3D Printing Technologies

2

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2.1 Introduction

The first three-dimensional (3D) printing technology was invented in the early 1980s to fill the need for rapid engineering of design prototypes. The process, also known as "rapid prototyping" and "additive manufacturing," widely expanded in the fields of architecture and manufacturing in the 1990s. Today there is a multitude of diverse 3D printing technologies that can manufacture objects using a vast array of materials, from thermoplastics and polymers to metal, capable of fulfilling most engineering and design needs. Medical applications of 3D printing can be tracked to the mid-1990s. It is only within the last 5 years, that it has gained tremendous momentum and is now used daily in hospitals and private practices around the globe.

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An early "3D printing lab" is rapidly emerging in many medical specialties. Many of these labs are in academic hospital radiology departments, while others are in cardiac or orthopedic surgery departments and practices. Their development will likely mirror the path of the "3D lab" as it evolved in radiology departments around the world. 3D labs began emerging more than a decade ago to fill the need of radiologists to communicate pertinent findings to medical care teams by visualizing the 3D volumetric imaging data acquired by diverse medical imaging modalities in anatomic rather than traditional acquisition planes (Fishman et al. 1987; Rubin et al. 1993). A handheld model derived from DICOM images represents a natural progression from its 3D visualization. The demand for such "anatomic" 3D-printed models for interventional planning is poised to grow as the technology becomes more available (Mitsouras et al. 2015; Giannopoulos et al. 2016). However, 3D printers offer a multitude of opportunities to benefit medical practice beyond anatomic visualization and hands-on surgical simulation. With 3D printing, patient-specific implants, guides, prosthetics, molds, and tools can also be manufactured to directly treat patients. This creates opportunities for 3D printing centers to be housed in hospital departments, for example, prosthetics, where the corresponding expertise exists. However, due to the large investment, it is economically sensible for hospitals to avoid duplicating these centers across specialties, and thus the model emerging in some

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institutions at the forefront of the technology involves a single 3D lab that is in its own division, staffed with faculty across specialties and cross appointed to that division. Such a centralized 3D printing division can effectively serve the needs of an entire hospital.

Until the technology is sufficiently proven and high-quantity "production" parts become commonplace in medical practice to support such centralized processes, rapid implementation of the 3D printing lab is currently underway in radiology, empowered by decreasing 3D printing costs and improvements in software tools to convert DICOM images to 3D-printed objects. The substantial start-up financial and physical space costs of purchasing and operating a 3D printer need to be wisely invested based on the needs of each practice. Furthermore, there are many factors which contribute to the construction of an accurate 3D-printed model (George et al. 2017a). Doing so requires diverse staff that possess expertise spanning many disciplines from engineering, physics, chemistry, to medical specialties starting with radiology and surgical and rehabilitation specialties. This chapter reviews 3D printing technologies without assuming a specific background so that all stakeholders may utilize it. The review of 3D printer capabilities, including communicating 3D models to them and the types of materials they can use, will assist the clinical practice in the informed investment of a 3D printing technology based on specific clinical needs.

The first additive manufacturing technology, stereolithography (SLA), was invented in 1980, patented in 1983, and commercialized by 3D Systems in 1987. Many other 3D printing technologies have since emerged that use energy or chemistry to produce printed objects. At present, the term 3D printing is used to collectively refer to additive manufacturing technologies or rapid prototyping. We have prioritized the technologies used for 3D printing from medical images based on emerging uses reported in the medical literature, including pre-/postsurgical models, custom surgical guides, prosthetics, and customized 3D-printed implants. 3D printing in medicine involves the fabrication of organs depicted in DICOM images, and potentially tools, guides, and implants that fit those organs. 3D bioprinting, the process by which living replacement tissues or organs are manufactured, is not covered in this chapter.

2.1.1 Communicating with a 3D Printer: The Standard Tessellation File Format and Beyond

3D printers cannot interpret DICOM images. Instead, 3D printing technologies accept a digital description of a 3D model, which they then manufacture into a physical object. To date, these digital object descriptions are limited to 3D surfaces that enclose a region of space. A 3D printer manufactures these objects by filling (entirely or in a porous fashion) the space enclosed by each such surface with a solid material. The solid material is created by energy deposition, for example, by melting a solid and selectively laying it in the region enclosed by that surface, or by a chemical reaction, for example, by solidifying a liquid selectively in the locations enclosed by that surface. How these surfaces are described and stored is thus a critical component of understanding and using 3D printing technologies. How these surfaces are generated from a patient's DICOM images to describe the specific organ, tool, guide, or implant that is to be manufactured is discussed in Chap. 3.

A standard file format to define these surfaces is the Standard Tessellation Language or, as also commonly referred to, the stereolithography file format, abbreviated as "STL." The STL format defines surfaces as a collection of triangles (called facets) that perfectly fit together without any gaps, like a jigsaw puzzle (Fig. 2.1). There are two types of STL files: "binary" STL files that can only describe a single "part" and "ASCII" STL files that can contain multiple independent parts. A single part is a single, fully connected surface that encloses a single region of space. It can be printed with a single material property (e.g., a specific color and hardness). STL files are thus ideal for printing a single organ, implant, guide, or

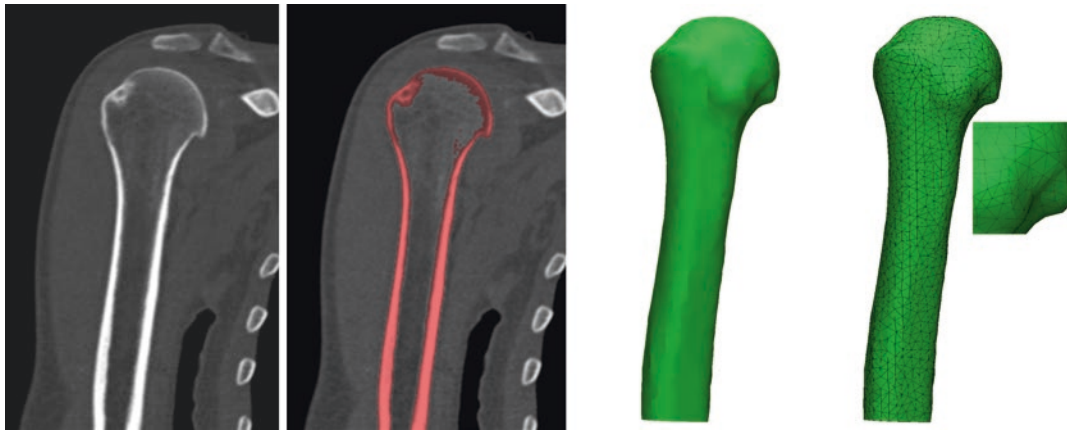

Fig. 2.1 DICOM images cannot be directly communicated to 3D printers for printing. 3D printers currently accept digital 3D models, typically defined by surfaces stored in the STL file format. A CT (*left panel*) from which the humerus is segmented (*second panel from the left*) for 3D printing must be converted into an STL file (*two right-most panels*) for sending to the 3D printer. Although STL files are usually presented by a rendering (*third panel from the right*), the underlying surface is in fact composed of simple triangles (*far right panel*) that fit together precisely and exactly as a jigsaw puzzle, with no gaps between any triangles (*inset*)

component of a tool that is not connected to other components (e.g., a single gear of a tool). This is a limiting format for medical printing. For example, if one wishes to 3D print a vessel wall with a calcified deposit, with the wall and calcification printed in different color and/or with different material properties (e.g., a soft material for the wall and a hard material for the calcification), two STL surfaces are required, and these must be stored in either two binary STL files, one for the vessel wall, and one for the calcification, or one ASCII STL file. Some printers restrict printing all objects in a single ASCII file with a single material, so that the latter is not an option.

