

Using 3D printed models for planning and guidance during endovascular intervention: a technical advance

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ABSTRACT

Three-dimensional (3D) printing applications in medicine have been limited due to high cost and technical difficulty of creating 3D printed objects. It is not known whether patient-specific, hollow, small-caliber vascular models can be manufactured with 3D printing, and used for small vessel endoluminal testing of devices. Manufacture of anatomically accurate, patient-specific, small-caliber arterial models was attempted using data from a patient's CT scan, free open-source software, and low-cost Internet 3D printing services. Prior to endovascular treatment of a patient with multiple splenic artery aneurysms, a 3D printed model was used preoperatively to test catheter equipment and practice the procedure. A second model was used intraoperatively as a reference. Full-scale plastic models were successfully produced. Testing determined the optimal puncture site for catheter positioning. A guide catheter, base catheter, and microcatheter combination selected during testing was used intraoperatively with success, and the need for repeat angiograms to optimize image orientation was minimized. A difficult and unconventional procedure was successful in treating the aneurysms while preserving splenic function. We conclude that creation of small-caliber vascular models with 3D printing is possible. Free software and low-cost printing services make creation of these models affordable and practical. Models are useful in preoperative planning and intraoperative guidance.

Three-dimensional (3D) printed vascular models have been manufactured for the heart and aorta and used preoperatively for planning and testing prior to surgery (1). Creation of intracranial vessel models has been described using 3D printing indirectly to create a scaffold, which aided in creation of hollow models using a manual painting process (2). Direct manufacture of hollow small vessel models using 3D printing has not been described, and it is unknown if it is possible with existing technology, or of any clinical utility.

In a complex case of multiple splenic artery aneurysms, 3D printed vascular models were successfully created using free software and low-cost Internet 3D printing services, and were used for preoperative planning and intraoperative guidance. Two models were created. The first was a hollow model of the splenic artery. The second was a solid model of the splenic artery lumen. Both models were full-size, anatomically accurate, and derived from computed tomography (CT) scan data. The models enabled a complex endovascular procedure to be practiced and refined before the actual procedure on the patient, leading to a success that preserved the patient's spleen.

Case background

A 62-year-old female presented with multiple asymptomatic splenic artery aneurysms that had been incidentally detected on a CT scan performed during a workup for a urinary tract infection. She was asymptomatic and had no known risk factors, including portal hypertension, liver cirrhosis, or current or past pregnancy. A contrast-enhanced CT scan revealed a significantly tortuous splenic artery, having a 360° loop followed by three 180° hairpin turns. Two 2 cm aneurysms were present, located at the second and third 180° hairpin turns, respectively (Fig. 1a, 1b). A smaller, low-risk 5 mm aneurysm was also present and located in the proximal artery. Because the distal-most aneurysm was at the splenic hilum, infarction of the spleen was likely if treated with conventional transcatheter embolization (3). The patient declined conventional treatment, including splenic artery embolization and surgical splenectomy, desiring to preserve splenic function. Flow-sparing aneurysm embolization and stent-graft placement were considered, but a consensus of three board-certified interventional radiologists and a board-certified vascular surgeon determined it was not possible with conventional equipment given the unusually tortuous anatomy. Recent advances in neurovascular microcatheter equipment appeared promising, but this equipment was specifically designed for use in the cerebral vasculature. It was uncertain whether this equipment would work within the unusual anatomic limitations of this patient's splenic artery.

