Feasibility of 3D Printing Full Endovascular Models for Planning Image-Guided Neuro-Vascular Treatments

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ABSTRACT
The purpose of this study is to evaluate the feasibility of using 3D printed patient phantoms of patient vasculature in order to increase the benefits of endovascular therapies through treatment planning and reduce the high costs of device development. We used de-identified Computerized Tomographic Angiography (CTA) data from stroke patients and segmented vessel geometries as stereolithography (STL) files using a Toshiba Vitrea 3D station. Mesh-editing software and a 3D printer were used to generate the individual structures. A full vascular model of the endovascular treatment process was manufactured using CTA image data from the Circle of Willis, coronary arteries, aorta, and femoral arteries. Endovascular interventionalists have reported positive feedback about the full model’s similarity to patients after performing mock procedures. Full vascular replicas of patient-specific vascular anatomy allow interventionalists the ability to efficiently train and determine treatment solutions, such as stents orcoiling, before operating on patients with complex vascular anatomicies.

METHODS & MATERIALS

Geometry Acquisition
The desired vessel anatomy data is taken from 3D reconstructed CT, MRI, and CBCT volumes of patients from an ongoing stroke study. The reconstructed volumes are edited using Toshiba Vitrea software, which is used to manually segment vessel geometries, remove bone and tissue, and export the geometry as a high-definition stereolithography (STL) file.

Vessel Manipulation
MeshMixer, a mesh-manipulation software, is used to smooth inconsistencies of the continuous vessel surface, to alter the number of inlets and outlets, wall thickness and vessel diameters, and to add support and connecting structures.

3D Printing
The STL file of each vessel segment is printed using a Stratasys Objet Eden 260V, a high resolution 3D printer. Specifications for each model include:
- Technology: Inkjet, stereolithography (photo-solidification)
- Resolution: <32 μm in the z-axis, >200 μm in the xy-plane
- Volume: 255 x 252 x 200 mm
- Material: TangoPlus – A semi-transparent and elastic photopolymer resin
- Support: SUP705 – A water-soluble, acrylic photopolymer

RESULTS

Phantom Testing
The assembled full model contains the major vascular structures commonly involved in cardiovascular and neurovascular surgeries. Several printed phantoms connected together better simulate the traversal of a catheter from the femoral arteries to the treatment site. CBCT Imaging is used to analyze the accuracy of the phantoms, observe the flow through the vessels, and test endovascular devices.

Phantom Manufacturing
The full model is printed with a uniform 2.0 mm thickness. This provides the most accurate structural properties compared to actual arteries. Failures in the structure during mock procedures indicate possible perforations that could occur under the same catheter pressure within a patient.

The major vascular segments include:
- Left and right external iliac arteries
- Abdominal Aorta
- Descending Thoracic Aorta
- Aortic Arch, including the subclavian, brachiocephalic, and carotid arteries
- Coronary Arteries (not shown)
- Circle of Willis, including the carotid and vertebral arteries

Additional Features for Clinical Testing
- To make mock interventional procedures more realistic, several segments of patient-specific vasculature were printed to model the navigation of a catheter from the femoral artery to the treatment site.
- A Circle of Willis phantom with five aneurysms at different locations with different geometries was printed for use as an extensive training tool.
- Geometry of the model in MeshMixer. Middle – 3D printed model of TangoPlus. Right – Digital subtraction angiography (DSA) of the 3D printed model injected with contrast to measure patient-to-phantom accuracy

CONCLUSIONS
There is a need for safer and more reliable vascular procedures than the results of conventional open surgeries currently provide. Endovascular interventions provide this security, but accrue higher financial costs from research and device development. Patient-specific vascular phantoms provide a standardized experimental platform for device-testing trials, and can be used for familiarizing physicians with complex patient anatomies to anticipate changes in therapies, preoperatively. This may shorten the duration of the procedure, which will reduce the patient’s cost, as well as reduce the risk of thrombotic events, preprocedural complications, and the number of devices wasted on failed attempts. Patient-specific phantoms were successfully used in mock, image-guided endovascular procedures with positive feedback from multiple interventionists. They are a versatile and powerful tool, and offer a unique learning opportunity for neurosurgeons, their successors, and the endovascular field.

ACKNOWLEDGMENTS
Portions of this on-going research has been made possible as a result of funding from the following sources:
- NIH Grant R01-EB002873
- CURCA Student Grant

Procedural Phantom Results
The patient-specific phantom segments were successfully implemented in diverse mock procedures, including cloting retrieval methods, device development, and angiographic image acquisition.

Aneurysm Coiling Example: (a) A fluoroscopic snapshot of the initial part of the procedure. (b) Detail of the micro-catheter placed in the aneurysm. (c) Final fluoroscopic snapshot of a coil mass placed in the aneurysm dome. (d) DSA showing initial arrival of the bolus contrast.

Asymmetric Flow Diverter: A deployment study was performed using the new aneurysm phantom. The purpose of this treatment was to reduce blood flow in an aneurysm, but not in the anterior communicating artery. By examinating bolus arrival time in pre- vs. post-treatment DSA runs, the change in flow to the treated region can be seen.

Cardiac Phantom Example: A coronary phantom was used to acquire angiographic images to verify vessel patency and accuracy. A catheter was inserted through the aortic arch and contrast was deployed. (a) Result of averaged DSA sequence. (b) Sequence of DSA frames showing contrast flow. A cardiac phantom diversifies the suite of phantoms, which can be applied to a wider range of cardiovascular interventions.