Techniques in Vascular and Interventional Radiology

Three-Dimensional Printing for Procedure Rehearsal/Simulation/Planning in Interventional Radiology

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With the advances in affordable three-dimensional (3D) printing technology, 3D reconstruction and patient-specific 3D printed models are establishing a crucial role in the field of medicine for both educational purposes and procedural planning. 3D printed models provide physicians with increased 3D perception and tactile feedback, and enable a team-based approach to operational planning. However, performing an effective 3D reconstruction requires an in-depth understanding of the software features to accurately segment and reconstruct the human anatomy of interest from preacquired image data from multiple modalities such as computer tomography, 3D angiography and magnetic resonance imaging, and the different 3D printers/materials available in the market today. Increased understanding of this technology may benefit radiologists by developing techniques and tricks specific to interventional radiology and establishing a criterion to determine when to use these. Thus, the purpose of this manuscript is to provide physicians with an update on currently available 3D reconstruction software as well as printers and materials. Our initial experience using this technology is introduced based on a specific case of developing a 3D printed aorta for a patient with severe stenosis of the abdominal aorta.
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Indications for Seeking a 3D Printed Model

Deciding when a three-dimensional (3D) printed model is beneficial in the clinical setting based on patient outcomes is still being actively investigated. It has been postulated that 3D printed models in the field of vascular surgery and vascular interventional radiology can provide patient education, improve the confidence of physicians for procedures and be useful for procedural planning.[1-6] A previous study on the applications of 3D printing in pediatric cerebrovascular interventional radiology found that printed models reduce the time of operations for arteriovenous malformations and vein of Galen malformations.[7] Clearly, there are some benefits that can be offered by 3D printing, but up to date, no guidelines have been released to give physicians a general idea of when a 3D printed model can provide substantial benefit to patient care.

In general, 3D printing can provide benefits in the following cases: (1) when the procedure is considered high-risk, (2) when there are limitations in obtaining diagnostic information, (3) for procedure planning, and (4) when the margin for error is narrow. 3D printed models can also allow physicians to create a sophisticated procedural plan, rehearse to prevent and manage complications, reduce intraoperative radiation which is desired in the pediatric population and in long complex vascular procedures,

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and when there are serious risks based on the location of an abnormality such as in arteriovenous malformation treatments.

Procedural Steps for Developing a 3D Printed Model

The general procedure needed to develop a 3D printed model could be simplified into 4 major steps: imaging, segmentation, postprocessing, and printing. Within each of these steps, there are several combinations of segmentation algorithms and postprocessing editing tools that can allow for a 3D printed model to be developed. However, selecting the appropriate methods at each level may expedite the process, and most importantly, provide more accurate results. In this manuscript, we will discuss an ideal approach for developing 3D printed models. We will discuss a specific case where the abdominal aorta and external iliac vessels of a patient with severe stenosis were 3D printed as in Figure 1. The techniques mentioned can be replicated for any vascular territory using contrast enhanced computed tomography (CT) data. The associated technical challenges that accompany the procedure of developing patient-specific 3D printed models will be mentioned.

In order to produce a 3D printed model, first and foremost, an appropriate imaging study must be obtained. The accuracy and quality as well as the complexity to reconstruct the 3D model heavily depend on how well the targeted structures can be clearly distinguished from the surrounding tissues on the study. Therefore, it is important to select the optimal imaging modality that provides maximum contrast differentiation between the anatomy of interest and the surrounding structures which depends on the properties of the target anatomy including size, density, and shape. For example, a CT scan is very effective at providing a high-resolution 3D reconstruction of bony anatomy, since differentiation of various tissues is well seen using CT. On the other hand, to create a reconstruction of the biliary tree, a magnetic resonance cholangiopancreatography is highly effective in distinguishing the biliary tree from surrounding structures whereas CT would not be helpful. Sometimes even when a particular imaging modality is well suited for a particular territory, technique modifications maybe needed as in accurately reconstructing the plateau of a tibia which requires thin slice thickness in order to accurately depict the fine contours of the bone's surface.