In any case, the operator generating these STL files must not only ensure that the tissues described in the files accurately represent the anatomy, but also that the two models touch along a single side of each of the two surfaces described by the STL files, without leaving any space between them, otherwise the printed model would neither reflect physiology nor remain in one piece after printing. This approach does not scale well; for example, there is no simple way to use STL files to print this vessel if it contains a mixed plaque, with several small calcifications within a lipid-rich core. For this example, a digital description of the plaque model would ideally describe a single anatomic model (plaque) and differentiate only specific locations within that model that are calcified versus lipid-rich so that they can be printed with different materials of, e.g., different colors to reflect their different tissue properties, rather than requiring independent STL files for each small calcification. Furthermore, STL files offer no opportunity to manufacture an object with a graded transition between two or more 3D printing materials, which could be used to 3D print a model that also conveys tissue "texture." For example, it is not readily possible to print cancellous bone with inhomogeneous material properties (e.g., hardness) that could represent information regarding trabeculae and marrow or the gradual transition to healthy tissue in the case of an infiltrating tumor.

Approaches to achieve 3D printing of organs with inhomogeneous material properties are an active area of research to enable medical models to convey not only tissue biomechanical properties but also radiographic properties. For example, we are actively exploring the use of inhomogeneous 3D printing material mixtures when printing a single organ to be able to generate a printed model that replicates the image signal characteristics of the organ under computed tomography (CT) and magnetic resonance

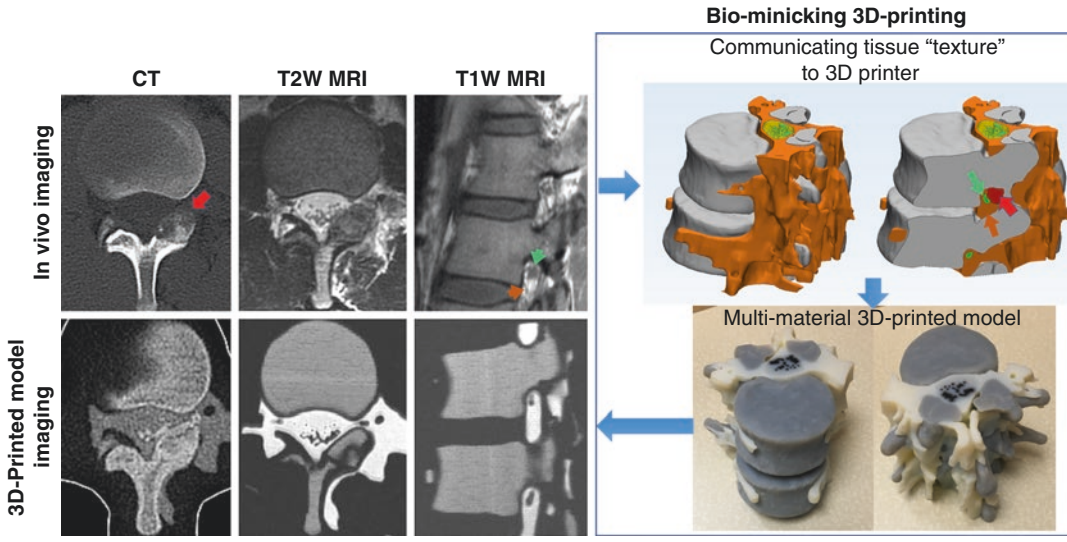

Fig. 2.2 3D-printed model of a patient with L1 left lamina osteoblastoma that replicates radiographic signal intensities similarly to in vivo patient imaging, including the tumor (*red arrows*), adipose tissue including foraminal fat (*brown arrows*), and spinal nerves (*green arrows*). At present there is no way to readily communicate such models to 3D printers

(MR) imaging (George et al. 2017b; Mitsouras et al. 2017; Guenette et al. 2016; Mayer et al. 2015). Such radiographically "biomimicking" models (Fig. 2.2) could enable the use of 3D printing for interventional radiology procedures such as thermal and nonthermal ablations, ultrasound-guided biopsies, and invasive catheter angiography-based procedures that are an important field in which 3D printing currently has only limited applications.

A second limitation of STL files is that there is no standard that is portable across softwares to store the intended color and material properties for a tissue model. At present, 3D printer-specific software is used to assign these properties to each STL file loaded for printing, which can be a tedious process and error-prone if there is a disconnect between the needs of the clinician producing the model and the technician running the printer.

The Additive Manufacturing File Format (AMF) and 3D Manufacturing Format (3MF) are newer file formats designed to overcome many of the limitations of the simple STL format, including the ability to incorporate features such as surface texture, color, and material properties into each part (Hiller and Lipson 2009). The AMF format standard was approved by the American Society of Testing and Materials (ASTM) in June 2011 (ISO/ASTM 2016), but with a few exceptions, it is not yet available in most softwares used to convert DICOM images into 3D-printable models. We expect it will become more commonplace in the next few years as the medical applications of 3D printing are expanded to better fit the richness of tissues differentiated by present-day imaging, for example, producing elastic vascular models with embedded hard plastics to represent stents or calcifications.

It is likely however that these newer formats will also be insufficient for emerging specialized medical applications, for example, the interventional radiology paradigm described above, where each location in the interior of a digital organ model would ideally need to be assigned different material properties (e.g., to achieve a model that possesses different CT numbers or MR signal intensities within the 3D-printed volume). We expect such complex medical 3D applications will lead to the development of additional file formats that are less reliant on the concept of a set of solid "parts" (e.g., organs) each of which has a single set of color and

material properties. Such future file formats will likely enable one to specify, radiologic and/or mechanical material properties within the volume occupied by the tissue to be printed, corresponding more directly to the concept of an organ composed of multiple tissues rather than a "part" commonly considered in engineering 3D printing applications.

2.1.2 3D Printing Technologies

3D printers use data encoded in the STL, AMF or other file format to successively fuse or deposit thin layers of material. Each layer is circumscribed by a set of closed curves that trace the outer surface(s) of the object being manufactured at that corresponding layer. The printer manufactures each such layer by filling the area enclosed by those curves with a material at a specified thickness (e.g., 0.1 mm). This is similar to the process of segmenting a tissue by successively identifying 2D regions of interest (ROIs) that circumscribe the tissue on consecutive cross-sectional images, each of which was acquired at a given fixed slice thickness. The 2D ROI is considered to fully circumscribe the tissue (and only that tissue) throughout the entire thickness of that cross section.