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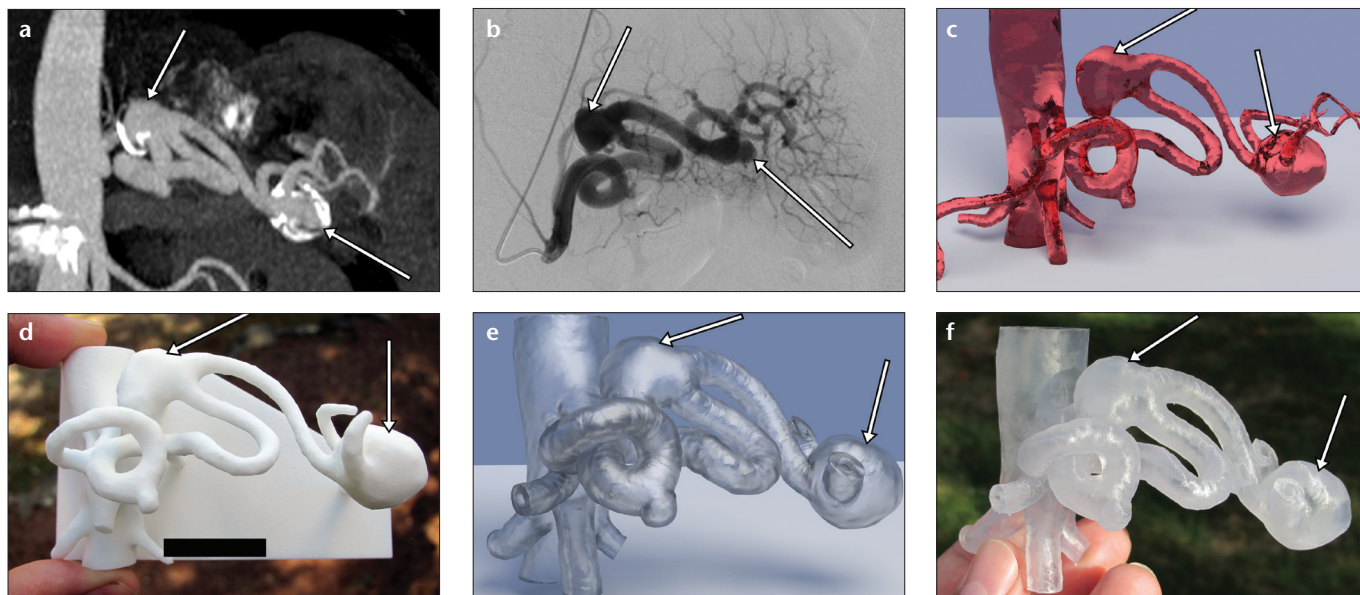


Figure 1. a-f. CT angiogram with maximum intensity projection (a), and catheter digital subtraction angiogram (b) of the splenic artery depicting the two 2 cm splenic artery aneurysms (arrows). A third, smaller 5 mm aneurysm can be seen in the proximal splenic artery. Digital rendering of the splenic artery lumen (c) and nylon 3D printed physical model of the splenic artery lumen (d) were created. A base and support structures have been added to the 3D printed physical model for additional mechanical strength. Digital rendering of the hollow splenic artery model (e), and transparent resin 3D printed physical model of the hollow splenic artery (f) were created.

Technique

To determine if 3D printed model creation was possible and whether catheters and stents could be tested in such a model, creation of an anatomically accurate hollow vascular model was attempted. Institutional Review Board approval and written informed consent from the patient were obtained. Utilizing free open-source medical image software (Osirix, version 5.8.5 for Macintosh, Osirix Foundation), axial images from the CT angiographic scan were segmented using a basic threshold segmentation algorithm, and a digital 3D surface model of the vessel lumen was created. The CT scan was acquired at 120 kV, 219 mAs, with a slice thickness of 1.5 mm. Iopamidol (Isovue-370, Bracco Diagnostics) 100 mL intravenous contrast was administered. The surface model was then exported to stereolithography (STL) file format and imported into free open-source 3D modeling software (Blender, version 2.67 for Windows, Blender Foundation). Errors in the digital mesh, such as duplicate vertices or non-manifold edges, were manually corrected. At this point a digital model of the solid vessel lumen had been created (Fig. 1c). The model was slightly

modified by adding a base and support struts to make it less fragile when printed. This was achieved by digitally creating the base and struts and merging them with the artery model using a boolean operator. To create a model that accurately represented the hollow nature of a real artery, the surface of the luminal model was digitally thickened and the space occupied by the lumen was subtracted using the solidify function in the software. This created an accurate representation of the hollow lumen of the artery (Fig. 1e). Drainage holes were digitally added to facilitate drainage of the liquid resin used during manufacture. This was also achieved using boolean operators to digitally cut the holes.