Once an appropriate imaging study is obtained, various segmentation techniques can be used to extract the features of the targeted structure for a 3D reconstruction. Segmentation is a technique of dividing an image into parts called segments based on certain image features like pixel intensity value, color, texture, etc. using various mathematical algorithms.[8-10] Prior to segmentation, it is essential to have optimal tissue differentiation between various tissues and structures so that the reconstruction will be more accurate.

The 3D reconstructed abdominal aorta model in Figure 1 illustrates an example of when a 3D printed model may be beneficial. In this case, the endothelial lining of the abdominal aorta has poor contrast with respect to the surrounding organs and visceral fat of the abdomen. In such cases, a CT with intravenous contrast would be the preferred study as it allows for optimal contrast enhancement of the lumen of the aorta. An angiogram can also be helpful in providing optimal contrast opacification and direct visualization of branch vessels, however; this would require a 3D rotational angiogram in order to produce an active 3D reconstruction using segmentation techniques. A magnetic resonance imaging may provide quality results when attempting to reconstruct the aorta. Specifically, contrast-enhanced MR angiography can be as effective as a CT with intravenous contrast while also avoiding the adverse effects of radiation and renal dysfunction from the use of intravenous

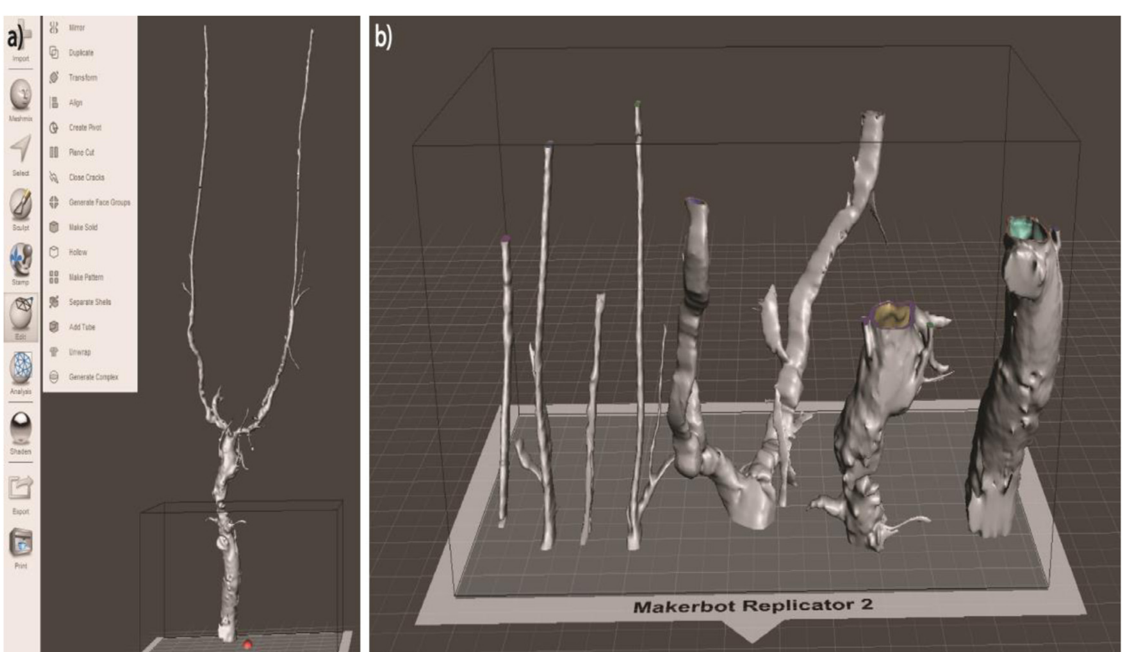

Figure 1 3D reconstructed model of the aorta.