The taxonomy and terminology of 3D printing, which conveys how each printer's technology achieves the process of solidifying each layer and/or the fusion of the successive layers, are rapidly evolving. Complicating matters further, to date there has been no standardization of the nomenclature used in the biomedical literature to convey these different processes (Chepelev et al. 2017). However, a thorough understanding of the principles of each technology using a current, commonly accepted classification (Huang and Leu 2013) adopted as ASTM standard F2792 and International Organization for Standardization (ISO) standard 17296-2:2015 (ISO 2015) enables the end user to understand, interpret, and replicate the various techniques published in the literature.

In the current standards classifications, there are seven specific groups of technologies. These are vat photopolymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and directed energy deposition. The first five technologies are those most commonly encountered in medicine. Sheet lamination and directed energy deposition are less commonly utilized but still may provide a benefit when used for certain applications. Each technology has strengths and weaknesses as it pertains to its uses in clinical 3D printing (Table 2.1), and these are reviewed below.

2.1.2.1 Vat Photopolymerization

This 3D printing process is more widely known as stereolithography (SLA) or Digital Light Processing (DLP). It has three basic components: first, a high intensity light source (typically ultraviolet [UV]-A or UV-B); second, a vat or tray that holds an epoxy- or acrylic-based photo-curable liquid resin which contains monomers and oligomers; and third, a controlling system that directs the light source to selectively illuminate the resin (see below). Layers of the resin are sequentially cured by exposing it to the light source in the shape of only that cross section (i.e., ROI) of the model that is being built at that layer (perpendicular to the printer's z-axis). The light initiates a chemical reaction in the resin which causes the monomers and oligomers to polymerize and become solid. Once a layer of the object becomes structurally stable, the model is lowered (or raised, for bottom-up printers) by one layer thickness away from the active layer so that liquid resin now covers the top (or the bottom for bottom-up printers) of the previously printed layer. Polymerization of each layer is typically not fully completed by the controlled light source in order to allow the next layer to bond to the last one.

Each layer thickness is thus printed until the final layer is complete. After printing, excess resin is drained, and a solvent or alcohol rinse (generally in an industrial parts washer) is used to clean the model. Lattice support structures (Fig. 2.3) that are automatically added by the printer to achieve printing of overhangs also need to be manually removed. A final post-processing step is required, which involves "curing" the model in a UV chamber to complete polymerization of the

Table 2.1 Summary of characteristics of 3D printing technologies commonly encountered in medicine, professional equipment (>$5000) only

Technology	Other common technology names	Common material(s)	Accuracy	Cost	Advantages (generally)	Disadvantages (generally)
Vat photopolymerization	Stereolithography (SLA) Digital light processing (DLP) Continuous digital light processing (CLIP)	Epoxy- and acrylic-based polymers Infused polymers	+++	$$	Accuracy Biocompatible (short-term) materials available Can print small hollow vessels with no intraluminal support Microprinting possible (e.g., for microfluidics)	Brittle, moderate strength Models are single material Limited color options
Material jetting	MultiJet Printing (MJP) Polyjet	Acrylic-based polymers	+++	$$	Accuracy, variety of materials Models can be multi-material/multicolor Biocompatible (short-term) materials available	Moderate strength
Material extrusion	Fused deposition modeling (FDM)	ABS, PLA plastics, composites, metals (rare)	+	$	Low cost Strong, durable materials	Lower accuracy Model surfaces have prominent stair stepping ridges
Binder jetting		Gypsum, sand, metal (rare)	+	$	Speed Variety of materials Color capability in external shell No attached supports	Low strength Model infiltration is necessary
Powder bed fusion	Electron beam melting (EBM) Selective laser sintering (SLS) Direct metal laser sintering (DMLS) Selective laser melting (SLM) MultiJet Fusion (MJF)	Plastics, synthetic polymers, metal	++	$$$	Diverse mechanical properties Variety of materials Material strength sufficient for functional parts Long-term biocompatible (implantable) materials available Attached supports not usually required (nonmetals)	Various finishes (dependent on the machine) Models are single material

Note: This table is a generalization of the multiple technologies; some exceptions will exist

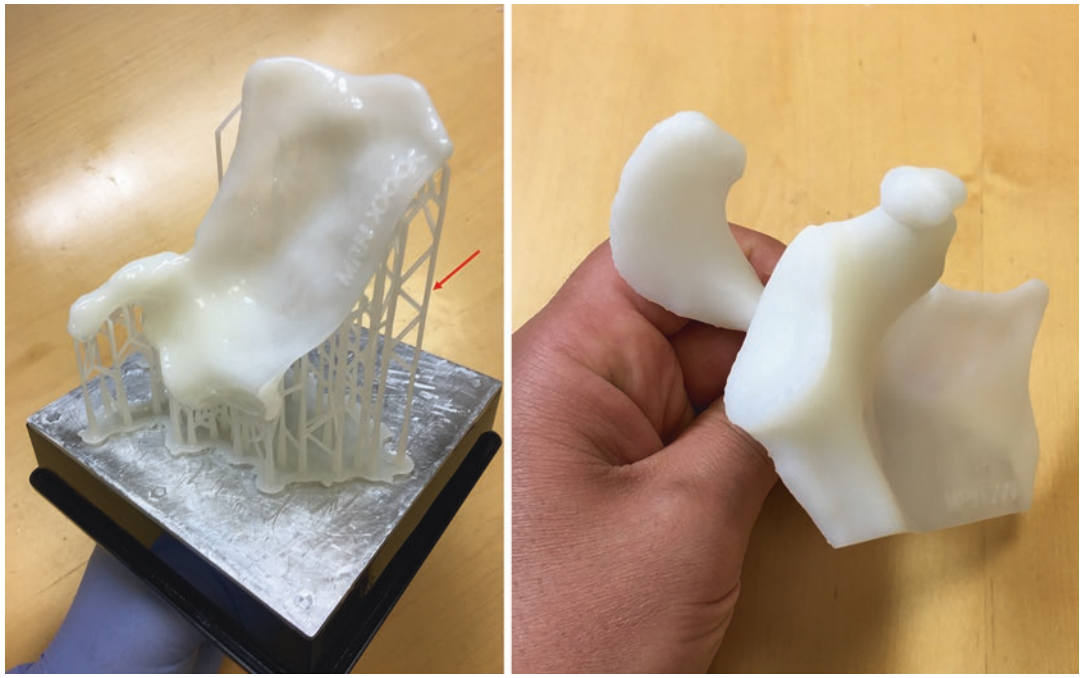

Fig. 2.3 Example of model of a scapula 3D printed using a bottom-up stereolithography vat photopolymerization 3D printer. During printing, the printer also prints a lattice of support rods (*red arrow*) that allow printing those portions of the model that would otherwise have nothing underneath them to support the printed material

