Aortic Model in a Neurointerventional Training Model – Modular Design and Additive Manufacturing

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Abstract. For training physicians in endovascular techniques such as mechanical thrombectomy in acute stroke, synthetic in-vitro models may replace animal models. A neurointerventional training model was developed in previous works using additive manufacturing (AM) for the reproduction of patient specific anatomy. Different patient anatomies, such as curvatures, can complicate the pathway of treatment. For this reason, realistic training requires a simulation of the entire access path from the femoral artery to the affected vessel in the brain, which includes the simulation of the aorta.

The training model currently uses a commercially available silicone aorta, which has several disadvantages, including high cost and unrealistic surface friction. Furthermore, the aortic model is not modular and therefore does not allow changes in configuration of the aortic arch, which is a strong factor influencing procedural difficulty and therefore an important variable for training.

In this study, a modular aortic model is designed and manufactured according to the requirements for training endovascular stroke treatment. AM offers many advantages in the production of anatomical models. Therefore, different manufacturing alternatives are tested based on a modular concept, using both direct and indirect manufacturing. Criteria for an evaluation of the production processes and the resulting models are defined and the test set-up is described. In this study, the procedures are first evaluated under cost and time aspect and a first assessment of the qualitative criteria is given.

Keywords: Synthetic aortic model · Modular design · Additive manufacturing

1 Introduction

1.1 Motivation

The training of catheter-based interventions for endovascular treatment of vascular diseases (e.g. thrombectomy for treatment of acute stroke) is mainly performed on

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animal models [1]. For example, an anesthetized pig is injected with previously collected and clotted blood and the mechanical removal of the blood clot via the femoral artery is trained [2]. However, training on animal models has many disadvantages. In addition to the general ethical aspects of animal tests, the vascular anatomy of pigs does not correspond to that of humans [1], which reduce the training effect. In particular, vascular curves that occur in elderly patients and challenge the intervention cannot be trained in the animal model [3].

In order to avoid animal models and achieve better training possibilities, various endovascular training models were developed and partly marketed. The training model of the company Vascular Simulations, Inc. (New York, USA) allows the training endovascular techniques, such as aneurysm or stroke treatment. The company produces patient-specific vascular models [4]. The model EVE (EndoVascular Evaluator) from FAIN-Biomedical Inc. (Nagoya, Japan) is also a holistic model for training endovascular diseases. It allows the exchange of different modules to allow training on different vascular diseases [5]. Spallek et al. pointed out the advantages and disadvantages of these models and justified the need for a new neurointerventional training model by stating that a simple and cost-efficient exchange of patient-specific models is not possible even during training with the commercial models [6].

In previous works the training model HANNES (Hamburg ANatomical NEurointerventional Simulator) was developed for training of aneurysm treatment [6]. HANNES is characterized by its high modularity, which allows for easy change of vessel models to represent a wide range of anatomies. Additive Manufacturing (AM) is used for the production of the vessel replicas because it offers a high degree of geometric freedom and enables fast production in small quantities [7].

Essential adaptations to HANNES for use in the training of stroke treatments were shown in Wortmann et al. [8]. This includes the possibility to replace the aortic arch with different models to achieve different levels of training difficulty. Currently, HANNES has a commercial silicon aorta (United Biologics, Inc., Santa Ana, USA), which is not modular and therefore does not allow the replacement of the aortic arch.

The aim of this study is to design a modular aortic model, utilizing AM to replicate patient-specific anatomy. Three different manufacturing processes are compared. Both direct and indirect AM is taken into account. A comprehensive evaluation is being prepared to assess cost, time and quality aspects. Criteria will be defined for this purpose. The different processes are evaluated in this study under the focus of cost and time aspects.

1.2 Medical Background

The common femoral artery often serves as the access point for endovascular treatment. The catheters and treatment devices are advanced via the aorta, the cervical arteries to the cerebral arteries where the treatment takes place.

The aorta is the central artery of the human body and transports the blood from the heart into the large blood circulation. The aorta is an elastic artery which, like the other arteries of the body, is made up of three layers of walls [9]. Anatomically, the aorta can be divided into the five segments aortic root, ascending aorta, aortic arch, descending thoracic aorta and abdominal aorta (Fig. 1).

