Transactions on Additive Manufacturing Meets Medicine
Trans. AMMM, 2024, Vol. 6, No 1, Article ID 1784, 4 Pages

Infinite Science Publishing

Original Research Article

Developing and Testing of a 3D Printed Middle Meningeal Artery Model for Training in Interventional Neuroradiology

E. Sobirey[1*], J. Schmiech[1], M. Wegner[1], F. Flottmann[2], M. Bechstein2, M. Jungnitz[2], M. Oertel[2], J. Fiehler [2], and D. Krause[1]

[1] *Institute of Product Development and Mechanical Engineering Design, Hamburg University of Technology, Germany*
[2] *Department of Diagnostic and Interventional Neuroradiology, University Medical Center Hamburg-Eppendorf (UKE), Germany*
[*] *Corresponding author, email: eve.sobirey@tuhh.de*

Abstract: Through technical progress and the further development of smaller and more navigable treatment instruments, it is now possible to treat small peripheral vascular diseases with a diameter of less than 2 mm, such as chronic subdural hematom caused by the middle meningeal artery, with neurointerventional procedures. These procedures are technically very difficult and require systematic learning by the physicians. This paper describes the development and manufacturing of a first middle meningeal artery model for the treatment simulation of chronic subdural hematoma, which is to be integrated into the existing neurointerventional simulator HANNES. The first 3D printed model enables learning and training in catheterization the small vessels.

I. Introduction

In neurointerventional procedures, diseased blood vessels in the brain are localized and treated with a catheter that is inserted into the artery under X-ray control and navigated through the vessels [1, 2]. As a result of technical progress and the further development of smaller and more navigable treatment instruments, the treatment of small peripheral vascular diseases with a diameter less than 2 mm is now also possible [3]. One of the diseases that can be treated using the new neurointerventional treatment methods is chronic subdural hematoma (cSDH). An cSDH is a hemorrhage, which is an encapsulated collection of fluid, blood and blood degradation products in the subdural space, a space between the hard and soft meninges [4]. A widely used treatment for cSDH is burr hole trepanation or craniotomy that targets hematoma evacuation, which is performed in an operation to open the skull and aspirate the blood [5, 6, 7]. This procedure has a recurrence rate of up to 37 % [5]. One cause of the recurrence of the hemorrhage is the feeding of the meninges with blood through the peripheral vessels of the middle meningeal artery (MMA) (see Figure 1) [4]. In neurointerventional procedures, the MMA is sealed using an embolization agent, stopping the bleeding from the inside [5, 7]. MMA embolization can be used as a combination procedure and, in selected patients, also as a primary treatment procedure. In both cases, the method reduces the recurrence rate significantly [5].

Figure 1: Digital subtraction angiography image of a MMA highlighted by red arrows.

As this treatment method is a relatively new treatment concept, there is a need for systematic learning of the

techniques and continuous training of the treating physicians. The treatment simulation of MMA embolization has so far been carried out in animal experiments, which have disadvantages such as ethical aspects or the artificial causation of the disease [8, 9]. This results in the need to develop an in vitro model that enables physicians to carry out continuous training in MMA embolization without the aforementioned disadvantages of the animal models. The aim of this work is the development of a first 3D printed MMA model for integration into an already existing simulation model for neurointerventional procedures of larger vessels such as strokes or aneurysms (Hamburg ANatomical Neuro-interventional Simulator - HANNES) [10, 11]. A realistic blood pressure is simulated using a fluid system with adjustable temperature, adjustable pulse and adjustable volume flow. The individual patient-based vascular models integrated into the simulation model have a modular structure, can be easily exchanged and enable an edge-free connection using standardized connectors.

II. Design and manufacturing of the MMA model

The development of the MMA model was performed based on the standard VDI 2221 the standardized process flow of Spallek et al for the development of vessel models from image acquisition to design and manufacturing [12]. The requirements agreed with physicians are shown in Table 1.

