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Towards Dual-Use Training Simulator in Interventional Neuroradiology

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Abstract: Cerebral aneurysms are common lesions in the general population and are increasingly treated by endovascular procedures. Training of these methods not only improves the learning period of physicians but also increases patient safety. However, the use of traditional medical training methods such as training in living animal models is decreasing due to high costs and ethical issues, so computer simulations and 3D-printed phantoms are being used instead. A more realistic simulation requires pulsatile blood flow that can be customized and has body temperature. Current simulators that use 3D-printed phantoms are mainly used under X-Ray in an angiography intervention room, therefore a dual-use simulator that is easy to transport and can be used also without X-Ray is desirable. Either it could be used traditionally in an angiography intervention room or externally in any regular room with an image simulation according to rotational angiography. In this work, a prototype for blood flow simulation is presented as a first step towards such simulator and its application is demonstrated through different investigations. The fluid system is capable of simulating a given blood flow profile and the heating system can generate an accurate body temperature. The case can be easily integrated into a modular phantom system and is convenient to transport, although the weight could be further reduced.

Keywords: Angiography, Training, Simulator, Neurology, 3D-Printing

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1 Introduction

Treatment of intracranial cerebral aneurysms plays an important role in modern medicine, as there is an estimated prevalence of 1 % to 5 % in the general population [1]. Although surgical as well as endovascular procedures are effective methods of treatment, there has been a shift towards endovascular technologies because they are less invasive and thus offer advantages such as shorter operative times and hospitalization time as well as being more appropriate for less healthy patients [2]. Training of endovascular procedures based on simulations may shorten the learning period and can increase patient safety [3]. Due to high costs and ethical issues, classical methods of medical training, such as training in living animal models, are becoming less common; instead, alternative learning tools such as computer simulations and 3D-printed phantoms are increasingly available [4]. To simulate patient physiology as realistically as possible not only an artificial vascular system is required, but also pulsatile blood flow that can be individually adjusted and is regulated at body temperature. Although simulators already exist that use 3D-printed phantoms [5, 6], they are mainly used under X-Ray in an angiography intervention room.

To reduce dependence on an operating room and increase accessibility of training, as well as to minimize radiation exposure, it is reasonable to develop an easily transportable simulator that can be dual used. By applying this dual-use concept, it could be used both traditionally in an angiography intervention room under X-Ray or externally in a regular room with an image simulation according to rotational angiography. As a first step towards such simulator, we present our developed prototype for blood flow simulation and demonstrate its application through different investigations.

2 Methods

To establish a basis for the future dual-use simulator, a blood flow simulating unit will be developed, that will be used together with the modular phantom system of Schwenke et al. [7] for training in endovascular procedures of intracranial aneurysms. In the following, the requirements of the proto-

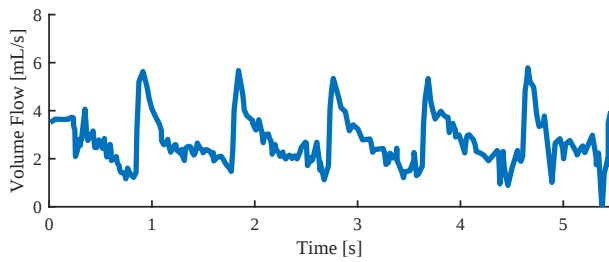


Fig. 1: Exemplary blood flow profile of the ICA [9].

type, which are derived from a typical training process, and the resulting prototype design will be described.

2.1 Prototype Requirements

A typical training in endovascular procedures of intracranial aneurysms consists roughly of the following steps: First, it is necessary to define the training scenario and the corresponding vascular and physiological environment including the blood flow. Afterwards, the training system will be assembled based on the chosen components. During training, either endovascular procedures or surgical planning can be performed. After the training is completed, it will be evaluated by the supervisors and the system will be disassembled again. This leads to requirements for the prototype in terms of functionality and its casing with regard to the realistic scenario and ease of use.

Since a realistic scenario has to be simulated during training, the patient individual blood flow has to be reproduced. The shape of the blood flow profile can vary between patients and specific vascular regions, but is basically made up of repetitive pulse-like curves [8]. An exemplary blood flow profile for the Internal Carotid Artery (ICA) is shown in Figure 1.

The temperature of the fluid is also relevant for realistic simulation. The blood temperature is typically around 37°C in human bodies and has a particular importance for the use of surgical materials, since the properties of their materials can be affected depending on the ambient temperature [10].