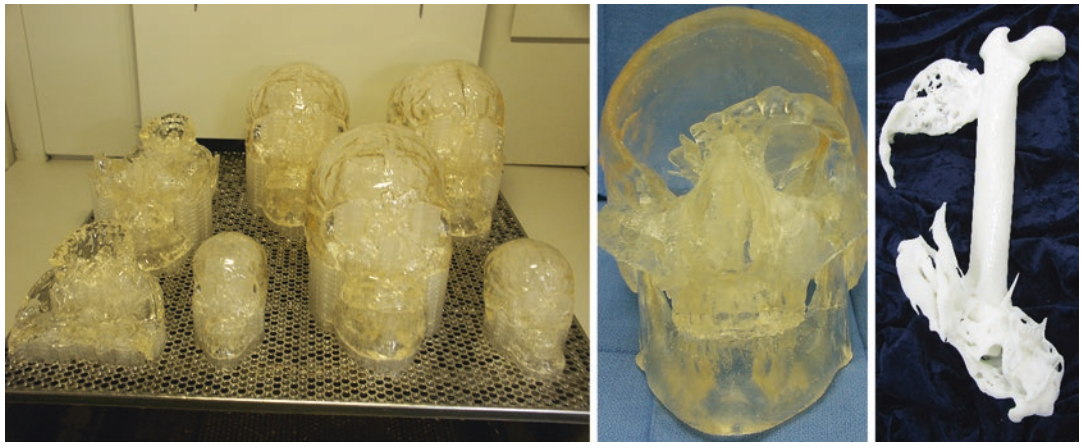

Fig. 2.4 Models 3D printed using a large, professional top-to-bottom stereolithography vat photopolymerization 3D printer (*left panel*). Printed models need to undergo UV curing to finish. Lattice supports present must be removed during model post-processing. Materials and machine size can vary

layer bonds (Fig. 2.4), rendering this as one of the more labor-intensive methods. Finishing may also be required, for example, to smooth step edges (light sanding) and application of a UV-resistant sealant.

The difference between SLA and DLP is the light source and how it is controlled to selectively illuminate and cure the resin. In SLA, the light source is a laser which is directed by mirrors to different locations on the liquid's surface (*x*–*y*

plane). The mirrors continuously and progressively cause the laser to trace the entire area of each layer of the object being printed. DLP instead uses a projector, such as those used in movie theaters, which instantly illuminates the entire shape of the layer of the object being printed onto the liquid's surface. DLP tends to require less time to print an object as each layer doesn't need to be progressively "raster scanned" but, apart from specific machines, most often lacks the high resolution of SLA afforded by a laser beam. An exciting new bottom-up DLP printer technology has been recently developed that uses an oxygen-inhibiting layer or "dead zone" above a membrane that sits at the bottom of the vat holding the resin. The oxygen layer inhibits polymerization at the interface of the membrane and the printed object. This proprietary technique, termed "continuous liquid interface production" (CLIP) by one 3D printer manufacturer (Carbon 3D, Redwood City, CA), reduces the mechanical steps involved in vat photopolymerization, offering prints at one or two orders of magnitude faster than other 3D printing technologies (Tumbleston et al. 2015), and can be as short as 5–10 min for, e.g., a scapula. Other similar approaches such as the Intelligent Liquid Interface (ILI™, NewPro3D, Vancouver, Canada) can provide larger build platforms, drastically cutting down build speeds and limitations on size. Mechanical steps are otherwise required in bottom-up printers to free the last printed layer from the transparent material (e.g., glass) floor of the vat to which the polymer adheres to as a consequence of the polymerization process. These steps typically involve lowering or shifting the vat by a small amount until the model, held in place by a base at the top, has come fully loose from the vat floor and subsequently returning the vat to just one layer thickness away from the previously printed layer. This process, in conjunction with constraints placed by the resin, e.g., to relieve internal stresses between layers and to allow flow of new resin below the model, accounts for the bulk of printing time with this technology.

Vat photopolymerization is frequently used for medical 3D printing, particularly for bone applications. It is also the only technology with which it is possible (with sufficient care taken in orienting the model in the build tray) to print hollow vessel lumens that are not filled with solid support material (Fig. 2.5) that may pose significant difficulty in removing, particularly for small, long, or tortuous vessels such as the coronaries, cerebrovasculature, and visceral aortic branches. However, materials are relatively expensive ~$210/kg. Top-down SLA printers require the resin to be maintained at a specific level in the vat, which can involve a costly investment for printers with larger build envelopes. Generally, the widely used commercial machine's build platform sizes range from less than 12.5 × 12.5 × 12.5 cm to as large as 210 × 70 × 80 cm or more. The smaller, desktop devices are often used to fabricate dental models and implant guides and hearing aids. Photopolymer materials are available in many colors and opacities ranging to translucent, as well as with material mechanical properties, such as flexible or rigid (Fig. 2.5). Older stereolithography-printed parts were relatively fragile. Newer acrylonitrile butadiene styrene (ABS)-"like" materials offer improved mechanical properties. Finally, short-term biocompatible material (see Sect. 2.2 below) are available and can be used to print sterilizable surgical tools and guides with appropriate post-processing. It is recommended to follow the manufacturer's specifications for proper material post-processing, cleaning, and sterilization particularly, but not only for tools and guides.

It is important to note that commercially available vat photopolymerization can print a model containing only a single material (color/properties), as only one liquid resin can be held in the machine's vat. To produce medical models with multiple materials (e.g., colors), each part of the model needs to be separately printed and later assembled together (Fig. 2.6). Transparent materials exist for higher-end printers that allow highlighting of internal structures (such as nerve spaces, tumors, teeth, plates) in the printed anatomy. This is done in the printer software by overexposing the material in the precise anatomical regions of those internal structures. The highlighting occurs via overexposure of the resin to the light source, that can be achieved e.g.,