Table 1 Software Packages Capable of Performing 3D Reconstructions

Software	Cost	Advantages	Disadvantages
3D Slicer	Free, open-source	Automatic image segmentation Polygon mesh visualization	Lacks postprocessing tools: Cannot correct surface errors, no preinstalled wizards to prepare object for 3D printing.
Embodi3D (democratiz3D)	Free, open-source	Automatic image segmentation Thresholding ranges preselected for different tissues	Lacks postprocessing tools
The Medical Imaging Interaction Toolkit	Free, open-source	Provides isosurface module for creating surfaces on object Various segmentation tools	No postprocessing tools available
OsiriX MD	$699 (1-year subscription)	User-friendly Various segmentation tools	Lacks postprocessing tools: Cannot correct surface errors, no preinstalled wizards to prepare object for 3D printing.
3D Doctor	$4800	User-friendly FDA approved for 3D imaging	Lacks postprocessing tools: Cannot correct surface errors, no pre-installed wizards to prepare object for 3D printing.
inPrint (Materialise)	~$9000 (Depending on modules)	User-friendly Several FDA approved applications Various segmentation tools Surface editing features available	Nonfully automated segmentation
Amira (Thermo Fisher Scientific)	~10,000 (Depending on modules)	Variety of surface editors	Non-fully automated segmentation
Mimics Innovation Suite (Materialise)	~$20,000 (Depending on modules)	Several FDA approved applications Various segmentation tools Surface editing features available	Costly
Vitrea (Vital)	Evaluation version (price unavailable)	Fully automated vessel segmentation	Lacks postprocessing tools: Cannot correct surface error

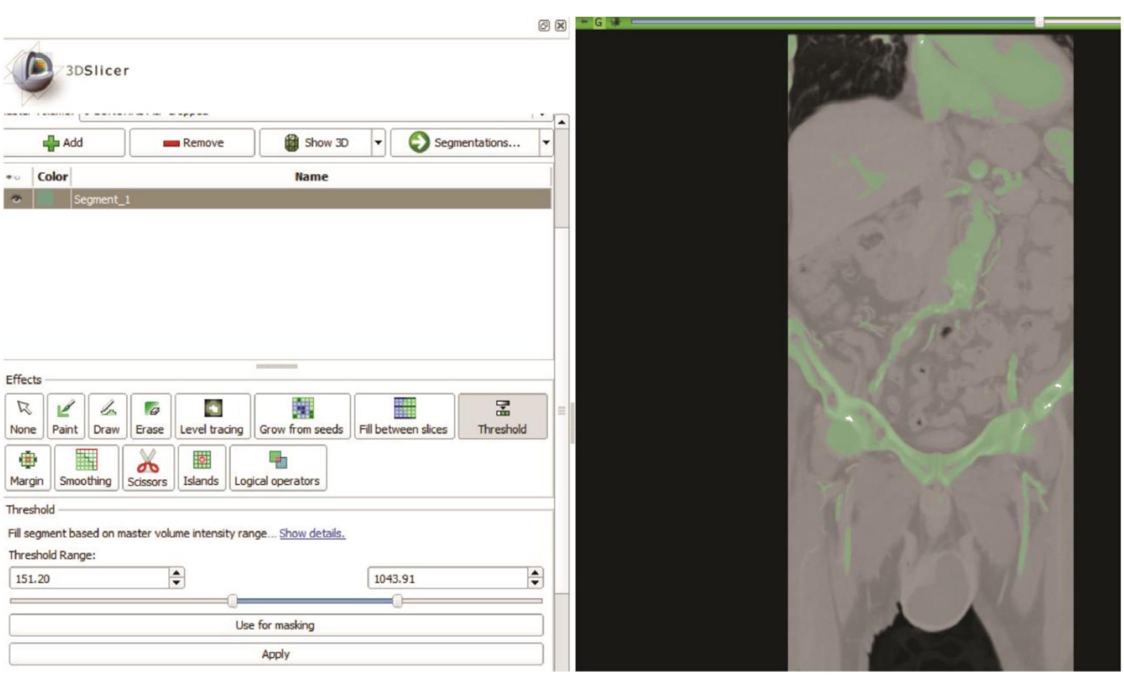

Figure 2 Thresholding effect for segmentation using 3D Slicer.

contrast. Deciding between these 2 studies depends on the availability of these imaging modalities, expertise of the center, and if there are any patient contraindications to the use of CT or magnetic resonance imagining.