Since simulators are only temporarily located in an operating room used for everyday clinical practice, they are frequently assembled and disassembled, in order to not disrupt the clinical process. Therefore, it should be possible to take as few steps as possible to assemble or disassemble the prototype on the existing phantom system and to set up the whole system. This ensures that the prototype is user-friendly and can be quickly removed from the operating room in clinical emergencies. In addition, the simulator should be easy transportable due to its future dual-use application. To ensure good handling during transport of the prototype, a practical form factor should be chosen to make it easy to carry and to keep

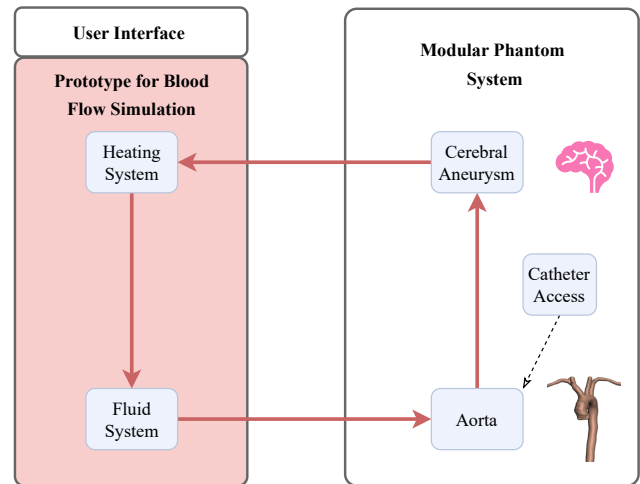


Fig. 2: Schematic design of the prototype connected with the modular phantom system. The blood flow is shown in red.

the weight relatively low to make it easy to handle during assembly and disassembly.

2.2 Prototype Design

Figure 2 shows the schematic design of the prototype connected with the modular phantom system. The prototype consists of a heating system for heating of the fluid and the fluid system for generating the blood flow profile. The fluid medium used in this work is water. The case of the prototype consists of the related electronics for operating these systems and a touch-screen for the user interface. The phantom system consists of an aortic phantom and aneurysm phantom that can be assembled in a modular manner. The access for catheters and associated surgical material is located on the aortic phantom.

2.2.1 Case

The case contains all components of the prototype and is made of aluminum struts and separately mounted plates. Quick couplings are provided for fluid inlet and outlet for easy connection to the phantom system. The switch and plug-in connection for the power cable are located on the opposite side of the couplings.

2.2.2 Fluid System

The fluid system consists of a centrifugal pump, a flow sensor and a variably proportional valve for adjusting the flow. Since a predefined blood flow profile consists of repeating pulses

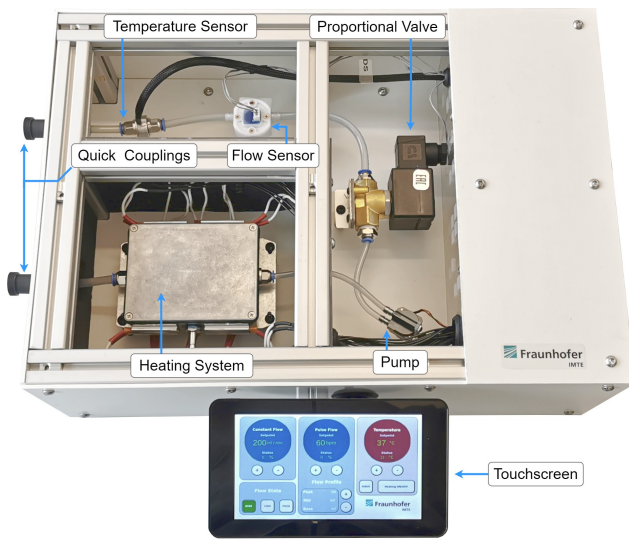


Fig. 3: Assembled case including the heating system, fluid system and touchscreen for the user interface. For demonstration purposes, the ceiling panel is not fully assembled.

(see Fig. 1), a pulse can be modeled with multiple set points. Based on the given pulse frequency, the repetition rate of the pulse can be determined. Finally, the necessary valve opening degrees are calculated using the given set points of the pulse and a PID controller.

