Creation of Neurosurgical Training Systems for Cerebral Aneurysm Repair

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Abstract

An aneurysm is the ballooning of a blood vessel wall that occurs when there is an abnormality in the structure of the wall. Cerebral aneurysms can potentially cause severe brain damage and death. Experienced surgeons are needed to treat cerebral aneurysms. The goal of this project is to develop a training device for surgeons to practice procedures that are used to treat aneurysms. Previous work was expanded on to create a hollow, three dimensional training device. A three dimensional model of an aneurysm was created to be produced using additive manufacturing. This model was to be cast in silicone and then removed, leaving a hollow, silicone “negative” of the model. Due to the complexity of the aneurysms geometry, it could not be printed during this ten week project. A stand-in model was created for the purpose of developing a method for the creation of a training system. Tubing and appropriate fittings were added to the inlets and outlets of the model, through which fluids could be pumped to simulate blood flow. When created with the accurate geometry, this model could potentially aid in the planning of complicated surgical strategies, as well as in the education of junior surgeons and therefore help to minimize the risk of surgical intervention related to aneurysm treatment. Secondarily, the model could be used to visualize and validate flow patterns from computational fluid dynamics calculations to characterize flow through the aneurysms.

Keywords: aneurysm, cerebral, intracranial, training, education, medical, surgical, surgeon, undergraduate, research, neuroanatomy

1. Introduction

1.1 Background
Cerebral aneurysms occur when there is a weakened area in the wall of a blood vessel. Pressure from blood flow causes the weakened area to bulge out to a blister-like structure. This bulging causes the wall to thin and, eventually, the aneurysm can rupture. The majority of cerebral aneurysms occur in an area near the brain’s base known and the subarachnoid space. Roughly 90 percent of bleeding that occurs in this area of the skull is caused by ruptured cerebral aneurysms.1 This bleeding is extremely dangerous and can lead to permanent disability, stroke, coma, and even death. An aneurysm is considered “ruptured” when any amount of blood is leaked from the aneurysm and into the surrounding area. Most of the dangerous symptoms of an aneurysm are caused by either a
rupture or by the mass effect of a giant aneurysm. Aneurysms are considered “giant” when they have grown to at least two centimeters in diameter. The increased strain, coupled with decreased structural integrity due to stretching, means that giant aneurysms are especially dangerous due to their increased risk of rupturing.² It is estimated that roughly five percent of people currently have a brain aneurysm.³ Most people will remain unaware of their aneurysm, as the majority of aneurysms are small and present no symptoms. Because of their asymptomatic nature, most aneurysms are found when a person is being screened for something else. There are three main treatment strategies used when dealing with an aneurysm once discovered. First, if a small and therefore low risk aneurysm is discovered, then a doctor may suggest periodic check-ups to simply observe the aneurysm and react should it grow. In this situation, the risk of surgical intervention outweighs any threat that a small aneurysm might pose.³ For larger aneurysms, a doctor may suggest either coiling or clipping of the aneurysm. Clipping is an invasive surgical procedure that involves removing a portion of a patient’s skull to allow direct access to the problem area. A surgical clip is then applied to the neck of the aneurysm for the purpose of cutting off blood flow to the aneurysm and therefore minimizing the risk of rupture or growth. Coiling, the more common of the invasive procedures, is performed by inserting a catheter into the femoral artery and carefully feeding it into the neck of the aneurysm that is being treated. A wire of some soft surgical grade metal is then coiled within the aneurysm so as to block off any blood flow into the aneurysm. Symptoms of a large or ruptured aneurysm may include: extreme headaches, eye pain, vision deficits, stiff neck, nausea, changes in mental state, dilated pupils, or loss of consciousness.⁴

1.2 Other models

Training devices have been successfully used in the past to educate surgeons on the layout of patient-specific aneurysms. In one case, models were created to help surgeons plan for clipping operations. When the models were used, the average number of clips wasted by surgeons went from eight to zero. The use of physical, three dimensional models allowed surgeons to obtain insight that was unavailable using standard tools. Surgical waste was minimized and surgeons were more confident when performing the clipping procedures. Overall, the models received positive reviews from the surgeons who had used them. These hollow silicone models were made by covering models of the internal geometry of various patients’ aneurysms with a thin layer of silicone. The plastic models of the aneurysms’ internal geometry were then softened with xylene and squeezed out, leaving the final hollow silicone models.⁵

In this study, it was hypothesized that a method could be developed using standard medical images to create hollow, flow-through models of patient specific aneurysms. The goal of the project was to create such a method for building flow-through models, as well as a prototype of said model for surgical planning and practice. A secondary goal was for the model to serve as a method of confirming and visualizing computationally characterized flow patterns.

2. Methodology

2.1 Three dimensional model

After being approved by the Institutional Review Board of the Milwaukee School of Engineering, access was granted to computed tomography angiography (CTA) images and digital three dimensional models of aneurysms from three anonymized patients. The initial 3D models were created by Brittany Callan, a past REU student, and the CTA images were obtained from the Department of Radiology at the University of Virginia. The model was recreated from the CTA images to check for accuracy and eliminate deformation and over-smoothing introduced during the final steps of the creation of the original model.