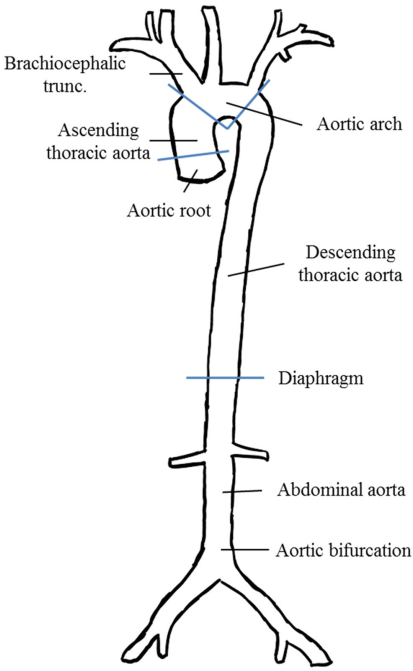

Fig. 1. Division of the aorta into segments (based on [10, 11])

The aortic root, shown on the left in the figure, connects to the aortic valves and, together with the ascending aorta, forms the transition to the aortic arch up to the outlet of the brachiocephalic trunc (the first large branching vessel). The supraaortic vessels brachiocephalic trunc dexter, carotis communis sinistra and subclavia sinistra arise from the aortic arch, which in turn ensure blood flow to the arm and the cervical and cerebral arteries [9].

Anatomically, three types of aortic arches can be classified [9, 12, 13]. These differ mainly in the position of their outlets to the cervical arteries (see Fig. 2) and thus represent different curves for the treatment path, resulting in different levels of difficulty in treatments [9, 12].

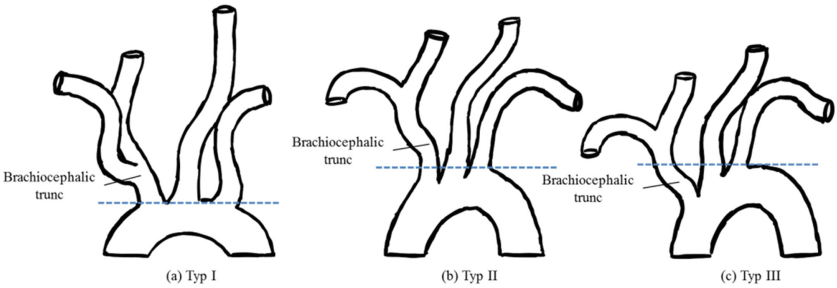

Fig. 2. Classification of the aortic arch by the location of the brachiocephalic trunc into three types (based on [9])

Type I aortic arch is characterized by the brachiocephalic trunc lying on the same horizontal plane that describes the curvature of the outer aortic arch contour (see Fig. 2, (a)). In type II aortic arch, the vessel outlet lies deeper between the outer and inner aortic arch curvature (see Fig. 2, (b)). An aortic arch is categorized as type III if the outlet of the brachiocephalic trunc is below the inner aortic arch curvature (see Fig. 2, (c)) [9]. Thus, a type III arch results in more severe curvature to overcome during catheter delivery, making the intervention more difficult [3].

The aortic arch is further bordered by the descending thoracic aorta, which extends to the diaphragm, and then the abdominal aorta, which extends to the aortic bifurcation [9].

In this study the focus is on the reconstruction and manufacturing of the aortic arch and the possibility of exchangeability of different aortic arch types in the training model.

1.3 Hamburg ANatomical NEurointerventional Simulator (HANNES)

The study is based on HANNES (Hamburg ANatomical NEurointerventional Simulator). HANNES is an endovascular training model for aneurysm treatment and has completely replaced animal-based training in the rabbit model at the University Medical Center Hamburg-Eppendorf (UKE) since 2016. HANNES was developed in a collaborative project between the Hamburg University of Technology (TUHH) and the Department of Diagnostic and Interventional Neuroradiology at UKE. HANNES consists of a base frame, electronic and control unit, fluid system, the purchased aorta, a head module with skull base and interchangeable cerebral and cervical vessel models. In-house developed adapters allow an easy change of vessel models even during training without creating inner edges [6]. Figure 3 shows HANNES in the angio suite environment.

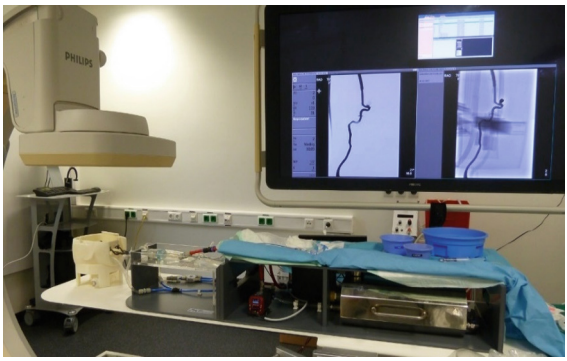

Fig. 3. HANNES in the experimental angio suite at the Medical Center Hamburg-Eppendorf (UKE)

Wortmann et al. show the extensions of the HANNES platform for stroke treatment. Besides the integration of synthetic blood clots and stenosis models, the different types of aortic arch will be integrated into the training [8].

