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Technical Note

Prototyping of cerebral vasculature physical models

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Abstract

Background: Prototyping of cerebral vasculature models through stereolithographic methods have the ability to accurately depict the 3D structures of complicated aneurysms with high accuracy. We describe the method to manufacture such a model and review some of its uses in the context of treatment planning, research, and surgical training.

Methods: We prospectively used the data from the rotational angiography of a 40-year-old female who presented with an unruptured right paraclinoid aneurysm. The 3D virtual model was then converted to a physical life-sized model.

Results: The model constructed was shown to be a very accurate depiction of the aneurysm and its associated vasculature. It was found to be useful, among other things, for surgical training and as a patient education tool.

Conclusion: With improving and more widespread printing options, these models have the potential to become an important part of research and training modalities.

Key Words: Cerebral aneurysm, physical model, rapid prototyping, stereolithographic methods, training tool, 3D modeling

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INTRODUCTION

The treatment of complicated cerebral vascular lesions, such as aneurysms, poses a challenge due their intricate anatomy. Over the past few decades, improving diagnostic imaging techniques have made it easier to determine the 3D structure of the aneurysm with its associated microvascular anatomy. While these virtual 3D depictions of the cerebral vasculature allow a good visualization of the aneurysm, there remain concerns regarding the interpretation of the actual image and the underlying anatomical structures.[13] Accurate physical 3D models of the aneurysm can counter this issue by providing tactile view of the aneurysm and its associated vasculature that can be scrutinized from any perspective.[12,13]

Historically, various milling methods have been used to carve out 3D models but these methods lack accuracy when faced with very fine structures and overhanging features.[10] The recent development of stereolithography (SL), a rapid prototyping method with the ability to accurately model highly complicated structures, is a step forward in developing human cerebral vasculature models. In this article, we will discuss the techniques used to prototype cerebral vasculature physical models and review the utility of these to various aspects of treatment planning, training, and patient and family education.

TECHNIQUE

For the purpose of a 3D aneurysm model production, we prospectively used the data of a 40-year-old female who presented new-onset headache. Angiography revealed a 4 mm right paraclinoid aneurysm [Figure 1]. Radiographic images were captured on a Philips Medical Systems Allura Xper FD20/20 system and viewed in the Philips 3D-RA Rotational Scan software on a clinical workstation. The proprietary software will create surface models of vasculature based on digital subtraction of noncontrast from contrast images. The vasculature surface model was edited at the clinical workstation to remove rendering artifacts and crop any unwanted vessels from the model. This edited file was exported in a PC-ready Virtual Reality Modeling Language (VRML) format onto an external storage device to be transferred to another nonworkstation computer for further analysis.

On the nonworkstation computer, the VRML file was imported into MeshLab, a free, open-source program for displaying and editing mesh-based graphics. Gaps in the rendered surface model were then filled by applying an existing editing function in MeshLab, and the file was converted to the SL format (file extension: *.stl).

To review the model before printing, the SL file was imported into STLView, a free program distributed by ModuleWorks, GmbH. The SL file was then sent to a local rapid prototyping business, and physical models were printed on a Stratasys Objet 500 Connex (Stratasys Ltd, Minnesota USA). This machine can print two materials at one time allowing someone to print a rigid model with a rubber over mold at the same time. The parts were printed with an encapsulation of support material that was washed away, and then dyed red to mimic tissue. The material used to construct the blood vessels and aneurysm is called Tango+ - a clear rubber material with a shore value of 27. The resolution of the printer was set at 30-micron (0.03 mm) layer levels for the model.

Images from each stage of the prototyping process are shown in Figure 2. As shown, the model is a very accurate representation of the aneurysm and superior to traditional images alone. Neurosurgical trainees also found the 3D physical model to be very helpful in understanding the anatomy of the aneurysm (dome size, orientation, and neck size) and the associated vascular structures from every angle [Video 1]. An informal survey from neurosurgeons showed that most felt a model of this nature could be helpful in judging the best surgical approach and selection of the best clip. It was also thought to have potential as a counseling and educational device for patients and their families.

