The role of 3D printed models in surgical planning

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Learning objectives

• To demonstrate the importance of the use of 3D printing in the orthopaedic and cardiovascular field as a relevant tool to create real anatomic models from virtually 3D rendered objects, allowing a better understanding of the normal and pathological anatomy for surgeons and consequently improving surgical planning.
• To briefly review the most common 3D printing process used in medicine.
• To describe the creation process of a 3D printed model.
Background

Three dimensional (3D) printing - also termed stereolithography - was invented in the early 1980s by Charles Hull, who has a bachelor's degree in engineering physics [1]. Since its inception, it has used a digital model to manufacture a 3D solid object [2]. The objects are made by fusing or depositing materials - such as plastic, metal, ceramics, powders, liquids, or even living cells - in layers [1].

The 3D printing has been used by the manufacturing industry for decades, primarily to produce functional prototypes in the automotive segment. In the last decade it has become a reality in several segments of industry, such as medicine, to produce anatomical models and customised prosthesis. In the early 2000s, the technology was first used to make dental implants and custom prosthetics [1]. In 2013, the Radiological Society of North America (RSNA) launched an educational program on medical 3D printing [2].

This technology allows us to take the next step from 3D virtual renderings to creating tactile 3D models [3]. It helps the radiologist to have a better communication and description of the pathologies to the clinicians and surgeons.

3D anatomic models are being used with increasing frequency in cardiovascular diseases, abdominal and orthopaedic surgery, prosthetics, and neurosurgery. They also are becoming an important tool in development of surgical guides and implants, and for bioprinting in regenerative medicine [4]. The models create a tactile feeling to the anatomic structure allowing surgeons to better understand the pathology.

According to the most recent classification by American Society of Testing and Materials (ASTM), there are seven major types of 3D printing technology. Although these technologies share similarities, they differ in speed, cost, and resolution of the product. [5]

- **Material Extrusion** - previously known as **Fused Deposition Modelling (FDM)** and **Fused Filament Fabrication (FFF)**, is a 3D printing process that uses a continuous deposition of a thermoplastic material. The plastic is pushed through a moving extruder head that melts the plastic in the nozzle. The head is moved, under computer control, to define the printed shape. Usually the head moves in layers, moving in two dimensions to deposit one horizontal plane at a time, before moving slightly upwards to begin a new slice. The speed of the extruder head may also be controlled, to stop and start deposition and form an interrupted plane without stringing or dribbling between sections.

- **Vat Photopolymerization** - also known as **stereolithography (SLA)**, is a laser-based technology that uses a UV-sensitive liquid resin. A UV laser beam scans the surface of the resin and selectively hardens the material
corresponding to a cross section of the product, building the 3D part from the bottom to the top. It produces models with a great surface quality.

- **Power Bed Fusion** - this category includes the **Selective Laser Sintering (SLS)** which is a technique that uses a laser as the power source to sinter powdered material (typically nylon/polyamide), aiming the laser automatically at points in space defined by a 3D model, binding the material together to create a solid structure. It is similar to **Direct Metal Laser Sintering (DMLS)**; the two are instantiations of the same concept but differ in technical details. **Selective Laser Melting (SLM)** uses a comparable concept, but in SLM the material is fully melted rather than sintered, allowing different properties (crystal structure, porosity, and so on).

- **Material Jetting** - it is often compared to the 2D ink jetting process. Photopolymers, metals or wax that cure or harden when exposed to UV light or elevated temperatures can be used to build parts one layer at a time. The nature of the material jetting process allows for multi-material printing. This ability is often used to print support from different (soluble) material during the build phase.

- **Binder Jetting** - it deposits a binding adhesive agent onto thin layers of powder material. The powder materials are either ceramic-based (for example glass or gypsum) or metal (for example stainless steel). The print head moves over the build platform depositing binder droplets, printing each layer in a similar way 2D printers print ink on paper. When a layer is complete, the powder bed moves downwards and a new layer of powder is spread onto the build area. The process repeats until all parts are complete. After printing, the parts are in a green state and require additional post processing before they are ready to use. Often an infiltrate is added to improve the mechanical properties of the parts. The infiltrate is usually a cyanoacrylate adhesive (in case of ceramics) or bronze (in the case of metals).

- **Direct Energy Deposition** - **Laser Engineered Net Shape (LENS)** utilizes a deposition head, which consists of a laser head, powder dispensing nozzles and inert gas tubing, to melt powder as it is ejected from the powder dispensing nozzles to build a solid part layer-by-layer. The laser creates a melt pool on the build area and powder is sprayed into the pool, where it is melted and then solidified. The substrate is typically a flat metal plate or an existing part that material is added on (for example for repair). **Electron Beam Additive Manufacture (EBAM)** is used to create metal parts using metal powder or wire, welded together using an electron beam as the heat source. Producing parts in a similar fashion to LENS, electron beams are more efficient than lasers and operate under a vacuum with the technology originally being designed for use in space.
• **Sheet Lamination** - this technique uses thin layered materials (paper or aluminum foil for example) to produce highly detailed and full color 3D objects. The sheets are cut following the 3D design of the desired object, often by lasers or a very sharp blade. Layers are then coated with an adhesive and glued together layer by layer, similar to other additive manufacturing techniques.