HANNES' current aorta is a commercially available model (United Biologics, Inc., U.S.A.). As shown in the Fig. 4, the aorta is not modular and an exchange of different aortic arches is not possible. To enable connection to the HANNES model, the supraaortic connections were replaced by the adapters typical for HANNES.

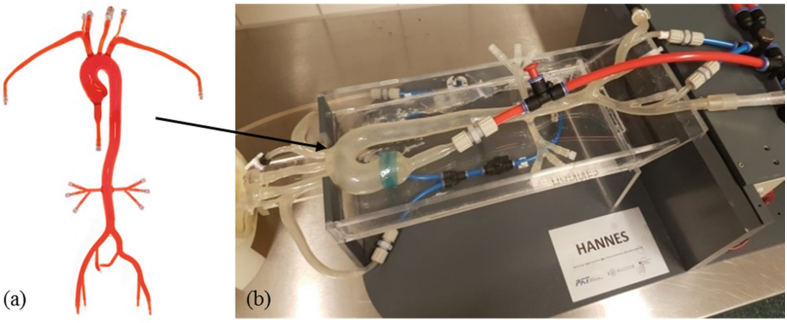

Fig. 4. Silicone aorta of the company United Biologics (a) [14] and the aortic model integrated into HANNES (b)

2 Modular Design and Manufacturing Process Selection

First, the requirements for the aortic model were determined together with the neuroradiologists of the UKE. The model should be transparent so that the catheter guide is visible even without fluoroscopy. Furthermore, the aorta should be elastic so that it behaves similar to reality and it should provide realistic friction between catheter and vessel material. An interchangeability of the aortic arch should be given so that training on the different arch types is possible. At the same time, compatibility with the adapters previously used in the model should be ensured.

The variety required by the customer (UKE) in relation to the aortic model was included in the form of a variety tree. The variety driving properties are especially the anatomy of the aortic arch.

Based on anonymized CT imaging data of a type II aortic arch, a model was designed with Meshmixer (Autodesk, U.S.A.) and reconstructed in CAD with CATIA V5 (Dassault Systemes SA, France), resulting in an hollow vessel model (Fig. 5). The wall thickness was set to 2 mm based on experience with the cerebral vessel models.

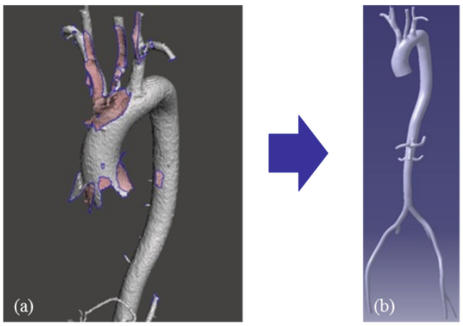

Fig. 5. CT-scan of an aorta of aortic arch type II (a) and the generated CAD model in CATIA V5 (b)

HANNES adapters were added to the CAD model at the supraaortic outlets. Due to the larger diameters at the transition between the aortic arch and the descending thoracic aorta, a new adapter was developed, which also allows an edge-free connection of the models (see Fig. 6).

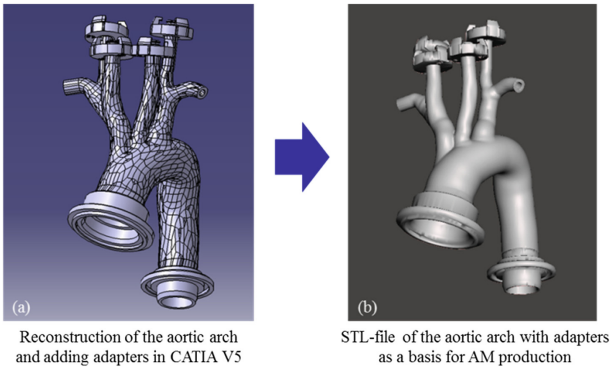

Fig. 6. Reconstruction of the aortic arch in CATIA V5 (a) and subsequent generation of the STL-file (b)

Spallek et al. compared different AM procedures and materials for the direct manufacturing of cerebral vessel models. It was shown that the procedures Material Jetting (MJ) and Stereolithography (SLA) are well suited for the fabrication of cerebral vessel models with aneurysms. For the MJ, the materials TangoPlus FLX930 and HeartPrint Flex (Materialise GmbH, Munich) on the Objet printer proved to be promising [7]. With the HeartPrint Flex material, Materialise is able to produce models such as vessels with elasticity similar to the real vessel. [15]. No elastic material was available on the Form 1+ from Formlabs (U.S.A.) at the time of the study, making MJ the preferred procedure.