Important requirements were agreed upon, which differ from the development of the existing vessel models and properties. The MMA model will be manufactured using the printing processes and materials in use for HANNES and already defined properties such as hollowness, freedom from edges and a smooth surface. As it is difficult to print models with a diameter of less than 2 mm using this method [13], an MMA model with a larger diameter is first manufactured. In addition, certain anatomical characteristics such as the foramen spinosum, which is specific to the course of the MMA in the body and is visible as a strong curve, are to be replicated. An important requirement is the subdivision of the MMA model into modular vessel segments so that only single segments and not the entire model are destroyed by the adhesion during a subsequent treatment simulation using embolization. For the first draft of the MMA model, the developed skull model with the corresponding skull base for the simulator HANNES [11], could not be used, as this allows the integration of brain vessels in the center of the skull and not in the skull periphery. According to the standardized process flow, image data of a patient using computer tomography (CT) was first acquired and then the relevant vessels for the model were segmented using a segmentation software (Seg3D, NIH Center for Integrative Biomedical Computing at the University of Utah, USA).

Table 1: Extract from the list of requirements for the MMA model.

Description of requirement	Type of requirement
Geometric requirement	
Hollow structure	demand
Ensure flow	demand
Patient-like geometries	demand
Vessel diameter (> 2 mm)	demand
Foramen spinosum mapping	demand
Smooth inner surface	demand
Edge-free inner vessel contour	demand
Tightness of the vessel model	demand
Modular vascular segments	demand
Manufacturing	
Use Form 3	demand
Material-requirements	
Use Flexible 80A	demand
User-specific requirements	
Integration in HANNES fluid system	demand
General requirements	
Simple, quick replacement	wish
Fixture for the vessel model	demand
Integration in HANNES skull model	wish

The segmented MMA model was saved in an STL file (Standard Triangulation Language) for further processing (see Figure 2a). The segmented image data is finally used to design a hollow MMA vessel model in the CAD program CATIA (Dassault Systèmes, Somerville, Vélizy Villacoublay, France). In this process step, the individual segments of the model are defined and connectors for connecting the segments and subsequent integration into the HANNES model are designed. Figure 2b shows the finished MMA model with the different segments and the skull base. The three individual segments of the model were finally printed out of Flexible 80A material using the stereolithography (SLA) printer Form 3 (Formlabs Inc., Somerville, Massachusetts, USA). To complete the manufacturing process, the model was post-processed and the support structures were removed. For post-processing, the model was washed in isopropanol according to the manufacturer's instructions and finally cured under UV light.

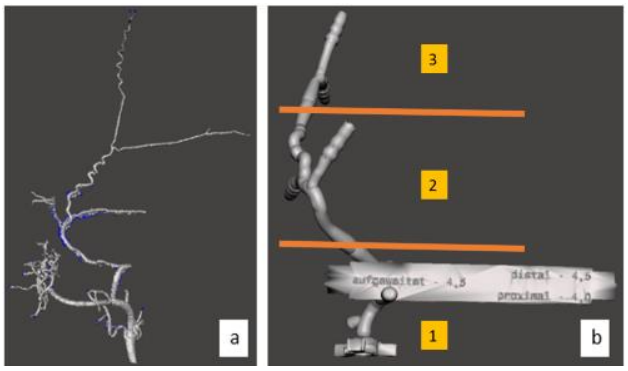
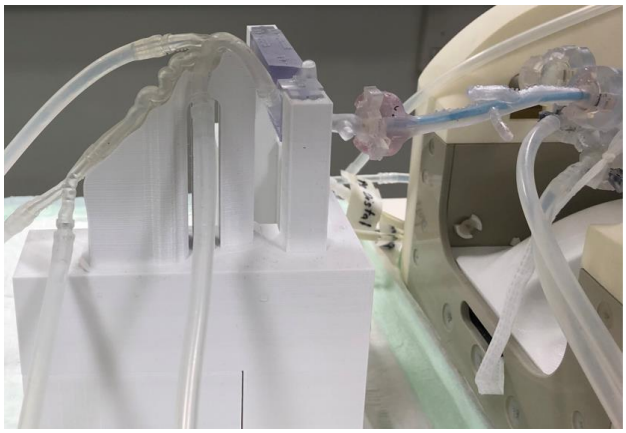


Figure 2: Visualization of the MMA in a) segmented patient data and b) reconstructed MMA model divided into different segments with the skull base.

