on engineering data. Can J Cardiol 2016;32:35–47.

56 Ho D, Squelch A, Sun Z. Modelling of aortic aneurysm and aortic dissection through 3D printing. J Med Radiat Sci 2017;64:10–17.

57 Rosen KR. The history of medical simulation. J Crit Care 2008;23:157–66.

58 Chakravarthy B, Ter Haar E, Bhat SS, et al. Simulation in medical school education: review for emergency medicine. West J Emerg Med 2011;12:461–6.

59 Sulaiman A, Bousell L, Taconnet F, et al. In vitro non-rigid life-size model of aortic arch aneurysm for endovascular prostesis assessment. Eur J Cardiothorac Surg 2008;33:53–7.

60 Kales J, von Segesser LK. Rapid prototyping of compliant human aortic roots for assessment of valve stents. Interact Cardiovasc Thorac Surg 2009;8:182–6.

61 Shah K, Ahmed J, Shenoy N, et al. How different are students and their learning styles? Int J Res Med Sci 2017;12:1–5.