2.2.3 Heating System

The heating system is made up of an aluminum housing with heating elements on the outside and a temperature sensor at the fluid outlet. For the temperature control, a set point is specified by the user. Whenever the temperature is below the set point, all heating elements are turned on until the target temperature is reached in the fluid. Also, whenever the temperature is above the set point, the heaters are turned off. Due to the distance between the heating system and the aneurysm phantom, a temperature drop exists. At room temperature of 20°C a temperature drop of approx 1.8°C was obtained by measuring the fluid temperature at the outlet quick coupling and the aneurysm phantom. To ensure that the correct temperature is represented in the aneurysm region, the offset was added as a positive value to the users set point. Although this results in a deviating temperature in the aortic region, this compromise can be accepted since the surgical material is primarily used in the aneurysm region.

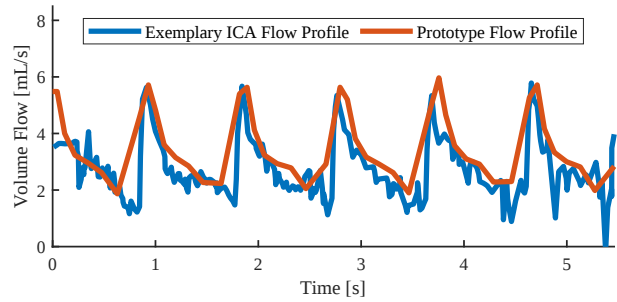


Fig. 4: Exemplary blood flow profile of the ICA (blue) [9] and generated blood flow profile by the prototype (orange).

3 Results

Figure 3 shows the assembled case including the heating system, fluid system and touchscreen for the user interface. The prototype weighs 10.9 kg and has a box-like shape with length of 51 cm, width of 36 cm and height of 18 cm (measured without touchscreen and quick couplings). The complete assembly and disassembly consists in total 6 steps. First, the two quick couplings must be connected or disconnected (2 steps). By disconnecting, the system remains watertight and does not need to be drained or filled if it is already filled. The power cable must then be connected or disconnected (1 step). For the touchscreen, this includes the attachment to the prototype and the two USB cables for data transfer and power supply (3 steps).

To evaluate the capability of the fluid system to simulate an individual flow profile, it was attempted to reproduce the flow profile from Figure 1. For this purpose the set points for the repeating pulse and the pulse frequency were determined by the given flow profile. The given and generated flow profiles are shown in Figure 4. The generated flow profile is able to follow without noticeable noise in the measured values. The average deviation of the two flow profiles is 0.71 mL/s . Furthermore, it can be seen that the generated flow profile can follow higher values more precise than lower ones.

Three series of measurements were conducted to investigate if the temperature of the fluid could be raised from 20°C to 37°C and kept constant. During the measurements, an average room temperature of constant 20°C was measured and the flow was set to a constant 6.66 mL/s . In all experiments the target temperature of 37°C was reached. After the target temperature was reached, the standard deviation over a measurement period of additional 10 min was 0.39°C .

4 Discussion

The assembly and disassembly of the fluid system consists of only 6 steps, which encourages a simple and quick setup and can be done by one person. However, the weight is still relatively high at 10.9 kg. However, due to its box-like shape, the prototype can be packed into a matching wheeled case, which makes it easier to transport. Although the set requirements can generally be met, it is recommended that the prototype should be further reduced in size, thus also reducing the weight, in order to make transportation even easier.

Based on the generated flow profile, it can be concluded that a given flow profile can be followed quite well, as the average deviation of 0.71 mL/s is relatively low. However, there is still room for improvement in the area of low flow values, where the performance can still be increased. One possible cause for this could be the flow sensor, whose resolution may not be sufficient for low values. However, additional different flow profiles should be tested in the future to further evaluate the performance of the system and make improvements as necessary.

Due to the fact that the target temperature of 37 °C was reached and the standard deviation from the target value of 0.39 °C is relatively small, it can be concluded that the requirement for the heating system can be met under the boundary condition of a room temperature of 20 °C. However, the room temperature may vary depending on the location, so further investigation will be conducted in the future to ensure that the heating system will operate reliably under different room temperatures.

5 Conclusion

The developed prototype is a first step towards a dual training simulator that can be used both in angiography and external. The fluid system is capable of simulating a predetermined flow profile, which in the future could correspond to a patient's individual blood flow profile or pre-recorded flow patterns depending on the cerebral region of the aneurysm. The heating system is capable of generating an accurate body temperature at a room temperature of 20 °C. The case is easily integrated into the overall modular system and its shape makes it convenient to transport, although the weight could be further reduced. Future plans include the development of rotational angiography simulation and evaluating usage in the operating room, considering assembly and disassembly times as well as clinical utility in training. Furthermore, in the distant future, the system could be used as a test station for robotic surgery, micro-swimmers or in the testing of surgical materials.

Author Statement

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