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Original Research Article

Influence of additive manufacturing parameters on patient-specific small vessel models based on the neurointerventional simulator HANNES

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Abstract: With the increasing technical development, neuroradiological treatment of diseases in small vessels (diameter of < 2 mm), like arteriovenous malformations, is becoming possible. Endovascular interventions are technically very difficult and require learning and practice in the use of the instruments. There is a great need for in-vitro training simulators to avoid inappropriate animal experiments. This article describes the analysis of influencing parameters additively manufactured patient specific small vessel models based on the existing neurointerventional simulator HANNES and an established workflow for the fabrication of vessel models. Many printing parameters during the design or fabrication of the model may have an influence on the small complex hollow structures. In this article, a selection of parameters of the stereolithography process and their possible influence are explained in more detail. Subsequently, the findings should be investigated in a printing study for a more detailed analysis of the parameters.

I. Introduction

Endovascular treatment, which uses catheters within vessels, is increasingly considered the standard of care in many areas of vascular medicine [1, 2]. With increasing technological development, neuroradiological treatment of diseases in small, peripheral vessels is also now becoming possible using more navigable and smaller devices [3]. In neuroradiology this concerns in particular the procedures for treating small vessels with a diameter of < 2 mm. These include the pathologies arteriovenous malformations (AVM), acute strokes in distal vessels, and subdural hematomas (see Figure 1). Arteriovenous malformations are predominantly congenital cerebral vascular pathologies characterized by the development of multiple small arteriovenous shunts. These shunts represent direct connections between arteries and veins without an intervening capillary bed [4]. In neurointerventional treatment, the affected feeding vessels are located with the aid of a catheter inserted via the femoral artery under radiographic control and shut off either by the use of small embolization particles or by the use of adhesive fluid [5, 6]. Treatment of distal vessel occlusions in strokes can be performed in the same way as treatment of larger brain arteries using mechanical thrombectomy. However, the more distal the vessel is occluded, the more difficult is the selection and navigation of the appropriate catheters and wires [7, 8]. A subdural hematoma (SDH) is a hemorrhage in the subdural space, a space between the hard and soft meninges, and is treated endovascularly by embolizing the middle meningeal artery [4, 10].

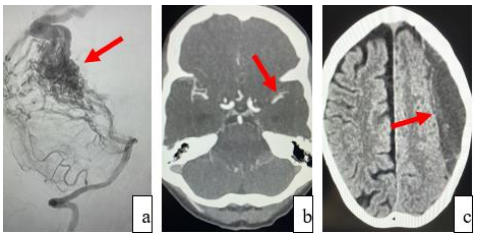

Figure 1: Small vessel diseases highlighted by the red arrow 1a) arteriovenous malformation, 1b) distal stroke, 1c) subdural hematoma

The necessity for systematic learning of the techniques and continuous training on the part of the treating physicians for the presented diseases of the small brain vessels becomes apparent. Animal models have been used for train the treatment of strokes and AVMs [11,12]. These animal models have many disadvantages like ethical aspects or not being realistic due to the different anatomy to a human brain [11]. Currently, there is no in vitro simulation model for the training of endovascular treatment of SDH.

This results in the need for developing an in-vitro model that would eliminate the previous disadvantages of the animal model and allows physicians to reproduce a variety of treatments of different diseases of the small vessels in the brain in one training session. The aim of this work is to analyse an existing neurointerventional simulation model and an already developed workflow for the manufacturing of vascular models for possible influencing parameters for the additive manufacturing (AM) of small vascular models. Based on the results of this article, a printing study will be started to analyse these process parameters.

II. Initial situation and application

Analysis of possible influencing parameters on additively manufacturing patient-specific small vessel models is performed on the existing training model HANNES (Hamburg ANatomical NEurointerventional Simulator) [13]. In the Department of Diagnostic and Interventional Neuroradiology at the University Medical Center Hamburg-Eppendorf (UKE), HANNES is already being used for training applications under real conditions in angiography for aneurysm, stroke and stenosis treatment. A central focus of the simulation model is the integration of patient-specific and individualized vascular geometries. Due to the modular structure of the simulation model, individual modules can be easily exchanged and thus different training scenarios can be represented. The simulation model has a fluid system with adjustable temperature, adjustable pulse and adjustable volume flow, which mimics a realistic blood pressure. A standard process flow from patient imaging to vessel model design using Stereolithography (SLA) has been described in Spallek et al. [14]. Considering the data acquisition, the design of specifications, the additive manufacturing and the postprocess [14]. The individual process steps correlate with the subdivisions used in the following for the analysis of the influencing parameters.

III. Analysis of influencing parameters

Many process parameters for the SLA technology can be found in the literature [15, 16, 17, 18]. The following analysis considers only a selection of parameters that may have the greatest influence in the manufacture of small vessel models. Environmental factors are not taken into account.

Each step of the process flow is analysed in more detail below.

III.I Data Acquisition

The standardized process flow for fabricating patient-specific vascular models begins with the acquisition of patient image data. A high-resolution method will be required that shows the fine target structure with high contrast to the surroundings. The combination of the parameters could allow a detailed visualization of small vessels, where filigree structures are clearly represented. Computer tomography or a three-dimensional angiographic scan may be suitable for this purpose.