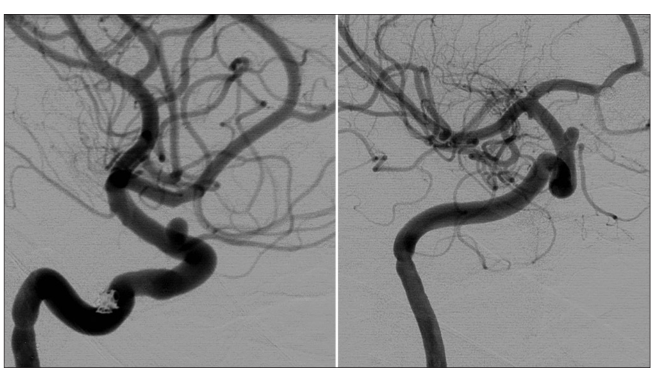

Figure 1: Noncontrasted CT image as displayed in the Philips 3D-RA Rotational Scan software on the clinical workstation

DISCUSSION

The term "stereolithography" was coined in 1986 by Charles Hull, who patented it as a method and apparatus for making solid objects by successively "printing" thin layers of an ultraviolet curable material one on top of the other to form a 3D structure.[3] Originally used for the aerospace industry, the SL manufacturing process was first used by Mankovich and colleagues to replicate human anatomy.[5] Since then the technology has been used in various surgical fields such as craniofacial,[9,13] orthopedic,[6] and cerebrovascular surgery.[1,2,11]

D'Urso and colleagues were the first to use this technology to model cerebral aneurysms by using 3D computed tomography (CT) and/or magnetic

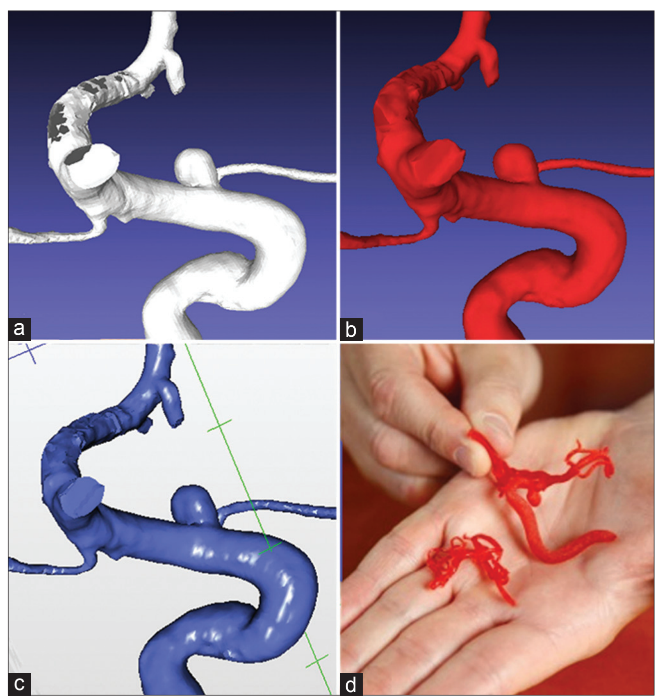

Figure 2: (a) Virtual Reality Modeling Language (VRML) file displayed in MeshLab. Note that areas of gray discoloration are gaps in the mesh rendering of the model. These gaps were filled using built-in functionality of MeshLab. (b) Stereolithography file created from the VRML file after filling mesh gaps. (c) Stereolithography file as rendered in STLView prior to printing. (d) Physical model printed in Tango+

resonance (MR) angiograms.[1] Wurm and colleagues further refined this technique by using 3D rotational angiography (higher resolution of images compared with 3D CT or MR angiographies) to manufacture their models.[13] Additionally, improved postprocessing techniques and newer generation printers (with thinner slices) have contributed to increasing the accuracy of the model. The development and increasing availability of end-user desktop 3D printers, to allow for more rapid prototyping, signify an important development in this regard as well.