III. Results and discussion

In order to evaluate the developed MMA model, it was tested by physicians at the University Medical Center Hamburg-Eppendorf (UKE). For this purpose, a treatment simulation of an SDH without embolization was performed with original instruments in a real surgical environment. Afterwards, the physicians' feedback was obtained and the model was evaluated for the defined requirements. To verify the result of the first concept of an MMA model with an increased diameter, the model was connected to the vessel tree of the simulator. As already mentioned, the skull of the simulation model could not be used as a base, so an additional holder for the skull base and the MMA model was produced using the Fused Deposition Modeling (FDM) printer Anycubic i3 Mega (Anycubic, Shenzhen, China). Figure 3 shows the integration of the MMA model and the holder to the simulator HANNES.



***F**igure 3: Integration of the MMA model with holder into the existing vessel tree of the simulator HANNES*

The integration of the new model was very simple due to the use of the already existing and standardizes connectors. The physicians simulated a SDH treatment to investigate the MMA model. The catheter was navigated through the existing vascular tree into the area of the MMA using X-ray. The catheterization of the MMA model was detected using digital subtraction angiography (DSA). For this purpose, a contrast agent was injected into the simulation model. The DSA image of the model and the catheterization is shown in Figure 4.

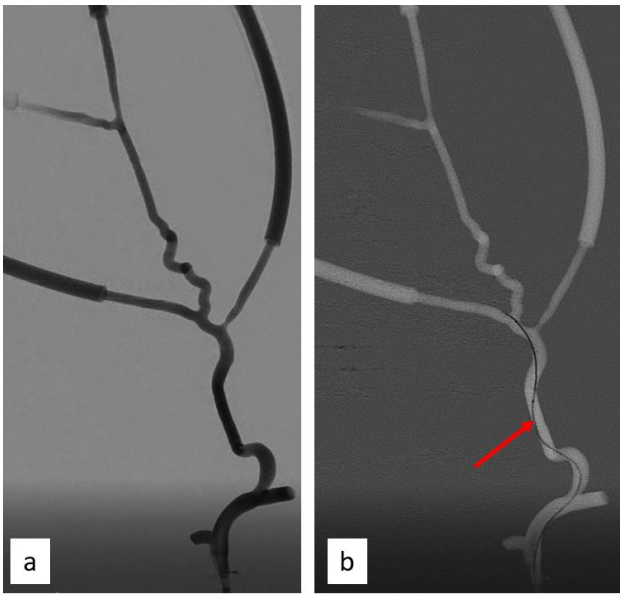


Figure 4: DSA X-ray image of a) MMA model and b) catheterisation of the model with a micro catheter highlighted by a red arrow.

The MMA model allowed a continuous flow and showed no leakage. Catheterization of the entire MMA model was possible and showed a smooth internal structure and no inner edges, according to the executing physicians. The replication of the foramen spinosum was rated particularly positively, as this is comparable to a human patient and serves as a landmark for the physicians in the MMA.

The patient-like geometry in the other areas of the MMA was rated acceptable, as the connecting adapters of the individual segments result in an unnaturally long and straight path. The first design of the MMA model fulfilled all the requirements defined at the beginning.

Only the requirement for patient-like geometry, which was impaired by the modularity, has to be modified. In consultation with the physicians, the division of the MMA model into 2 segments is sufficient. Segments 1 and 2 should be combined to prevent the unnatural lengthening caused by the connectors. The third segment should be retained so that only a part of the model and not the entire model has to be replaced in the case of embolization.