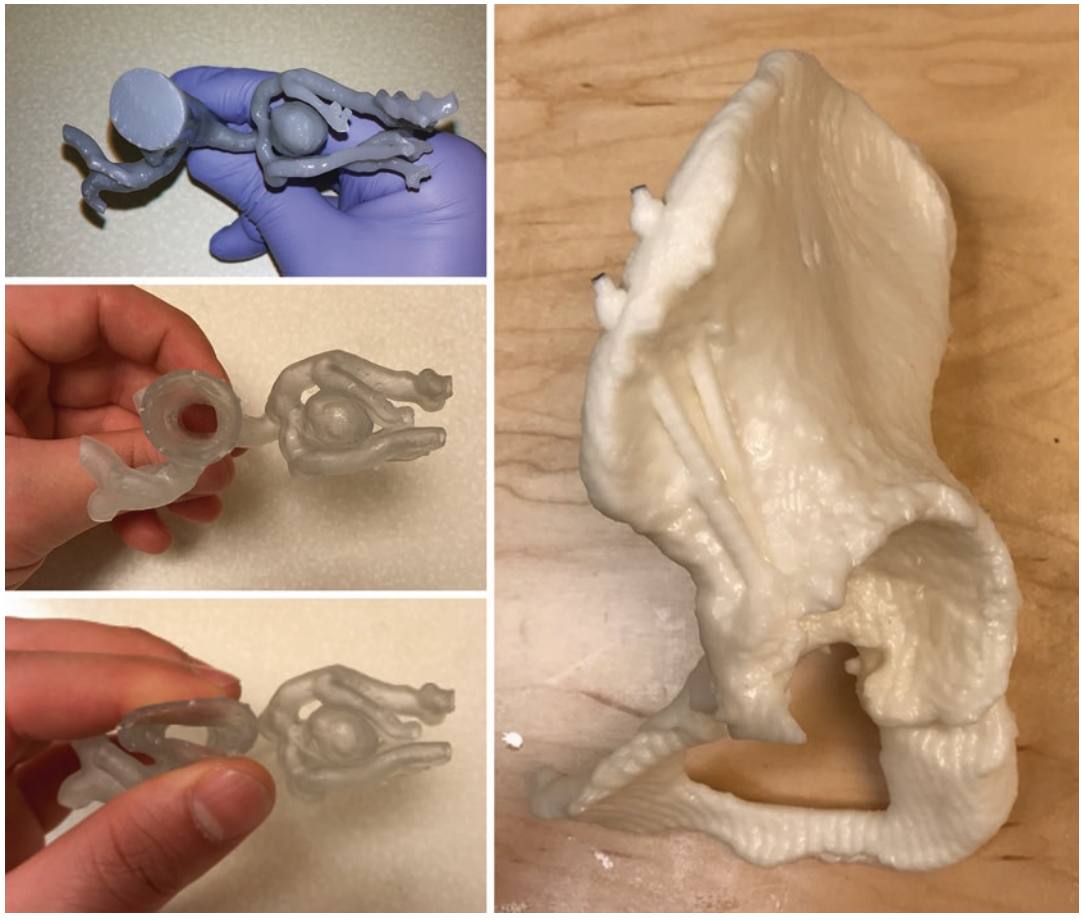

Fig. 2.5 Applications for which vat photopolymerization 3D printer technology is well suited, namely, small arterial models and particularly hollow models printed with a flexible material where a support lattice is only required external to the lumen with appropriate positioning of the model on the build tray (renal artery aneurysm shown in the *left hand panel*) and bone 3D printing (hemipelvis with prior hardware in the *right panel*)

by adding multiple copies of the structures to be highlighted (leading to multiple exposures of those model regions), or slowing the laser speed or increasing the laser intensity when printing those regions. The additional energy in this step tints the resin or activates a color additive within the resin to create the contrast. Finally, depending on the desired physical and mechanical properties of the photopolymer material, a heat treatment of 4 or more hours may be required. Thus, vat photopolymerization produces some of the smoothest, high-resolution models among 3D printing technologies, although it has limited versatility for printing multicolor/material models. In most cases, the lengthier (rate-limiting) step is the printing itself. New CLIP and ILI™ technologies can offer extremely fast printing speeds compared to other technologies, but cleaning and post-processing procedures may then become the rate-limiting step.

2.1.2.2 Material Jetting

Material jetting is a different technology but related to vat photopolymerization in that it relies on the same chemical principles. Unlike vat photopolymerization printers, material jetting printers do not hold the material in a vat. Instead, they are analogous to inkjet document printers. Just as inkjet printers jet ink onto paper and allow it to dry, material jetting 3D printers jet microdroplets

Fig. 2.6 Example of model of a bilateral renal aneurysm printed with vat photopolymerization (*left-hand panel*) with arteries printed in *gray*, veins in *black*, and kidneys in *white*. Each component was printed separately using the different-colored resins and later meticulously assembled together. This is not always readily (or at all) possible as shown for a model of a distal esophageal gastrointestinal stromal tumor (GIST) where the aorta curves around the esophagus (*right-hand panel*). This required printing the aorta in three pieces for assembly around the systemic veins and GI tract

of liquid photopolymer resin onto a build tray and polymerize it with UV light. The jetting heads scan across the build tray (e.g., left to right and front to back, i.e., the printer's *x*–*y* axes), and a controller instructs them to spray/extrude micro-droplets of the resin only when passing above those locations that are to be filled for the layer of the part currently being printed. Once the layer is completed, the build tray is incrementally lowered, and the jetting heads begin scanning across the *x*–*y* plane to print the next layer. In some printers, the print heads rise, while in others, the build platform lowers by one layer thickness to print subsequent layers. Two or more sets of jetting heads are required, one set for the photopolymer used to build the model and one set for "support material." The support material is a gel-like or wax material necessary to support overhangs and complicated geometries. Overhang support is essential to the build success of this technology, since resin cannot be jetted onto empty space below (Fig. 2.7). The composition of the support dictates the removal process. Common support removal processes include soaking in mild soap solutions, by hand, with pressurized water sprays, or by melting. Other part post-processing such as curing is not typically required, except for specific materials, e.g., a thermal treatment can enhance the printed part's thermal properties, to increase the part's heat deflection temperature. While like SLA material jetting enjoys high resolution, of the order of a few tens of microns in all three axes, models tend to have a matte surface finish. This may create a need to apply clear coat (paint or resin) to models to enhance transparency for clear materials and to give a smooth model appearance.

Overall, material jetting machines are a versatile technology for printing anatomic medical models. Material can more easily be swapped than for vat photo polymerization printers, since they are stored in cartridges, and multi-material machines allow for numerous different material colors and properties to be used to print a single model. Multi-material printers have multiple print heads, enabling a single model to be printed containing regions printed with each of the materials loaded in each print head. For example, transparent organ models can be easily printed with internal elements such as nerves, vessels, hardware, or tumors, each visible in a different opaque color (Fig. 2.7). In higher-end printers,

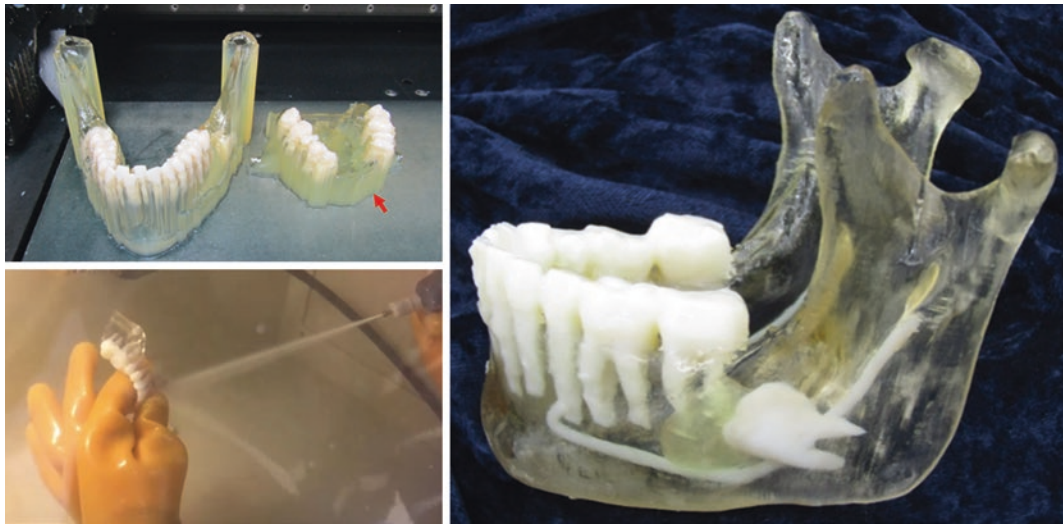

Fig. 2.7 Model of a mandible highlighting internal features (teeth, impacted molar, alveolar canal, and cyst) 3D printed using a material jetting printer. Support material (*red arrow*, *top left panel*) is removed using a water jet (*bottom left panel*). The model is then allowed to dry, and a clear coat is applied to aid in transparency yielding the final product (*right-hand panel*). In the above picture, one can see a mandible with internal features (teeth, impacted molar, alveolar canal, and cyst highlighted

the materials in each print head can also be mixed during the printing, thus allowing for tens to hundreds of "digital" materials (i.e., on-the-fly created combinations of materials) to be used to print a single model (Fig. 2.8). This is done by controlling the relative ratio and multiplexing of the microdroplets jetted from each head when printing each location of the object, allowing seamless mixing of the different materials held in each head. Flexible materials are also available and when mixed with a solid can be used to achieve different durometer (hardness) and mechanical properties, ranging from flexible (rubberlike) to hard/rigid. For numerous of these machines, short-term biocompatible material is available for printing of surgical tools and guides. A number of manufacturers of this technology market machines specifically for dental casts and dental implant guides. Again, it is recommended to follow the manufacturer's specifications for proper model post-processing, cleaning, and sterilization.