The full-size solid luminal model was then manufactured using laser sintering of white nylon (PA 2200, Electro Optical Systems) using the Internet 3D printing service Shapeways (www.shapeways.com), as shown in Fig. 1d. The full-size hollow vessel model was manufactured by a similar service, iMaterialise (www.imaterialise.com) using stereolithography and their transparent resin material (Fig. 1f). The total cost of manufacture and shipping for the two models was 50.34 and 235.03

USD, respectively. Time from online order to model receipt using standard ground shipping was 11 days and 16 days, respectively.

The procedure was then practiced on the hollow model using numerous catheter, microcatheter, and wire combinations. Although the model had not been sanded and polished to achieve maximum transparency, it was nonetheless adequately transparent to enable clear visualization of the endovascular equipment being tested. Non-sterile or expired equipment, which could not be used in humans but was suitable for testing, was donated by various equipment manufacturers. A NeuroForm cerebrovascular stent, the key element in the planned stent-assisted embolization of the distal aneurysm, was successfully deployed in the distal aneurysm of the model (Fig. 2a). A combination of catheters including a 6F 105 cm 070 Neuron guidecatheter (Penumbra), Marksman microcatheter (Covidien), and Synchro 14 wire (Stryker Neurovascular) were found to give optimal performance. It was also determined that a brachial approach was superior to a femoral approach due to more distal positioning of the guiding catheter. From a femoral ap-

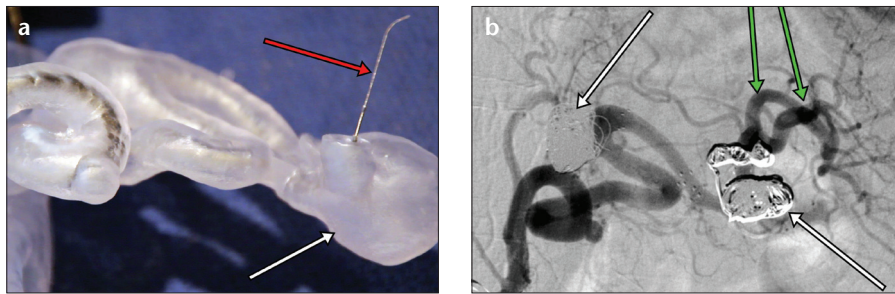


Figure 2. a, b. Preoperative testing was performed using the hollow splenic artery model. Panel (a) shows the guide catheter in the proximal model artery. The delivery wire for the NeuroForm stent (red arrow) was successfully navigated past the most distal aneurysm (white arrow) and the stent was successfully deployed in the model. Five-month follow-up angiogram (b) shows the coil-filled aneurysms (white arrows) with no detectable internal blood flow. The distal branches of the splenic artery (green arrows) are preserved and have normal blood flow.

proach the guiding catheter had difficulty navigating the acute angle at the celiac artery origin and could not be advanced deeply into the celiac artery. After adequate equipment testing with the model, the actual two-stage procedure was performed on the patient using the optimal equipment combination as determined by testing. In the first stage, the distal-most 2 cm aneurysm was treated with stent-assisted coiling after deployment of a 4.5×30 mm Neuroform stent (Stryker Neurovascular). During the procedure, the solid luminal model was used to determine the best angiographic angles for optimal visualization of relevant structures. Because each angiogram was optimally oriented, repeat angiograms were avoided, saving both time and intravenous contrast. The first stage was followed by the treatment of the proximal 2 cm aneurysm one month later using a balloon assisted aneurysm coiling technique. The equipment used during both procedures performed as predicted in preoperative model tests. Five-month follow-up angiography revealed complete treatment of the aneurysms while preserving adequate blood flow to the spleen (Fig. 2b). One year follow-up CT showed persistent occlusion and stable size of the treated aneurysms with preserved blood flow to the spleen.