Since 2019 Formlabs has been offering the material Elastic Resin. The properties can be taken from the material data sheet [16]. Due to its promising properties and to the fact, that this printer is available to the research partners at the university as well as at the university medical center, this material is included in this study.

Also the direct manufacturing out of HeartPrint Flex (Materialise) is to be compared.

Indirect manufacturing is chosen as another manufacturing alternative. In her work, Heidemanns produced a silicone model of the aorta [17]. First, she used the CT data to create native segments from a modelling compound in order to make an impression using wax, silicone and gypsum. The wax models were then poured into the prepared mould and served as a positive model to apply the silicone in several layers with a brush [17]. Heidemanns did not use the possibilities of AM in her approach. Macroni et al. produce a parameterized aortic model based on literature data. The model was produced by casting the silicone in a 3D-printed mould. Inner and outer shells were used and the model was cast under vacuum [18]. In both described studies the aortic arches are not interchangeable. In this work, a mould printed by means of Stereolithography is to be produced, which is then used to create a wax model. This in turn forms the core for the layered application of silicone.

3 Manufacturing

3.1 Stereolithography (SLA) with Formlabs Form 3

Method and Material: Stereolithography (SLA) with the Form 3 from Formlabs, Elastic Resin (209.25 ml), Form Wash (IPA (90%)), Form Cure, in-house production.

Production-Specific Preparation of the Model: The interfaces on the aortic arch model had to be modified in the CAD model so that the model fits into the permissible installation space of Form 3 145 × 145 × 185 mm. In the PreForm software by Formlabs, the model is virtually orientated on the building platform and support structures can be generated (see Fig. 7, (a)). The model almost fills the permissible installation space. From PreForm the model can be transferred directly to Form 3 and is ready for printing. The process of preparation is calculated at about 1.5 h.

Production of the Model: The Elastic Resin material is inserted at the printer and printing is started. The printing time for the model is 30 h. Figure 7, (b) shows the model after printing on the building platform and in (c) the finished model. The postprocessing time is about 1 h.

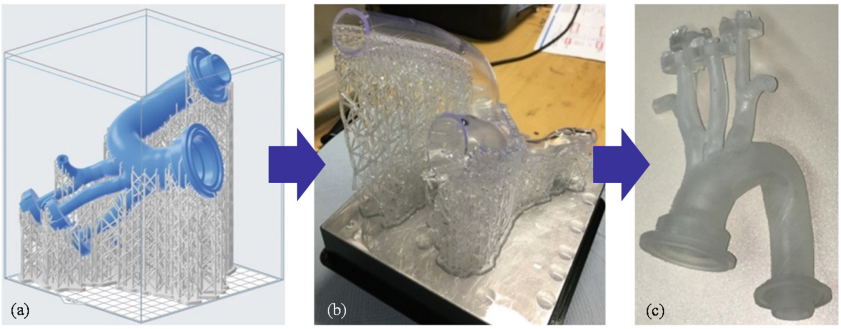

Fig. 7. Aortic arch model in the PreForm software (Formlabs) for preparing the print (a), model after printing on the building platform of the printer Form 3 (b), model after post processing (c)

3.2 Material Jetting (MJ) with Materialise

Method and Material: Material Jetting (MJ), HeartPrint Flex, order production.

Production-Specific Preparation of the Model: In a telephone conversation the requirements for the model were clarified and a decision was made to print it. The finished STL file is sent to Materialise for printability testing. With this printing method it is possible to have the model printed in places with different Shore hardnesses. For this model a uniform Shore hardness is chosen first. The material properties of the aortic arch model have a Shore hardness of 30 A and correspond to a tensile strength of 1.04 ± 0.04 MPa with the wall thickness of 2 mm used [19].

Production of the Model: The model is produced by Materialise after the STL file has been sent. From receipt of order the delivery time is 14 days. The total price including tax and shipping is just above the three-figure range. The model is shown in Fig. 8.