One of the major advantages of having a physical model of the aneurysm is the opportunity to plan a surgical procedure.[1,13] The anatomy of the parent vessel, aneurysm orientation, dome size and neck, and the associated vascular structures can be clearly seen from all angles. This helps in planning the surgery with regard to the approach, selection of the best clip, and techniques used to clip the aneurysm.[4] Additionally the presence of a sterilized model inside the operating room (OR) would also be beneficial as it may act as a reference for surgeons during the surgical procedure itself.

Complicated aneurysm clipping is a challenging procedure that can only be mastered under the guidance of a seasoned surgeon. However, the number of clipped aneurysms has been steadily decreasing with only the most complicated aneurysms being selected for surgical management.[7] These factors make training upcoming surgeons more and more challenging. A physical life-sized 3D model has the ability to fill this void to some extent. Surgical trainees can get familiar with the complicated structure of the aneurysm and its associated vessels and practice various techniques of clipping.[4] Having a library of these models, made from the data of various patients, can serve as a valuable teaching resource for trainees.

While the model can be used to plan the surgery, the act of clipping the model aneurysm itself may not be representative of actual clipping of the aneurysm if the resin used is very rigid.[13] Kimura and colleagues addressed this issue by using 3D hollow models made of elastic silicon to simulate clipping preoperatively.[4] They found that simulation of clipping using these models preoperatively helped them to easily identify the complex anatomy of the aneurysm and parent vessel during the actual surgery.[4]

Another limitation of these models lies in the fact that their surface represents the intraluminal surface of the aneurysm and its surrounding vessels rather than the outside surfaces that are seen during microsurgical exposures. The exclusion of the arterial wall can potentially mislead regarding of the true origins and courses of the adjacent arteries on relation to the aneurysm neck and dome in terms of proper placement of clip(s). The concomitant reconstruction of the bony anatomy in the region of the diseased vasculature can further help in surgical planning with regards to head positioning during the surgery.

SL aneurysm modeling can also be used for coiling considerations. Wetzel and colleagues used the lost-wax technique to form a tubular model from the original wax SL aneurysm model.[12] The model was then connected to a circulatory pump to use for simulation of endovascular procedures. A silicon tubular model thus formed was shown to be helpful in simulation of endovascular procedures but had a major drawback of relatively higher surface friction compared with *in vivo* catheterization, which limited the impression of a realistic procedure.[12] Ohta and colleagues addressed this issue by using poly-vinyl alcohol hydrogel (PVA-H) to build an *in vitro* aneurysm with low surface friction.[8] PVA-H stiffness was found to be closer to soft tissue when compared with silicon and allowed for pulsations during flow simulations.[8] A realistic model thus has the potential to be used not only as a training tool, but also as a means to test new and emerging endovascular techniques.

These models can also be used for patient education and counseling. According to an informal survey by Wurm and colleagues, patient and family understanding of the complex disease condition was increased with the use of these models.[13] This helped in the disclosure of treatment options available and their concomitant risks.

While there are multiple advantages of accurate physical prototypes of aneurysms, there remain a few limitations and challenges for the future. Due to the imaging processing techniques, the model does not have the ability to demonstrate the presence or extent of an intraarterial thrombus and the aneurysm wall thickness. The other disadvantage is the time it takes to manufacture and ship such a model (in the magnitude of days), making it impractical for patients presenting with ruptured aneurysms. With the increasing availability of desktop 3D printers, however, it is possible to manufacture these models much quicker (in the magnitude of hours). Improving techniques and printing technology will make manufacturing these models even quicker and, in the future, viable for the management of patients who require urgent intervention.

CONCLUSION

We described the technical details behind the production of 3D physical SL aneurysm models. These models can be used to help in various aspects of treatment planning, biomedical research, patient education, and training. With improving and more widespread printing options, these models have the potential to become an important part of research and training modalities.

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