Material costs are among the highest across 3D printing modalities, (~$300/kg), but are delivered in cartridges for as-needed use. Each individual printer manufacturer tightly controls materials, using microchips located within the cartridges that are read by the printer to identify the cartridge. In addition to the inability to use third-party materials, expiration dates stored on the chip block material limit use after expiration. Machines with different-size platforms are available with a maximum size of 100 × 80 × 50 cm, but the technology is somewhat slow, with, for example, a pelvis requiring of the order of 24–48 h to print, rendering printing time the rate-limiting step.

2.1.2.3 Binder Jetting

Binder jet printers are also in some aspects similar to document inkjet printers. A print head scans the *x*–*y* plane and jets a liquid binding agent on to a bed of fine powder in the shape of the currently printed layer of the object. The binding agent selectively bonds the powder wherever deposited. Many binder jetting printers incorporate color print heads or binders, to achieve color either throughout or only on the outer (visible) surface of the model. Colors in a large range are possible with this technique, similar to that of paper-printed documents. The color is achieved by either mixing multiple colored binders or mixing colored ink

Fig. 2.8 High-end material jetting printers allow printing models using mixtures of two to four base resins loaded into the machine. Here, 14 cubes were printed in a machine with two material heads, one loaded with a flexible black-colored material (cube in *top left corner* was printed with that material at 100%) and the other loaded with a rigid white material (cube in *bottom right corner*). The cubes between these two were printed with a "digital" mixture (specially designed matrix of interwoven droplets from each material) to achieve different mixtures of the two base materials having different properties from flexible to increasingly rigid and color from black to white

Fig. 2.9 Model of skull printed using a binder jet printer. Powder bed onto which colored binder has been laid is shown mid-print (*left panel*). Once the print is completed, the model is dug out from the powder using a vacuum (*middle panel top row*), and any unbound powder remaining is removed using an air jet (*middle panel bottom row*). The model is completed by infiltration to strengthen it (*right-hand panel*)

onto a monochrome, usually white, binder during the jetting process. After each layer is bonded, the build tray is lowered, and a roller is used to deposit a new thin layer of powder covering the print tray. Binder jet offers a versatile option for economical printing of multicolor models, with the color palette of a single model easily being in the thousands of colors. Limitations of commercial printers in this family are the inability to print translucent or flexible models and that the printed models can be composed of only a single powder, usually primarily composed of gypsum, ceramic, or sand. Printed models are rough in surface finish, and intricate models are fragile before post-processing (Fig. 2.9). Post-processing involves first vacuuming and blowing off unbonded powder to clean the model and then "infiltration" of the model with cyanoacrylate, wax, resin, or metal. The choice of infiltrate is dictated by the material in the printer and contributes to the final strength of the part. Generally, for medical models printed with powder composed primarily of gypsum, sealing with cyanoacrylate is adequate. With some materials, infiltrating with an elastomer can be used to produce models that are somewhat deformable (elastic). It is unlikely that biocompatible models can be easily produced with this technology as powders, binders, infiltrates, and possible infiltration depth would all affect biocompatibility; however, it may be possible to attain this characteristic with certain infiltration processes.

Binder jetting is used extensively to print models for anatomic visualization with color-coded anatomy (Fig. 2.9). Newer software also allows for bony anatomy to be colored according to the bone density and vascular data populated

from DICOM reconstructions such as typical 3D visualizations. The popularity of this technology is driven by two significant strengths. First, materials are relatively less expensive than other printing modalities, at ~$150/kg after infiltration. Second, support structures are not needed since the model is continuously supported by unbonded powder that fills the build tray during fabrication. This allows fine overhanging structures such as small vessels to be directly printed *a proviso* great care in powder removal and model cleaning is exercised, since the plaster-like or sand materials are generally fragile before infiltration. Accordingly, care must be taken in general when recovering the printed model to ensure that small pieces are not damaged. In special cases, support structures can also be incorporated so that larger overhangs of a model will not fracture from its own weight and green strength during the powder removal process. The largest build platform currently available is roughly 180 × 100 × 70 cm. This technology is widely used in medicine for anatomic models due to its affordability, reliability, and speed capable of, e.g., printing a full skull in approximately 8 h, color capability, and ability to print parts without supports attachment sites that need to be disloged (broken off) the model.

2.1.2.4 Material Extrusion

Material extrusion, also known as fused deposition modeling (FDM), represents the most widespread and economical 3D printing technology, especially when including nonmedical applications. It is the most commonly used technology for consumer-based "at home" printers and has thus been widely used by researchers in medical 3D printing. Due to the broad range of printers that fall into this category, this chapter will focus primarily on FDM 3D printers viewed as commercial machines. In this technology, one or more heated extrusion head(s) are used to melt a thermoplastic filament and deposit it selectively on the build tray in the shape of the layer of the object being printed. The extrusion heads and/or the build tray move in the x–y plane in a path precomputed by the printer driver software to efficiently trace the shape of the printed object at each layer. Once extruded at each location occupied by the object, the material hardens by cooling. The material is typically a filament wound on a coil which is unreeled by motors feeding it to the extrusion head.

Various thermoplastics including ABS and polylactic acid (PLA) plastics, and polymers including biocompatible polyether ether ketone (PEEK) and metals can be printed with FDM. Biocompatible thermoplastics are available, for example, ABS that can be gamma or ethylene oxide sterilized. Specific printers tend to use materials specific to the hardware. Most "at-home" printers have a single extrusion head, allowing only a single material to be printed at a time. In these lower-end printers, supporting lattices are made of the same printing material and can be extremely difficult to pry off. Most medical models have difficultly printing with these printers, as printing the complex overhangs of human anatomic structures (e.g., visceral aortic branches) in thermoplastics will most likely deform if inappropriately supported. Most commercial-grade printers possess a second extruding head allowing a support material to be used. This support material is typically soluble in a hot water or other solvent (e.g., weak lye solution) bath; however, depending on the material one desires to print, dissolvable supports may not be available as not all materials will stick to the currently available support material. Occasionally, machines that possess additional print heads can be used to print a model that contains multiple colors and/or materials. The finish quality of FDM-printed parts is generally inferior to other technologies, due to both the fact that typical layer thickness is approximately 250 μm, larger than with other technologies, as well as because bonding at the interfaces of consecutively extruded tubular filaments is partial, with voids in the mesostructure (Fig. 2.10). However, printers are now capable of printing near 100 μm or less, similar to that of the previous technologies, offering improved finish. Nonetheless, FDM models may be suboptimal for simulation of endovascular procedures, especially when printed at larger layer thicknesses, as in addition to the rough surface

Fig. 2.10 Model of a hemimandible 3D printed using a material extrusion printer. *Inset* shows the typical striations on the surface of models printed with this technology due to its typically lower layer resolution than other technologies and partial bonding of the filament layers and voids in the mesostructures due to the tubular filament nature

finish that precludes reasonable resistance to catheter insertions, models require infiltration with an appropriate sealant to become watertight, which can alter the intended anatomy.