Fig. 8. Heartprint aortic arch model ordered from Materialise

3.3 Silicone Cast with a Wax Model

Method and Material: Paraffin pastilles (idee. Creativmarkt, Germany) (200 g), cooker, melting pot, silicone shore hardness 33 (250 g), thickener (Thixotropic additives) (silikonfabrik.de, Germany) (2 ml), mixing bowl, mixing paddle, brushes, Formlabs Form 3, Clear Resin (547,53 ml), Elastic (Formlabs, USA) (103,9 ml).

Production-Specific Preparation of the Model: To produce the wax model, a casting mould needs to be created from the CAD file first. For this purpose, a block is created around the model in CATIA and the model is removed using Boolean operations. The mould created in CAD then has to be further divided to allow casting and wax removal. Holes are provided for fixing the mould parts (see Fig. 9 (a)).

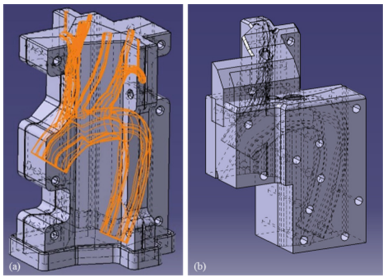

Fig. 9. Casting mould generated in CAD for the wax model, failed attempt with one casting mould (a) and several moulds for the individual vessel models (b)

The first attempt to create the wax model failed because the relatively thin branches of the aortic arch broke off when the mold was removed. The arch itself could be produced well by the mould. It was therefore decided to produce separate casting moulds for the individual branches (see Fig. 9, (b)). The construction of the mould in CATIA and the production is calculated with about 75 h (65 h printing time). The adapters were printed separately in Elastic. An exemplary form is shown in Fig. 10, (a). The individual wax patterns were casted into the pre-warmed casting moulds and cooled down completely. Afterwards the individual wax models were melted at the interfaces and connected to form a uniform model (see Fig. 10, (b)). The process of creating the wax model is calculated at about 11 h.

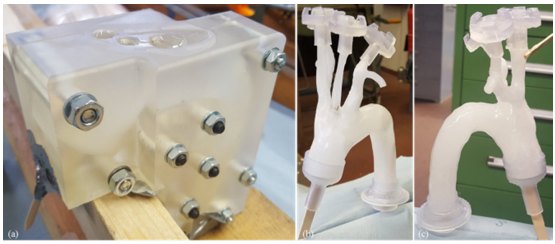

Fig. 10. Casting mould (Clear Resin) for the creation of the wax model (a), the assembled wax model with attached adapters/Elastic Resin) (b), application of the silicone layers (c)

Production of the Model: The silicone was mixed in a ratio of 1:1 base: catalyst and thickened with one percent by weight thixotropic additives. The model was coated with two additional layers at intervals of 2 h, with the third layer dispensing with the thickener in order to produce a smoother surface (see Fig. 10, (c)). The process of silicone application is calculated with 2 h. The model is then melted out in a water bath (Fig. 11). The process step is calculated with 1.5 h.

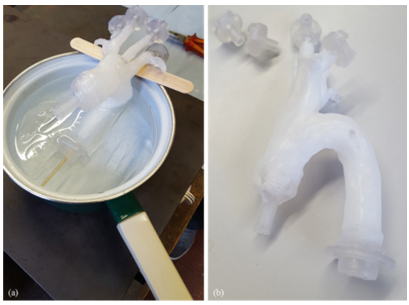

Fig. 11. Melting of the wax in a water bath (a), silicone model after loss of wax with detached adapters and wax layer outside and inside (b)

3.4 Production of the Other Aortic Model Parts

The remaining aortic model sections are divided into thoracic aortic section, abdominal aortic section and femoral arteries. These models are made with Formlabs 2/3 and connected with adapters with outer shells (Tough Resin, Formlabs). The complete aorta is shown in Fig. 12. It was decided to use Elastic Resin for the rest of the aorta because the catheter-vessel wall contact is not as high as in the aortic arch and the models can be produced at low cost by the authors themselves.

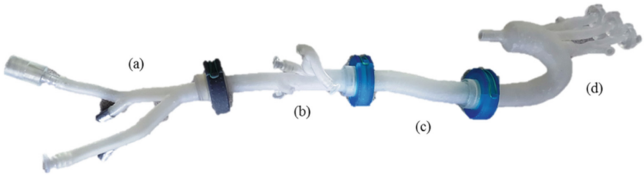

Fig. 12. Total aortic model consisting of (a) femoral arteries, (b) abdominal aorta, (c) thoracic aorta, (d) aortic arch

4 Evaluation of the Production Processes and Materials

4.1 Evaluation Criteria

The evaluation criteria are stored based on the production requirements and defined as follows: The production process must not restrict the accurate reproduction of the inner contour of the aortic arch model. The model should be made of an elastic material. The model should have a certain degree of transparency to facilitate catheter positioning. The production must guarantee a tightness of the model wall. The aim is to produce the model as quickly as possible so that it can be put back into use as soon as possible after any damage (Wish). The material should be robust so that it can be used for several training sessions (Wish).