The model was then edited using MAGICS software (Materialise, Plymouth, MI) to exclude blood vessels that do not directly lead to or from the aneurysms, as well as one connected vessel through which minimal flow was expected. The aneurysm that is modeled in this project occurred near the intersection of the internal carotid, middle cerebral, and anterior cerebral arteries. These inlets and outlets were retained in the edited model. The final model contained one inlet and two outlets from the large aneurysm. Cylindrical extensions were added to the inlets and outlets of the model to allow for the connection of fittings to which rubber tubing could be attached for the purpose of pumping fluid through the final model. This resulted in a model that would require less time and material to
create while maintaining the necessary geometry to simulate the original aneurysm. Figure 1 shows the new model with the added geometry for fittings on the right and the original, unedited model on the left.

Figure 1. Left: original model | Right: new model

### 2.2 Physical model

A method was devised to create expendable ores from 3D-printed models. These models were produced using additive manufacturing with a Z-corp printer (3D systems, Rock Hill, SC). Z-corp series 3D printers produce fragile plaster based models. Typically, these plaster models are infiltrated with a resin after initial production to make the model more durable. For this project, the resin step was skipped to make the model removable from the final flow-through system. The models are then typically waxed with paraffin wax to further increase their durability. Here, the wax was heated to roughly 70 degrees Fahrenheit, and the model was dipped into the wax. At this temperature the wax was hot enough to easily infiltrate the model while remaining cool enough to manipulate. This left a plaster model that was only infiltrated with wax, which served two purposes: (1) it held the model together at room temperature, while allowing it to be easily crushed and removed upon being heated above the melting temperature of the wax and (2) it improved the surface characteristics of the model by smoothing over pores and ridges that are produced during the 3D printing process without changing the geometric dimensions of the model. Due to the aneurysm model’s complex geometry, it was not successfully printed during this ten week project. A stand-in model was created from other incomplete, untreated models. Pieces were selected from these unfinished projects to create a model with two outlets and one inlet. This stand-in model was then used for the same purpose for which the aneurysm model was intended. For the outer material of the flow-through system, a transparent mold silicone (SORTA-clear 18, Smooth-on inc, Macungie PA) was selected. It was determined that transparency would add to the model’s educational value. Silicone was selected as a commonly used material for anatomical models. It is relatively resistant to heat and is relatively inert. A support layer of silicone was prepared following the manufacturer’s instructions and left to cure for roughly six hours. The core was then placed on top of the support layer and cast in the transparent mold silicone and left to cure for sixteen hours. Unfortunately, due to time constraints, the model created in this project was not degassed. Degassing improves transparency of cured silicone by removing embedded air pockets. The expendable core was removed from the silicone mold using a hot water bath to melt out the wax infiltration from the core. The silicone mold was then pressed and crushed manually to break down the expendable core without deforming the outer mold. A thin, solid wire was then used to further break down some of the larger chunks of the core that were left after the initial manual crushing. After the core was
removed, the silicone mold was finally cleaned by pumping xylenes through the model to dissolve the waxy film that had accumulated during the removal of the core. A peristaltic pump (Cole-Parmer Masterflex, model no. 7520-40, Vernon Hill, IL), rubber tubing (Masterflex, model no. 96400-17), and rotary vain flow sensors (McMillan Co., model no 101, Georgetown, TX) were attached to the final model using barbed fittings. The final model included one inlet and two outlets to and from the main aneurysm. The geometry of the stand-in model allowed for the easy addition of barbed fittings. In the flow loop, the peristaltic pump drew fluid from a reservoir. The pump led to a pulse dampener to create a steady flow through the model. Next, the flow sensor was placed to measure the inlet flow. An adaptation was added to allow for the insertion of intravascular surgical tools. Finally, the single inlet was connected to the model. Flow sensors were attached to the two outlets and the system was closed with the outlets connected back to the reservoir. Figure 2 shows the setup of the flow loop with the stand-in model.

3. Discussion

3.1 Discussion
The goal of this project was to develop a method for creating an effective training tool for surgeons to prepare for the treatment of patient specific aneurysms; specifically intravascular treatments. Once perfected, this modeling approach could potentially be used to explore new intravascular treatments and study the change in flow due to said treatments but further research is necessary to determine the actual effectiveness of this model as a simulation. In this project, the final model that was created was not the intended geometry. In spite of this fact, a potential method for the creation of a flow through model was developed. Because the actual aneurysm’s geometry was not used, it is difficult to predict whether this method would be useful in the long run with any certainty; this would largely depend on whether the method could be streamlined to produce patient-specific models in a timely manner. The expendable core was removed with minimal damage to the silicone mold and it was successfully attached to the flow system. With this in mind, it can be determined that this method of model creation shows some potential as being effective or at least a building block for a more refined method. In the future, once a model of the aneurysm’s geometry is successfully printed with the desired material, this project could benefit greatly by being critiqued by a surgeon. Insight regarding the effectiveness of the model could lead to fine tuning of the model itself and the method of its creation. The materials that were used to create the final model are widely available and easy to work with. The additive manufacturing techniques used for the creation of the expendable core are becoming more accessible as additive manufacturing equipment becomes cheaper and more user friendly. The solvents used are also extremely...
common and, in future projects, could potentially be replaced with something even more effective and safer to work with. The silicone used in this project required roughly 24 hours to cure completely. In future projects, the use of silicones with shorter curing times could be explored to expedite the process for use in real world situations. Finally, flow visualization could be performed on such models for comparison to computational fluid dynamics (CFD) results to confirm the accuracy of simulations used to optimize surgical treatments. Unfortunately, because the aneurysm’s geometry was not used, this was not tested during the project. The development of the methods used in this project will expedite future work with this project. Once a core is successfully printed, a future researcher could easily follow the methods developed during this project and quickly begin analysis of the model’s performance.

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