The most commonly used software packages which can perform segmentation of DICOM data are summarized in Table 1.[11] The general procedure of segmentation is described based on an example of the reconstruction of the abdominal aorta, external iliac vessels and femoral vessels using a freeware software, the 3D Slicer.[12] The initial step for segmentation is the "Thresholding effect," which highlights and masks regions of interest depending on the selected intensity value window from the CT images. The lower and upper limits were set so that the selected region included all the large vessels that were filled with intravenous (IV) contrast (aorta, iliac arteries, and femoral arteries), which in turn also selected the heart and bones from the lower thorax to the mid-femur as in Figure 2.

To complete the segmentation step, the vasculature of interest is isolated from the bones included in the thresholded region. Luckily, these segmentation software packages provide several algorithms to perform these types of tasks. One of the commonly used powerful tools is the automated 3D region-growing algorithm, which allows isolation of all continuous segments starting from a seed location within a region of interest. However, if the vasculature is in close proximity to the vertebral structures then the 3D region-growing tool may not be as effective. Another reliable tool for this step is the mask tool, which allows the user to manually isolate the structures of interest slice-by-slice using a paint tool that applies only on the thresholded regions as in Figure 2. This task may be done manually for every slice or for efficiency it can be done at a reasonable interval and interpolation algorithms can be used to fill in skipped regions using the fill between slices effect. Once the vasculature has been isolated in the thresholded region, the 3D model can be generated and exported as a Stereolithography file in the form of a solid model. This model maybe then postprocessed in a mesh editing program to be appropriate for 3D printing.

Postprocessing techniques are diverse and can be modified based on the technology available for computer automated design and 3D printing. Extrusion printers are capable of depositing melted plastic in layers to create a 3D model. Transparent polylactic acid (PLA) is a cost-efficient material for 3D printing and the transparent color selection allows for preoperative planning with the model. A list of existing 3D printing technologies and available materials are summarized in Tables 2 and3, respectively.[1,13,14]

If use of an extrusion printer is desired, postprocessing to convert the segmented solid model of an abdominal aorta to a shell model to maintain the patency of the lumen of the vasculature during the printing process. To accomplish this, the wall of the lumen was designed to be a solid 1 mm shell using the MeshMixer (AutoDesk) program. The steps for this is as follows. First, the Stereolithography model of the reconstructed aorta is imported into the software as in Figure 3(a). Then, the "Inspector" tool is used to fix any errors in the mesh. Once the mesh is prepared, the hollow tool is used to convert the solid model to a shell model with 1 mm thickness. Finally, as the aorta exceeds the size of the printer workspace, the vessels are

Table 2 3D Printers

Printing Method	Technology	Printers	Cost Range	Materials Supported	Advantages	Disadvantages
Fused deposition modeling	Extrusion of molten material	MakerBot Replicator, Ultimaker,	\$200-\$4,295	Thermoplastics (ABS, PLA, HIPS, TPU, nylon)	Low material cost and high build volume	Low complexity prints possible, slow printing speed, print materials tend to be weaker
Stereolithography	Photopolymerization, laser draws each layer	XYZprinting Nobel Formlabs Form 2	\$1,799-\$4,999	Photoreactive liquid resin	Faster print and higher complexity prints possible	High cost of photopolymers
Digital light processing	Photopolymerization, entire layers projected onto the resin	Phrozen Make, B9Creations B9Creator	\$980-\$4595	Photoreactive liquid resin	Faster print than stereolithography printers	High cost of photopolymers
Material jetting	Jetting material followed by cooling or photocuring	Stratasys Objet30 Pro	\$19,900	Wax, photopolymers	Novel materials available, biocompatible materials	High cost of materials and machine
Selective laser sintering	Melting powdered material together	3D Systems ProX SLS 500	\$270,000	Metals, nylon, polystrene	High strength, good surface finishing, high complexity prints	High cost of materials and machine, prints have a porous surface