Discussion

3D printing, or additive manufacturing, was first described in the early 1980s (4). This manufacturing process is unique because an object is built up layer by layer rather than being cut from a larger block of material, as is

done using subtractive manufacturing techniques like machining. For the past three decades, use of 3D printing has been mainly limited to engineering and prototyping applications, primarily due to the high cost of 3D printers and required software. Recently, the cost of printers and software has declined and availability of 3D printing services has increased, allowing the applications for 3D printing to grow (5).

To date, 3D printing applications in medicine have been limited but are expanding. 3D printed models have been used for surgical training and education (6), creation of custom airway implants (7), surgical planning for congenital heart disease (8, 9), and for aortic aneurysm repair (1). Unfortunately, these applications used proprietary software (1, 7, 8) or expensive on-site printers and printing services (6–9).

Individuals outside of research institutions are unlikely to have access to such resources. The recent availability of free, open-source software and online Internet 3D printing service bureaus makes 3D printing available to ordinary health professionals, hospitals, clinics, and even laypeople. Osirix is a free, open-source picture archiving and communication system and digital imaging and communications in medicine viewer for the Macintosh operating system (10). The basic version can be downloaded and used for free. Osirix has the ability to create a digital 3D surface model from a medical scan. It is possible for the digital model to be exported into an STL file format, a format commonly used in computer aided design engineering software. Once

in this format, the data can be manipulated with a variety of nonmedical software packages.

Blender is an open-source 3D computer graphics software program that is primarily used for computer animation. It is free to download and use, and is available for Windows, Macintosh, and UNIX operating systems (11). Once the STL file is imported into Blender, the software can be used to correct errors in the model, such as imaging artifacts, and prepare the digital model for 3D printing. It is at this stage that modifications can be made. For instance, support structures can be added to the model to improve its physical strength when printed.

The recent growth of Internet-based 3D printing services such as Shapeways, iMaterialise, and Ponoko, brings 3D printing within reach of ordinary individuals via the Internet. Physical access to an expensive 3D printer is no longer required. Now it is possible to upload a digital file to the printing service's website. The file is then 3D printed and shipped to the user. These 3D printing companies make use of economies of scale to keep prices as low as possible. Automated software checks models for design errors and provides feedback. Once a model is designed, it can be printed in an ever-increasing variety of materials. For many purposes inexpensive plastics can be used. But for specialized applications, transparent plastic, rubber, bronze, stainless steel, titanium, silver, and even 14 karat gold are available (12, 13). Of course, it is also possible to use an in-house 3D printer to print 3D models. The main advantage of this approach is rapid turn-around. Models can typically be manufactured within 12 hours, much faster than can be obtained using online procurement. The major disadvantage is expense. High quality 3D printers can cost more than 30,000 USD. A single in-house printer may also quickly become obsolete, whereas online printing services constantly update their print quality, material selections, and types of available printers.

Complex endovascular interventions are often approached with operator experience as the primary guide for

selection of appropriate catheters and guidewires. CT or MRI angiography have proven to be useful adjunctive technologies, giving the interventionalist detailed anatomic understanding for procedural planning (14). However, anatomic understanding alone does not predict the behavior of catheters and wires during a procedure. Variables like torquability, rigidity, size, and curvature are important considerations in equipment selection. Operator experience and in-procedure trial and error have been the primary means with which optimal catheter and wire combinations have been determined. The use of patient-specific 3D printed vascular models may help to eliminate this uncertainty. By preoperatively testing catheters and wires in a full-scale anatomically-accurate vascular model, equipment performance in the patient's unique anatomy can be evaluated in a controlled environment. Optimal equipment combinations can be determined ahead of time, thus minimizing the need for intraprocedural trial and error, reducing procedure time, and increasing the chance of procedural success, as was illustrated in this case.

There are limitations to this technique. 3D printed models may not have the same softness, resistance,

wall fragility, and endovascular flow of a real arterial system, and these limitations should be considered during testing.

In conclusion, direct creation of 3D printed small vessel models is possible. Models are useful for preoperative planning and intraoperative guidance. Creation of anatomically accurate 3D printed vascular models is now feasible and affordable due to low-cost Internet 3D printing services and free and easily obtainable design software.

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Conflict of interest disclosure

The author declared no conflicts of interest.

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