Material extrusion is nonetheless favored by early 3D printing labs because it is overall economical and easy to use; materials tend to be more rugged and strong than previously described technologies and cost less than $100/kg. Large build platforms with maximum dimensions of roughly 91 × 61 × 91 cm are readily commercially available at smaller cost than comparable size printers for other technologies. In general, this technology is not optimal for anatomic modeling applications such as surgical planning and simulation, except for musculoskeletal printing for orthopedic applications, since large bones can be printed at lower cost and reduced post-processing than with other technologies. However, assistive technology providers may prefer this technology due to the higher strength of the materials. In the future, we expect it to be most useful for the printing of patient-specific guides and surgical tools due to material strength, biocompatibility, and cost. Finally, many advances in this technology are currently underway to create parts with more isotropic characteristics.

2.1.2.5 Powder Bed Fusion

This category of 3D printing technologies includes selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM). These technologies generally use a high-power laser or electron beam to fuse small particles of plastic, metal, ceramic, or glass that is held in a tray in powder form. The powder is typically pre-heated to just below the material melting point. The target of the energy source is then controlled by the printer, allowing it to selectively fuse or melt the powder at each successive layer on the surface of the powder bed. After a layer is fused, the powder bed is lowered by one layer thickness, and a new powder layer is laid on top by a roller, and the next layer is printed. Like binder jetting, most of the non-metal materials in powder bed fusion technologies do not require support structures since the model is always fully surrounded and supported by unsintered powder. However, metal materials may require supports to transfer heat away from the part and reduce swelling during the printing process. The support bed enables powder bed fusion printers to construct 3D geometries such as a lattice, useful for implants that promote osseointegration not readily possible with other methods.

Powder bed fusion technologies are used extensively for 3D printing of medical devices including implants, fixations, and surgical tools and guides (Fig. 2.11). Specifically, material groups compatible with the technology are

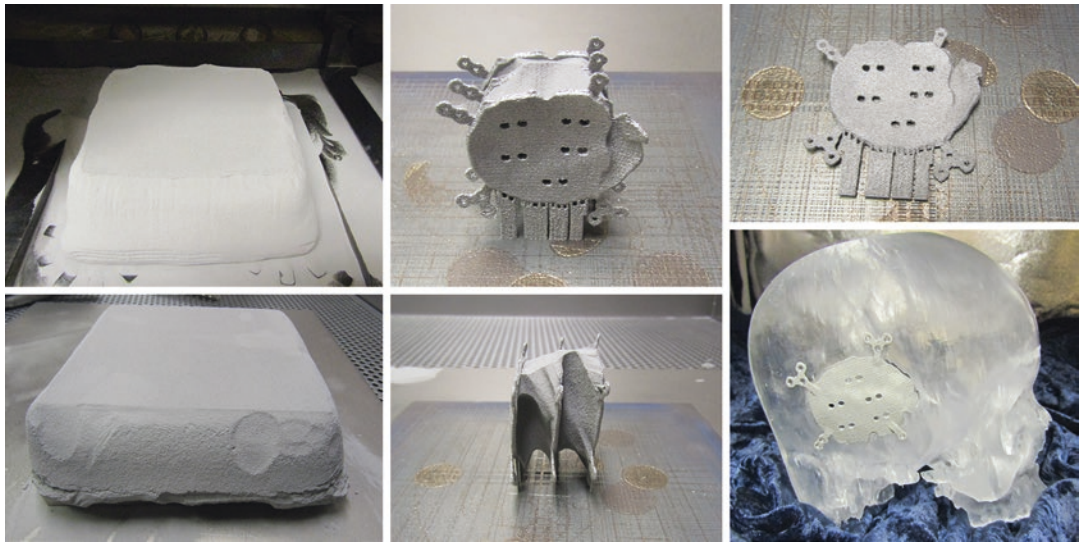

Fig. 2.11 Model 3D printed using a metal powder bed fusion printer. After printing the model is encased in the powder (*left-hand column*). After removal from powder (*middle column*), the cranial plate is cleaned and placed on a model of the patient's skull to confirm fit (*right-hand column*)

synthetic polymers (e.g., nylon, polyether ether ketone [PEKK]) and metals (e.g., titanium and cobalt-chrome alloys) that are biocompatible and sterilizable and can be safely implanted. Bioresorbable materials that can be printed with these printers offer exciting advances for patient-specific temporary devices such as splints (Morrison et al. 2015). The print material that is used may dictate the usefulness for anatomic models. For example, for a model used for presurgical planning, metal would most likely not be a useful (or acceptable) material. Metal parts would primarily be used for implants, guides, and surgical tools. Nylon models are versatile and possess good mechanical properties and heat resistance that allows for parts to be drilled or sawed with surgical instruments without melting. However, accuracy of most powder bed fusion machines is less than that of vat photopolymerization and material jetting machines.

Powder bed fusion materials are expensive, exceeding $200/kg, and some metals can exceed $400/kg. The rate-limiting steps of this technology are largely dictated by machine thermal cycles and model post-processing (Fig. 2.11). Many of these machines need to heat to a desired temperature to print, and parts need to cool before the operator can remove them from the machine. Required post-processing steps are highly dependent on the particular technique/material. For example, heat hardening/residual stress relaxation may be required for metals. Metal parts may need to be released/cut from the build platform, and finished parts may require computer numerical control (CNC) milling to achieve smooth, polished surfaces. One of the most significant hurdles when using this technology for medical devices is the difficulty of ensuring that unsintered powder remaining in printed model cavities will not affect biocompatibility and sterilization, especially in lattice-type structures (Di Prima et al. 2016).

2.1.2.6 Other Technologies

Three additional technologies are discussed in this section that are not currently encountered in medical 3D printing applications. The first is a newly developed technique introduced by Hewlett Packard, termed Multi Jet Fusion. This technology shares elements of both powder bed fusion and binder jetting technologies. It jets both a fusing and a detailing (inhibiting) agent on a bed of powder, which are activated with energy (heat) to fuse (rather than bind) the raw powder

material. This technique promises multicolor printing, exceptional part strength, and the ability to introduce texture internally within printed parts. It appears this technology has applications for medical modeling, but printers are only at pre-commercial release as of this writing.