Table 3 Materials for 3D Printing

Material	Cost to Print Abdominal Aorta (3D Hubs)[15]	Material Property	Useful Applications
PLA (Polylactic acid)	$8.08	Brittle	Rapid prototyping
ABS (Acrylonitrile butadiene styrene)	$7.50	Good impact strength	Rapid prototyping
HIPS (High impact polystyrene)	$16	Impact-resistant plastic	Durable prints
PVA (Polyvinyl alcohol)	$59.43	Water soluble , used as support material	Support material for complex prints
Nylon	$35	Good mechanical properties and chemical resistance	Durable prints
PP (Polypropylene)	$19.30	High flexibility, great toughness, resistance to chemicals and electricity	Electric components
Acrylic/Resin	$33.14	Brittle, high-detail, smooth surface finish	Small, high accuracy models
PET (PETG, PETT) (Polyethylene terephthalate)	$7.45	Chemical and moisture resistance	Models in contact with liquid
ASA (Acrylonitrile styrene acrylate)	$12.10	UV stability and high chemical resistance	Outdoor exposure
TPU (Thermoplastic polyurethane)	$9.84	Rubber-like, flexible	Flexible models

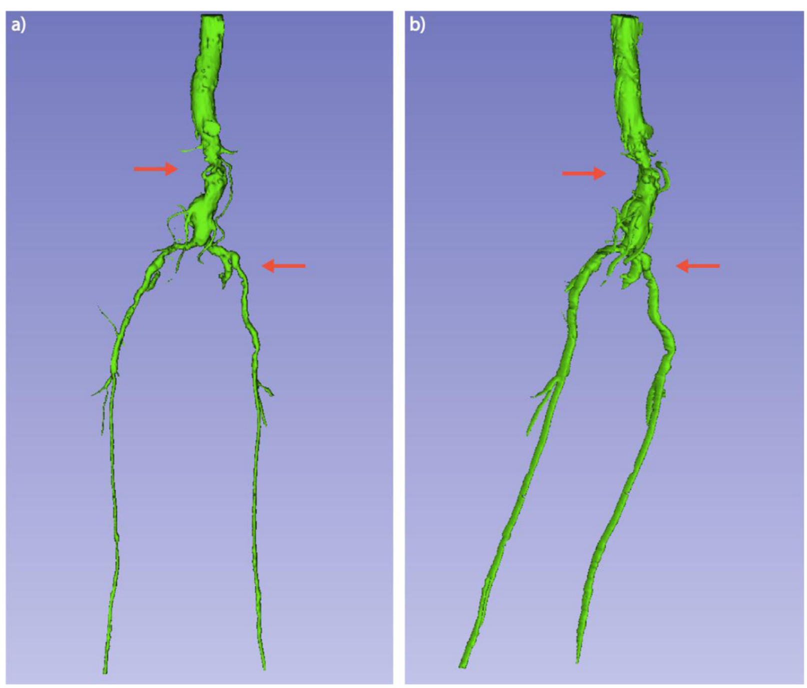

Figure 3 (a) Postprocessing and (b) model preparation for 3D printing in Mesh Mixer.

divided into 5 individual parts using the "Plane cut" feature so that it can fit within the printing space as in Figure 3(b). The printed parts are then glued together using Loctite. The final 3D printed model is presented in Figure 4(a) and (b).

Overcoming Technical Challenges

One of the most challenging aspects of creating a 3D reconstruction for vasculature is performing the segmentation process. As discussed previously, having an imaging study with a high degree of contrast differentiation greatly enhances the simplicity and accuracy of the segmentation process. In addition to using a CT with IV contrast, smaller slice thickness allows for higher resolution for the 3D reconstruction, and consequently, a more accurate 3D printed model. These adjustments also allow for the use of automated 3D region-growing tools during segmentation instead of performing a manual slice-by-slice split mask segmentation. As an added benefit, this limits including locally calcified structures within the segmentation which can result in an inaccurate model. In general, it is more effective to utilize a software that has both segmentation and postprocessing tools such as

