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High-precision, patient-specific 3D printed models of brain aneurysms for training and therapy planning in interventional neuroradiology

H. Schwenke[1*], A. Kemmling[1,2], and P. Schramm[1]

[1] *Department of Neuroradiology, University Hospital Schleswig-Holstein, Lübeck, Germany.*
[2] *Department of Neurology, University Hospital Münster, Münster, Germany.*
[*] *Corresponding author, email: hannes.schwenke@uksh.de*

Abstract: Endovascular treatment of complex intracranial aneurysms is challenging because the configuration of each aneurysm is unique. Using 3D printing, the individual anatomy of the aneurysm can be reproduced with high precision, allowing a deep understanding of the diseased vessel. Here we present a method for the high-resolution and patient-specific production of 3D models of brain aneurysms using stereolithography 3D printing techniques.

I. Introduction

Brain hemorrhages caused by ruptures of untreated aneurysms are often fatal or lead to severe disabilities [1]. Incidental cerebral aneurysms with a high risk of bleeding therefore require embolization, which is increasingly performed via endovascular procedures [2]. Complexly configured aneurysms require particularly careful treatment planning because each aneurysm configuration is unique, and the different endovascular treatment methods are specific to each patient's aneurysm shape. Currently, treatment planning is based on diagnostic imaging using three-dimensional (3D) digital subtraction angiography and time-resolved two-dimensional (2D) angiography to select the most appropriate type and size of devices. Since each aneurysm is different for each patient, uncertainty remains as to how the devices will behave, especially with variable expertise from interventionalists. This is particularly relevant for complex shaped large aneurysms with a wide neck where full embolization is difficult.

In order to improve endovascular training, therapy planning and to minimize the individual error rate, aneurysms can be replicated as anatomically accurate 3D printed models [3, 4, 5]. To best visualize the anatomy and to allow procedure rehearsal, the models should be transparent and map very small arteries so that the exact simulation of patient treatment and device use is possible. In addition, the models must be hollow to allow the simulation of endovascular procedures. Two main goals can be achieved with the 3D printed models. First, teaching and further training through repeated treatment training of complex aneurysms. Second, patient-specific treatment planning, whereby the embolization of complex aneurysms can be simulated with stent remodelling or flow diverters.

Here we present a method in the evaluation phase to produce 3D printed models of brain aneurysms using a low-cost stereolithographic method with short production times, making it suitable for upscaling to a high number of cases. For demonstration purposes, two 3D printed models were selected to illustrate the production process and to demonstrate clinical applicability.

II. Material and methods

3D clinical rotational angiography data for both models were acquired using an Allura Xper FD 20/20 angiography system (Philips Healthcare, Best, Netherlands) with the following acquisition parameters: 5-second acquisition, 220° rotation, 150 individual images at a frame rate of 30/s, 15 to 48 cm detector FOV, 512 acquisition matrix. The images were reconstructed with a soft tissue kernel of isotropic voxel size (edge length range 0.1 - 0.3 mm).

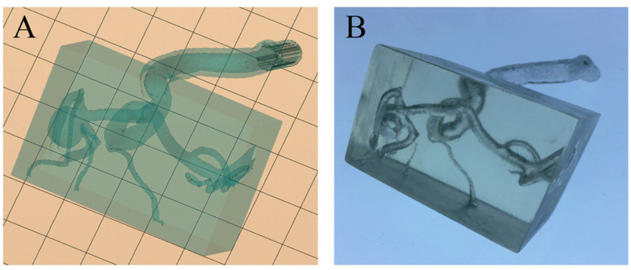

Figure 1: A) Simulated 3D model of a brain aneurysm. B) 3D model after printing and post-processing.

Segmentation of brain arteries was performed using Analyze Pro 1.0 (AnalyzeDirect, Overland Park, Kansas, USA), while a semi-automated approach using a region growth algorithm was applied. For this purpose seed areas were defined at different points in the vessels. Small perforator arteries were removed if the diameter was less than half that of an angiographic microwire (< 0.15 mm). The segmented anatomies were converted to .stl format and imported into NetFabb Premium 2019.2 (Autodesk, San Rafael, California, USA). The .stl file was repaired using the automatic repair function implemented in NetFabb Premium.