On the first level, this results in the criteria of cost, time and quality for the evaluation of the models from the various production processes. Figure 13 shows the sub-criteria for evaluating the finished models in terms of time, cost and quality.

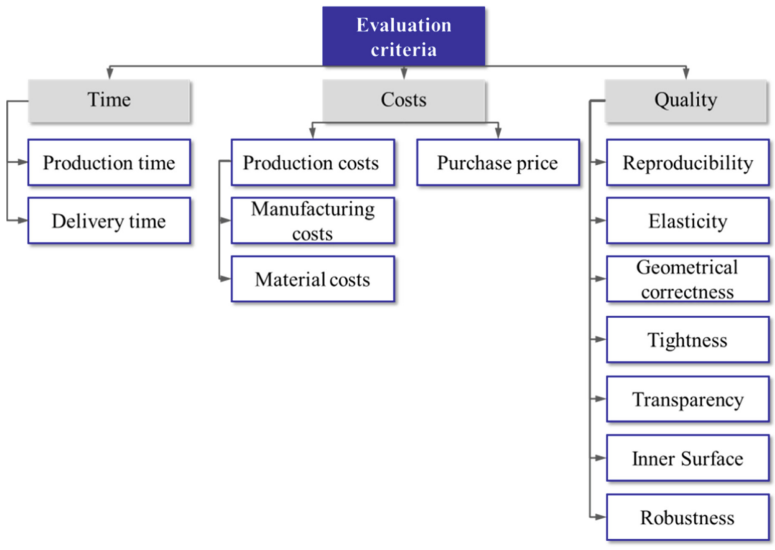

Fig. 13. Criteria for the evaluation of manufacturing processes and the resulting models

A quantitative testing of criteria would go beyond the stress limit of the materials (e.g. testing of elasticity). Due to the requirement to keep the models non-destructive, which results from the high costs and the unit of 1, the criteria are mainly tested qualitatively. The existing aortic model from United Biologics serves as a reference for the evaluation. The sub-criteria are described in more detail below.

The *production time* is considered from the point of production initiation to the finished and usable vessel model and includes the necessary preparation and follow-up procedures. The basis for the production of the aortic arch is the completed CAD construction, which was exported as an STL file.

For the aortic arch from contract manufacturing, the *delivery time and costs* are included in the evaluation.

The *production costs* are the sum of the manufacturing and material costs. The manufacturing costs include the labor costs for production. Production overheads are calculated under assumptions.

Statements on *reproducibility* can be made qualitatively on the basis of production.

The *elasticity* is assessed by the physician on the basis of experience with real aortic vessels and is put into practice with the existing aortic model.

An evaluation of the *geometrical correctness* of the models by overlaying the scanned models with the CAD model is not carried out for two reasons. Firstly, the geometric correctness of the aortic model is only partially relevant for the intended intracanial treatment simulation and the CAD model was reconstructed on a patient-based level (no patient-specific model). On the other hand, the elasticity of the model allows a certain deviation.

The *tightness* of the aortic arch is tested in itself and at the junctions to the cervical vessels and brachial vessels in the existing neurointerventional training model.

The *transparency* of the model is assessed during operation with the blood surrogate (water and soap). For this purpose, it is assessed whether the catheter is adequately visible.

The *surface quality* is qualitatively evaluated after production and in tests with the physicians. Therefore the behavior of the catheter on the vessel wall is evaluated qualitatively.

For the reasons mentioned above, a stress test is not carried out. The *robustness* of the model is qualitatively assessed in the application at HANNES. For this purpose, it is assessed to what extent the model shows material stress in the application, e.g. during assembly at the interface and during pressurization in the system.

The quality criteria will be tested by means of qualitative testing in HANNES together with experienced neuroradiologists. The behavior in angiography and in interaction with the treatment devices will be tested. The focus in this study is on the evaluation of the different production processes in terms of cost and time and a first assessment of the qualitative criteria resulting from it. The test setup in HANNES is planned.