The other two technologies, sheet lamination and directed energy deposition, have limited medical applications. Sheet lamination is an inexpensive 3D printing method that bonds paper, metal, or plastic film. Each sheet is rolled/pulled onto the build tray, and then a knife or laser cutter traces the outline of the shape of the printed object at the layer of the object being printed; glue and/or a heat treatment is applied between the layers for adherence to the previous layer. The sheet can be pre-printed with color to produce colored models. Post-processing involves the removal of excess material, by manually peeling off geometry not included in the printed model. This may not be easy (or possible) for complex anatomic geometries, such as cavities or areas surrounding tortuous structures such as vessels. Paper sheet lamination may however be economical for some orthopedic applications where only the outer bone surface needs to be evaluated. Additional post-processing by infiltration with a sealant or wax may be appropriate for paper models. Although this technology is generally cheaper than other processes, the printing and post-processing time may be extensive. Finally, directed energy deposition directly deposits material to a location where a high-powered energy source is also directed to melt/fuse the material. This technology combines aspects of material extrusion and powder bed fusion (laser or electron beam) and offers metal printing. It is unique because it can add to or repair an existing part, but this option is likely of limited use in medical applications.

2.1.3 3D Printer Resolution, Accuracy, and Reproducibility

In general, the highest resolution achievable by 3D printing modalities in all three axes is roughly 0.05–0.1 mm, superior to the resolution of images created by most clinical imaging modalities. For 3D printers, the *z*-axis resolution (layer thickness) is typically considered separately from the *x*–*y* plane resolution and is the most commonly encountered "resolution" figure found in literature. Similar to slice thickness in medical imaging systems, layer thickness is user selectable for most printers, and, similar to medical imaging protocols where slice thickness directly affects scan time, its choice directly affects printing time. If thinner layers are chosen, the print heads or energy sources will need to trace proportionally more layers, and the print will require a proportionally longer time. Partly because of its effect on printing time, layer thickness is the dimension of lowest resolution of 3D printers.

Of note however is that currently most printer's layer thickness is less than that of most medical CT images. Material extrusion printers print at typically 0.1–0.4 mm layer thickness; vat photopolymerization printers have 0.02–0.2 mm layer thickness; material jetting can print layers as small as 16 μm thick; and binder jetting layer thicknesses are typically 0.05–0.1 mm. Unlike imaging systems, where slice thickness can usually be arbitrarily large, for 3D printers, the layer thickness has an upper limit, and this upper limit may be dependent on the material being used to print. For example, a laser cannot penetrate a resin that uses a pigment for color to the same extent as it can a clear resin, and in either case penetration depth is limited. Although laser power is automatically adjusted by an SLA printer based on the resin being used, there are limits which, for example, might allow a 0.2 mm maximum layer thickness for a clear resin and a 0.1 mm maximum thickness for a colored resin. Similar implications exist for other technologies, for example, infiltration of a powder by the jetted binder in a binder jet system.

Most 3D printers have a fixed resolution in the *x*–*y* axes that is not as immediately clear in literature and requires some interpretation of equipment specifications. In SLA and SLS printers, *x*–*y* resolution is determined by the laser beam spot size (diameter), which is roughly 0.1–0.2 mm for most commercial systems. For DLP printers, it is determined by the projector resolution, optics, and build

platform size. One measure used to convey resolution of DLP printers is the number of dots per inch (dpi). The higher the dpi, the better the *x*–*y* plane resolution of the printer. A printer with 800 dpi has 800 individually controlled dots of the printing source (e.g., individual print head or energy source target points) with which to print 1 in. (25.4 mm) of the model. This printer thus has an in-plane "resolution" of 0.03175 mm. DPI is also commonly used to measure binder jet and material jetting printer resolutions, which typically lie in the 600–1200 dpi range.

Importantly, despite the high resolution of printers mentioned above, models usually cannot be printed successfully with features <0.3 mm in size (George et al 2017a). The minimum size of a feature that can be successfully printed depends on the printing technology and is often only partly dependent on the printer's in-plane resolution. For example, the minimum feature size is roughly 1.5 times the laser beam spot size (*x*–*y* resolution) for SLA printers. For material and binder jet printers, jetted droplets have distinct dimensional tolerances and spread characteristics that affect minimum feature size beyond the stated printer dpi. For these two technologies, manufacturers typically indicate the minimum feature size, which is usually 0.1–0.3 mm.

Resolution is the smallest scale that a 3D printer can reproduce and is only one factor affecting accuracy. Certainly, models can only be as accurate as the lowest resolution of the printer in each of the three axes (typically the *z*-axis layer thickness); a model printed with a printer operating at 0.4 mm layer thickness cannot be accurate to less than 0.4 mm compared to the intended medical model. In contrast to resolution, accuracy refers to the degree of agreement between the dimensions of the printed object compared to those intended, i.e., the dimensions of the digital object as stored in the STL file (Liacouras 2017). The accuracy and reproducibility of 3D printing medical models has unfortunately not been thoroughly investigated to date. Chapter 11 further discusses accuracy, reproducibility, and quality of medical 3D printing.

2.2 3D Printing Materials

Most printer manufacturers, and for many printers, third parties offer a choice of materials for use with each machine. Different materials are formulated for different needs, for example, low-cost prototyping, strength for tools, color, and biocompatibility. Many printing materials have undergone testing for US Pharmacopeial Convention (USP) Class VI or International Standards Organization (ISO) 10993, referring to levels of minimal in vivo biological reactivity (FDA 2016). These materials may be generally preferred, but are likely not necessary for models for surgical planning, teaching, and patient-physician interaction purposes. The use of materials that meet the requirements of those standards is however required to produce surgical guides and tools. Metals such as titanium and cobalt-chrome alloys can be used to print implants and implantable devices, and nylon can be used to print surgical guides. These are primarily printed with powder bed fusion and rarely material extrusion technologies.

Many printing materials can be sterilized for intraoperative use. Appropriate sterilization techniques depend on the material and may involve steam, chemical, and radiation sterilization (Mitsouras et al. 2015). At present, 3D printer and material manufacturers generally provide sterilization recommendations for appropriate materials. Generally, printed guides and implants will require ethylene oxide or other non-heat sterilization such as gamma radiation, while metal and some nylons can withstand autoclaving.

2.3 Conclusions

To date, medical researchers and clinicians have had limited access to and knowledge of the underlying 3D printing technologies. This is rapidly changing, and many surgery and radiology practices are starting their own 3D printing labs. Knowledge of the capabilities and limitations of the various 3D printing technologies is key to successful investment and foray into medical 3D printing.

As demonstrated in this chapter, each printer technology may have its own optimal application(s); therefore, before a facility decides to invest large capital to purchase a 3D printer, it would be beneficial for them to decide what their focus will be. Three-dimensional printers to date require manual intervention from an experienced user to properly manufacture parts and maintain the machines. Additional considerations include the diagnostic imaging processing software to produce STL models, and computer-assisted design software that allows 3D digital model processing and optimization for printing, or to plan surgical reconstruction. These are also large investments and require additional trained operators.

The potential medical uses of three-dimensional printing may only be limited by one's imagination. Imagination, however, is only one aspect of a successful implementation. Interdisciplinary communication and collaboration, knowledge exchange, and a firm grasp of the technological advances are essential to the successful implementation of medical 3D printing toward enhancing the expert care provided to patients.

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