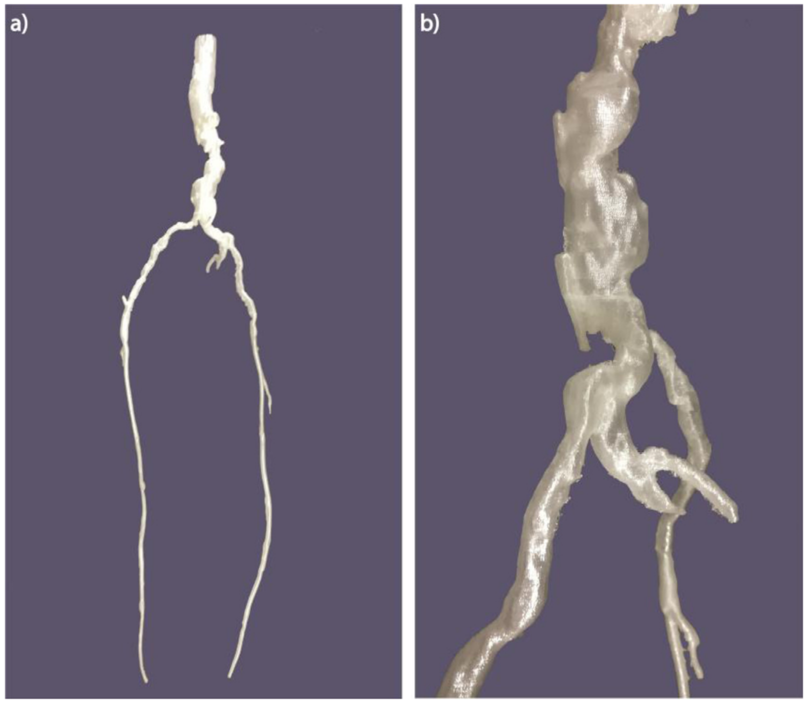

Figure 4 3D printed model of the aorta.

inPrint, Amira, or Mimics Innovation Suite, however, these tend to be more expensive.

Executing the printing of the aorta is also a challenge due to the tortuosity of the vessels and severe stenosis in various locations. Extrusion printers are very limited in printing structures with a high degree of overhang. Print supports may be incorporated by the 3D print generation software to overcome this limitation. However, some objects cannot be successfully printed even with print supports using an extrusion printer. Printing a shell model that requires inner support materials also introduces a great challenge. In the included aorta example, the lumen of the aorta needed to be filled with a support structure which was later removed manually. While this process has benefit, it can also possibly compromise the integrity of the external surfaces of the model due to limited accessibility. Resin-based printers may be considered to overcome such challenges as they are capable of printing such objects without the use of support. However, the cost of printing with this type of printer is significantly more expensive. Another alternative is to use a deposition based printer that has 2 nozzles. In this case, one nozzle prints the shell model in PLA and the other nozzle prints the support structures in polyvinyl alcohol (PVA), which is water soluble and can be easily washed away.

We favor the transparent PLA material for several reasons. First, it allows for easier visualization of the inner walls of the vessel so the print could be used for preoperative planning. The radiologist may then utilize the 3D model to plan or practice different interventions. For complex cases, being able to predict possible complications may serve as a significant advantage. Surgeons may be able to rule out certain techniques ahead of time and favor others long before the patient is sedated and being operated on. Ideally, this may reduce surgery time, which in turn would enable to treat more patients by freeing up the limited resources such as the angio suites. Also, a thorough preoperative plan can reduce intraoperative radiation exposure which can be of particular interest in the pediatric population and in complex vascular interventions. Another significant advantage is using 3D models for training purposes. Vascular Interventionalists may use real-life complex cases to practice catheterization techniques, treatments, and learn the ability to maneuver a catheter through unfamiliar variations such as those in the presented aorta model. Another application would be percutaneous cholangioscopy training based on 3D reconstruction of the biliary tree from magnetic resonance cholangiopancreatography, which has gained renewed interest in the recent years.

To comment on the feasibility of this procedure, it is imperative to mention the learning curve associated with the use of segmentation software packages. It is challenging to organize a personalized workflow that allows the development of a printable model, but once the appropriate workflow is composed, producing subsequent models becomes more efficient.

One option is having an assistant perform these reconstructions. Another option is outsourcing the print to local facilities, since the initial investment to acquiring a 3D printer can be expensive.

Depending on the material type, size, and length of duration of the print, the cost can range from hundreds of dollars to thousands of dollars. If a more streamlined and efficient process is available, including cheaper materials, in-house printers, and experienced personnel, the price can be reduced significantly.

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