4.2 Evaluation of the Production Processes

The evaluation of production time and costs is based on certain assumptions: The costs are calculated excluding all taxes. The labor cost rate for one hour is estimated at 40 €. The printing time on the AM printers is not included in the working time, as they can run unattended. The starting point for the calculation is the finished STL file of the aortic arch.

Production overheads are assigned to the manufacturing costs using the machine hour rate [20]:

$$machine\ hour\ rate = \frac{machine\ dependent\ costs}{running\ hours} \tag{1}$$

Machine-dependent costs represent cost-accounting depreciation, accounting interest, costs for maintenance & repair, space costs and energy costs [20].

The cost-accounting depreciation of the machine is calculated as follows [21]:

$$cost\ accounting\ depreciation = \frac{replacement\ value - residual\ value}{useful\ life} \tag{2}$$

The replacement value is calculated as follows [21]:

$$replacement\ value = acquisition\ cost\,(1 + inflation)^n \tag{3}$$

The acquisition cost of the Form 3 was 3299 € without taxes and shipping costs. The average of the inflation rates for the years 2015 to 2019 was used as the calculated inflation rate [22], resulting in a value of 1.14%. The residual value and the useful life of the printer were estimated. It is assumed that the printer has a useful life of 5 years and a residual value of 500 €. This results in the replacement value of Form 3 at 3491.38 € and the cost-accounting depreciation at 598.276 € per year.

The accounting interest and space costs are not included in the calculation. The repair costs are estimated at 100 € per year.

The energy costs are calculated on the basis of the energy requirement of 220 W of the Form 3 [16], the machine running time and an electricity price of 0.29 € per kWh.

The machine running time results from the assumption that the printer is used two days a week with an average printing time of 6 h. With 230 working days per calendar year, the machine running time is 552 h/year.

These assumptions result in an annual electricity price of 40 € for the Form 3 [23]. The calculation of the machine hour rate is shown in Table 1. Based on the assumptions made, this results in a machine hour rate of 1.52 h/€.

Table 1. Calculation of the machine hour rate of the Formlab Form 3 (based on assumptions)

Machine hours per year:	552 h
Cost-accounting depreciation	698.28 €
Accounting interest	−€
Maintenance and repair cost	100 €
Space cost	–
Energy cost	40 €
Summe	838.28 €
Machine hour rate	1.52 €/h

Evaluation of the Current Aorta Model of the Company United Biologics. The purchase price of the entire Aorta model was in the four-figure € range at that point in time. The model was characterized by its good and constant transparency and high robustness. The elasticity appears good. The connections to the HANNES model cannot be made immediately. The friction of the catheter on the model vessel wall is also considered by the physicians to be too high. It is not possible to change the aortic arch type.

Evaluation of the SLA Print in Elastic Resin. *Production time:* The process of preparing the model for the printer consisted of the creation of the PreForm file with 1 h and the machine preparation with about 0.5 h. The printing time of the aortic arch was 30 h. For the post-processing of the model 1 h was needed.

Production Costs: The material costs are calculated on the basis of the material consumption calculated in PreForm and the cost of a tank of Elastic Resin (1 l). This results in material costs of 39.76 € for the aortic arch. The labor costs for a total working time of 2.5 h at an hourly rate of 40 € results in 100 €.

With a machine hour rate of 1.52 €/h, the production overheads for printing the aortic arch are 1.52 €/h × 30 h = 45.6 €. The production costs are calculated in total at about 186 € (exclusive taxes).

The production of the model is subject to high reproducibility due to the settings on the printer. The first impression of the model in terms of elasticity, geometrical correctness and tightness appears good. At first the model shows a high transparency, which however decreases over time and appears rather milky. The inner surfaces of the models are initially sticky after post-treatment, but this also subsides over time. In terms of robustness, the models appear to be relatively sensitive.

Evaluation of the Heartprint Flex Model by Materialise. *Production and delivery time:* With the aortic arch model manufactured by Materialise, it is not possible to divide production and delivery time. The total time is the period from order confirmation by Materialise until delivery of the aortic arch model. This results in duration of 14 days.

Purchase Price: The purchase price includes the total cost price of the product, which cannot be further broken down. The purchase price without taxes and transport is in the upper three-figure € range.

The production of the model is subject to high reproducibility due to the settings on the printer. The first impression of the model in terms of elasticity, geometrical correctness and tightness appears good. The model initially shows good transparency and seems to maintain this over time. The inner surfaces seem to be smooth and the whole model robust.

Evaluation of Silicon Casting. *Production time:* Since moulds have to be developed, the design time for the initial production is taken into account (95.5 h).