The first five technologies are the most commonly used in medicine. Direct energy deposition and sheet lamination are less common but may show promise in the future [2].
Fig. 1: Lumbar spine arthrodesis

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**Fig. 2:** Coronary stent

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Fig. 3: Aorta

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Fig. 4: CT Angiogram

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Findings and procedure details

Digital Imaging and Communications in Medicine (DICOM) files generated from a computed tomography (CT), magnetic resonance imaging (MRI) or ultrasound scan (US) cannot be used directly for 3D printing. Further steps are required to make them readable by 3D printers. Also, specific machine acquisition settings (CT/MR/US scan parameters) are necessarily required for the correct post-processing of the files.

The acquisition parameters for each modality are as follows:

- **CT** - Volumetric acquisition and slices of 1.25 mm or less. Ideally standard filter should be used for post-processing as the high resolution/hard filter generates excessive noise to the imaging.
- **MRI** - Mandatory isotropic voxel \((x=y=z)\) and higher matrix as possible without compromising signal-to-noise ratio (SNR).
- **US** - Mandatory 3D or 4D scan. A special attention for the US scans as they are spherical or trapezoidal volumes and not cartesian XYZ as CT or MRI scans.

The best modality to use will depend on the focus of the study. CT is better for evaluation of bone anatomy, and should be used a standard rather than a bone algorithm. Dual Energy CT should be chosen in cases where there are metallic artefacts because it allows significant reduction in beam hardening artefact. For cardiovascular anatomy and pathology, CT angiogram or MRI angiogram are used [3].

After appropriate imaging acquisition, the generated DICOM files are ready to be post-processed. The first phase of post-processing is **segmentation**, with consists of including or excluding a specific area of the volume using an automatic or manual Region of Interest (ROI). This is an important step in post-processing the images, as it separates the anatomical parts to be printed.
Fig. 7: Segmentation

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The segmented data is exported in a file format that can be addressed as a 3D object. To date, the most widely used format is Standard Tessellation Language (STL). This process is the conversion of 2D images to 3D triangular facets that compose a mesh surface [5]. The STL file also represents the position and orientation of the 3D object in space, allowing that multiple mashes that are related to one another to retain their orientation with respect to each other. This file format only encode the surface geometry of the 3D object and does not contain color or texture information [3].
The next step is to edit the resulting 3D mesh and to remove all the errors that would cause the print to fail. A Computer Aided Design (CAD) software is used for this purpose. When the adjustments are complete, the data can be loaded into a slicer program to generate a gCode file which can be read by a 3D printer.

A key part of 3D printing is choosing the appropriate printer technology and material to be used, depending on the purpose of the printed model. For anatomical models a FDM or SLA printer should be used. PLA is the material of choice for FDM and resin for SLA. For orthodontic models, SLA is the printer of choice because of its higher resolution. Below we describe some common thermoplastics used in FDM printer.

- **Polylactic acid (PLA)** - made of natural materials and biodegradable. Releases no toxic fumes.
- **Acrylonitrile butadiene styrene (ABS)** - crude-oil based, cheap, more flexible than PLA but sensitive to ultraviolet light causing it to riddle. Releases toxic fumes and needs adequate ventilation.
- **Polyvinyl alcohol (PVA)** - used as a support material. Water soluble.
- **Nylon** - Better mechanical stress and chemical resistance the ABS and PLA. Absorbs moisture easily.
- **Ethylene and Polycarbonate plastics** - Industrial grade materials, tough, durable, can be printed crystal clear, can withstand higher temperatures. Very high extrusion temperatures.
The radiologist, along with the surgeon, will define the best method and material to be used in each specific case, to create an exact tactile model of the patient's anatomy, allowing a better preoperative planning, reducing surgical time and improving postoperative recovery.
Fig. 9: Tricuspid valve

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Fig. 10: Hip arthroplasty

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Fig. 11: 3D printed model of hip arthroplasty

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Fig. 12: Ankle osteosynthesis

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Fig. 13: 3D printed model of ankle osteosynthesis

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Conclusion

3D printing applications in medicine are rapidly growing and radiologists should be familiarised to this technology. It allows a perfect reproduction of patient's anatomy and pathology. The 3D printed models aids surgical planning and reduce surgical time minimising peri and post operative complications, improving patient recovery.
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