III.II Segmentation

The segmentation ensures that only the relevant vessels are preserved. For the segmentation of fine structures, manual and technical parameters could influence the quality of the result. The manual factor of segmentation is the person performing the segmentation. The person should already have experience in the execution of small complex structures and have good anatomical knowledge. A key factor in segmentation is the software. There are many different programs, which show their advantages for specific applications. For the segmentation of small vessels, programs specially developed for medicine (e. g. Seg3D, NIH Center for Integrative Biomedical Computing at the University of Utah, USA) should be used. The technical parameters of the software include the selection of the segmentation procedure, such as automatic methods, or manually set parameters. The latter include the threshold value, which isolates objects with certain properties in the image, or the smoothing factor, which can be used to change the image noise. The segmentation is followed by the translation of the not hollow brain vessel model into an STL file (Standard Triangulation Language) for the design process.

III.III Design of specifications

The previously segmented image data is used to construct hollow vessel models in a CAD program. In this process step, connectors to the vessel models are designed for later integration into the HANNES model. It is important to consider certain model specifications for smaller vessel models. These include defining the wall thickness of the vascular wall for the model. The correct choice of wall thickness determines, among other things, the stability of the vessel model as well as the surface quality in terms of smooth and uniform printed models. Another parameter is tessellation, which divides the part into smaller geometries and creates an STL file for printing. The quality of tessellation can affect the accuracy, surface quality and printability of a 3D model. Too coarse tessellation can result in visible steps on the surface, while too fine tessellation can unnecessarily increase the file size. Small vessel models may have complex branching patterns and intricate geometries. Ensuring that the additive manu-

facturing process can accurately replicate these complex structures without distortion or loss of detail is important.

III.IV Manufacturing

AM is used for the production of patient-specific vessels, because the manufacturing process is predestined for the production of complex components. To expand HANNES to include the small vessel diseases mentioned in the introduction, the stereolithography AM process is chosen for producing the small vessel models. This method is already used for the manufacturing of the other vessel models in HANNES [14]. Stereolithography (SLA) is an AM process in which a liquid photopolymer is cured layer by layer using a UV laser to create a three-dimensional object. Accuracy of SLA is influenced by different process parameters [15]. Based on experience from previous projects, the selection of material for the small vessel models will be limited by the requirement for realistic haptic properties and flexibility (e. g. Flexible 80A, Formlabs Inc., Somerville, Massachusetts, USA). In addition, the material must be able to be used in an X-ray environment and not cause artifacts. Layer thickness, which refers to the vertical resolution (z-direction), can have an effect on smoother surface quality as well as better rendering of fine filigree structures. Different print qualities are determined with regard to model hollowness and roundness, surface roughness and dimensional accuracy. The orientation of the component on the printing platform should also be studied in view of the surface quality, uniform wall thicknesses, the use of support structures, and the hollowness of the models. Other possible printing parameters that could have an influence on the curing of the material in the SLA production of small hollow structures are the hatch spacing, the hatch overcure and the associated exposure time and the temperature. The laser with the size of the laser spot limits the resolution in x-y direction. By changing the parameters, the resolution and the fineness of the print can be adjusted which are important for the small vessel models.

III.V Postprocess

Finally, after manufacturing the vessel models are postprocessed. The parameters washing time, the type of washing process and curing time should be investigated with regard to their influence on the hollowness of the manufactured small vessel models. For this purpose, the factors temperature, duration of post-processing and washing material can be analysed.

IV. Conclusions

The in-vitro model named HANNES and the associated workflow for the production of vascular models were investigated with regard to possible influencing parameters for the production of small vessel models (< 2mm). The analysis revealed some possible influencing factors in the different steps of the workflow. For an accurate mapping of the complex geometries, the target structure must already be generated in high resolution during data acquisition and segmentation. Good anatomical knowledge should be available for this purpose. In the following process workflow, it is important to ensure that the additive manufacturing process can accurately replicate the complex structures without distortion or loss of detail. In a subsequent printing study, these parameters and their influencing factors are to be investigated, especially with regard to the accuracy and hollowness relevant for small vessel models. Figure 2 shows the individual phases of the planned parameter analysis.

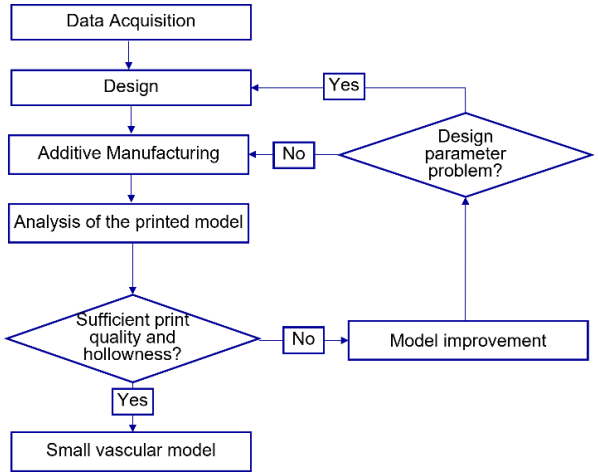

Figure 2: Phases of the planned parameter analysis

The analysis of the influence of the parameters, taking into account the pressure quality and the hollowness, will be carried out iteratively. The quality of the print is analyzed on the factors model roundness, surface roughness and dimensional accuracy. Here, the tolerance for small structures should not be more than 0.1mm. This procedure should be applied to all parameters and factors listed in the article.

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Author's statement

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