IV. Conclusions

In order to learn new treatment methods for small vascular diseases such as SDH and the associated MMA embolization, a first 3D printed MMA model was developed for integration into the HANNES simulator. The model was developed using patient data. In this case, the diameter was enlarged, due to the challenges of manufacturing small hollow structures with the printer and material already used for other HANNES vessel models. The model can be used to learn how to navigate a catheter into the MMA. In further studies, the suitability of different

materials and printing processes for the manufacturing of an MMA model with anatomically correct vessel diameters of less than 2 mm should be investigated in order to replicate a realistic model. In addition, not only the catheterization ability but also the treatment by embolization should be mapped. Tests are needed for this, as on the one hand the behaviour of the embolic agent outside the body must be analysed. On the other hand, investigations should be carried out into how disadvantageous the embolic agent is for the simulation model and the fluid system used.

ACKNOWLEDGMENTS

The authors would like to thank the Federal Ministry of Education and Research – BMBF for funding the project MONTYPIE (FKZ: 16LW0301K).

AUTHOR'S STATEMENT

The authors state no conflict of interest. No animal experiments were carried out. Consent was obtained from all persons involved in this study. The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

REFERENCES

[1] A.Y., Liu, Update on interventional neuroradiology, The Permanente Journal, vol. 10, No.1, 2006, pp. 42-46.

[2] W. Hacke, Neurologie, Springer-Lehrbuch, 14., überarbeitete Auflage, Springer Berlin Heidelberg, Berlin, Heidelberg, 2016.

[3] J.L. Saver et al., Thrombectomy for Distal, Medium Vessel Occlusions: A Consensus Statement on Present Knowledge and Promising Directions, vol. 51, issue 9, 2020, pp. 2872–2884.

[4] E. Edlmann et al., Pathophysiology of chronic subdural haematoma: inflammation, angiogenesis and implications for pharmacotherapy, Journal of Neuroinflammation, vol. 14, 108, 2017.

[5] D. Sila et al., Middle Meningeal Artery Embolization versus Surgery in Patients with Chronic Subdural Hematoma-No More Fence Sitting?, Neurology International, vol. 15, No. 4, 2023, pp. 1480-1488.

[6] Z. Qian et al., Risk factors for recurrence of chronic subdural hematoma after burr hole surgery: potential protective role of dexamethasone, British Journal of Neurosurgery, vol. 31, No. 1, 2017, pp. 84-88

[7] M. Haldrup et al., Embolization of the middle meningeal artery in patients with chronic subdural hematoma-a systematic review and meta-analysis, Acta Neurochir (Wien), vol. 162, No. 4, 2020, pp.777-784.

[8] M. Mokin et al., A novel swine model of selective middle meningeal artery catheterization and embolization, Journal of NeuroInterventional Surgery, 2024.

[9] J. L. A. Larco et al., Evaluation of an in vivo preclinical model forhuman middle meningeal artery embolization using the posterior intercostal artery of the swine, Journal of NeuroInterventional Surgery, vol. 15, No. 9, 2023, pp. 924-930.

[10] J. Spallek et al., Design for Mass Adaptation of the Neuro-interventional Training Model HANNES with Patient-specific Aneurysm Models, in Proceedings of the 22nd International Conference on Engineering Design (ICED), 2019

[11] J. Schmiech et al., Development of an additively manufactured skull model for the neurointerventional simulator HANNES, Transactions on Additive Manufacturing Meets Medicine, 5(1), 816, 2023.

[12] J. Spallek et al., Comparing Technologies of Additive Manufacturing for the Development of Vascular Models, DDMC, Fraunhofer Verlag, Berlin, 2016.

[13] E. Sobirey et al., Printing study and design guideline for small hollow structures in medical technology, Proceedings of the Design Society, vol.4,2024, pp. 1849-1858.