A cuboid box in .stl format was designed to enclose the target volume of the anatomy and the parts were merged. Enclosing the blood vessels with a box allows even very small blood vessels to be printed without supporting material, which in turn makes post-processing of the model much easier. In addition, the box provides stability for the smallest blood vessels and ensures excellent visibility of the blood vessels, even for camera assisted simulations. A standardized adapter was attached to the opening of the proximal carotid artery to connect the model to a vascular flow model (*see Fig. 1A*).

The data were exported to PreForm 3.0.1 (Formlabs Inc., Somerville, Massachusetts, USA) and the support material was digitally attached. Printing was performed on a Form 2 stereolithography printer (Formlabs Inc.) using a 25 micron layer length and clear photopolymer resin (Formlabs Inc.). After the printing process, the post-processing steps wash-out, drying, post-curing with UV light and surface polishing were performed (*see Fig. 1B*).

In a clinical example, a p64 flow diverter (Phenox, Bochum, Germany) was planned for the treatment of a broad-based intradural aneurysm of the left carotid artery. A high-precision 3D model of the aneurysm was used to select and test the appropriate size of the device (*see Fig. 2A*). The next step was the therapy of the aneurysm with the selected materials (*see Fig. 2B, C*).

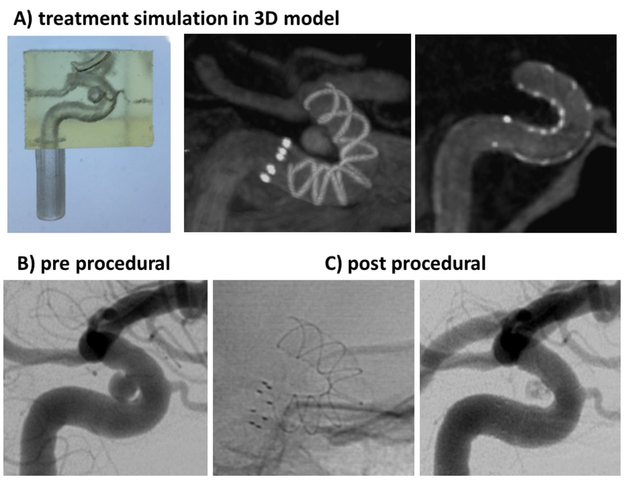

Figure 2: A) Treatment simulation of an aneurysm of the left carotid artery using a p64 flow diverter in a 3D printed model. B) Pre-procedural images and C) Post-procedural images in a clinical setting using the same device.

III. Results and discussion

The production of the 3D printed model currently took approximately 10 hours, including approximately 2 hours for segmentation, approximately 8 hours for printing and 1 hour for post-processing. In addition, 6 hours for isopropanol and clear coat drying times, where the application of clear coat is not necessary for fluoroscopy but rather for longer preservation and camera visualization.

Unlike previous manufacturing processes for 3D printed models of brain arteries [3, 4, 5], the special design of our models in a block allows a very fast production time by reducing the number of manual work steps. A complex planning and removal of support material is not necessary. In addition, a very fast exchange of the models can take place via standardized adapters, with which different scenarios in clinical training can be simulated quickly.

Furthermore, patient-specific therapy planning is possible, whereby a device to be implanted in the patient can be implanted in advance into a patient-specific 3D model by the neuroradiologist. Anatomical properties of the aneurysm can thus be evaluated directly and included in therapy planning via direct haptic feedback. If the decision for a specific device is made solely based on the intervention experience in the model, which is not the case in current practice, further evaluations must be carried out regarding to safety and material properties of the 3D printed models.

IV. Conclusions

Treatment of complex brain aneurysms requires great expertise in dealing with various treatment methods, but the handling of the devices in a complicated aneurysm configuration is challenging even for experts. Great expertise in interventional neuroradiology is achieved by repeated training, while the first steps and all basics should taking place as far as possible outside the patient.

With our method, high-resolution 3D printed models of cerebral aneurysm can be produced using rapid prototyping to enable patient-specific treatment simulation of brain aneurysms. The focus here is on rapid manufacturability, reproducibility, low material costs and portability. The method allows patients to benefit from the optimal choice of devices for brain aneurysm treatment, increased confidence of the treating physician and reduced risk of endovascular surgery. Training in animal models can also be avoided.

Author's statement

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