Production Costs: For the calculation of the labor costs, the construction of the casting moulds, the production of the wax pattern, the application of the silicone and the melting of the wax are considered. This results in labor costs of 980 € at a calculated 40 €/h. The material costs include the proportionate costs for Clear Resin (mould), paraffin wax, 2-component silicone, thickener and Elastic Resin (adapter). This results in material costs of about 105 €. The production costs are calculated on the basis of the machine hour rate of Form 3. With a printing time of 65 h for the mould and 4 h for the adapters, the manufacturing overheads are approximately 105 €. In total the production costs amount to approximate 1190 €.

The reproducibility of the model is estimated to be low, as no reproducibility can be guaranteed, especially by manual application of the silicone. The first impression of the model in terms of elasticity and geometrical correctness appears good. The tightness of the model is not ensured due to many defects caused by an irregular wall thickness. There is no transparency of the model due to wax residues inside the model. The inner surface of the model has adopted the structure of the wax core and is therefore rough. In terms of robustness, the model appears to be very sensitive, especially due to the insufficient wall thickness.

4.3 Test Set-Up for the Evaluation of Quality Criteria

For a further evaluation of the qualitative criteria, the aortic arch models must be connected in HANNES and tested with the experienced physicians at the UKE. For this purpose, the connections must be designed for the new aortic arch model. Figure 14 shows a first test for the geometric requirements of the aortic arch model.

Questionnaires were created to evaluate the criteria, which should first give an assessment of the current aorta model. Based on this, the criteria are to be evaluated in real terms in relation to the current aortic model. The focus of the evaluation is on the aortic arch model.

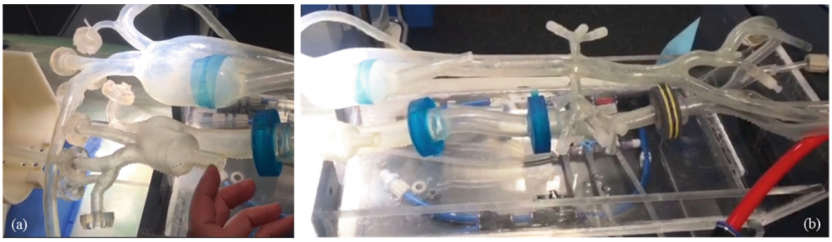

Fig. 14. Geometric comparison of the aorta model from United Biologics (above) with the aorta model made of Elastic Resin, manufactured on Formlabs Form 3 (below). (a) Comparison of the aortic arch with outlets, (b) comparison of the remaining aorta

5 Discussion of the Results and Outlook

This study described the design of an interchangeable aortic arch and its fabrication using the SLA fabrication procedure with Formlabs Form 3, the contract fabrication by Materialise with HeartPrint Flex and the fabrication of a silicone model by applying it to a cast wax model. The evaluation of the different manufacturing processes was quantitatively based on production costs and time. An initial assessment was given with regard to a qualitative evaluation of the models resulting from the processes.

Some disadvantages have occurred when fabricating the silicone model using a wax model. The production of the casting mould based on the positive model is very time-consuming. The wax model must cure for several hours. To create the smoothest possible surface inside the silicone model, the wax model must be finished. Between the applications of the different layers, the silicone must be cross-linked for at least 2 h, which prolongs the whole process. When applying the silicone to the wax model it is difficult to create a constant wall thickness. In addition, the wax could not be completely removed from the silicone model when melting it in a water bath, the surfaces were covered with wax and no good surface properties or transparency was produced. The process is far more expensive than direct printing and the reproducibility is low.

Direct production with Formlabs in Elastic Resin has several advantages. It is particularly convincing due to its short production time and low production costs in comparison to the procedures compared. The good availability of the printing process at both project partners (TUHH and UKE) plays an important role. In addition to these criteria, the model scores well in terms of the qualitative criteria in the first estimation. The HeartPrint model seems to be the best in terms of quality, although it is much more expensive than the manufacturing process in Elastic Resin. A comparison of the two models in HANNES with the medical professionals is necessary to make a final selection.

Further work consists in the integration of other production processes and materials in the evaluation. Based on the currently purchased aorta, it could be observed that silicone is very well suited for long-term use, while e.g. the Elastic Resin shows material changes in the long run. Due to the complex manufacturing process of the silicon casting, a silicone print is to be included in order to be able to evaluate the materials silicone, Elastic and HeartPrint in comparison and in realization to the current

aorta model of the company United Biologics. The models are to be tested qualitatively regarding their suitability in the training model HANNES with the experienced physicians of the UKE.

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