

Replicating Aneurysm Rupture

Report 1

Anna Mellin: Team, Design, and 3D Printing Lead

Amanda Ortiz-Velazquez: Budget and Testing Lead

Caden Adams: Casting and CAD Lead

Fall 2024-Spring 2025



Project Sponsor: Dr. Zhongwang Dou

Instructor: Dr. David Willy

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

Cerebral aneurysms cause approximately 500,000 deaths each year. To address this urgent issue, Dr. Zhongwang Dou, the team's client, has tasked the team with developing a way to create predictable aneurysm rupture models. These models could play a crucial role in preventing and repairing aneurysms. In the final design, the aneurysm model will be suspended in gelatin that simulates the pressure of brain tissue. This model will be connected to a pump that will send a blood-like fluid through the model. Flow and sensor pressures will be placed throughout the system for data collection. The client requires that the models be functional, predictable, and measurable.

The first step of the project was material analysis. A list of criteria that the materials must fulfill was created and heat resistance was identified as the most important factor. The material's ability to maintain shape, even with extremely thin walls was also considered a key component. These specifications resulted in the decision to use methods using 3D-printed material and silicone. The next step was to develop hollow models and molds within SolidWorks. Constructing the hollow models proved to be simpler than designing the molds. A three-part mold was one of the methods chosen to develop the hollow model. This consisted of a solid version of the aneurysm that would fit into the cavity of a two-part shell. The solid models required supports to ensure stability and contain the silicone within the mold. The cavity itself would be in the shape of the aneurysm geometry with a space of 0.75 mm to maintain even silicone distribution along the walls. The team experimented with different mold designs, which included versions with holes and keys. The final design, however, had neither.

Once the design was finalized, the resin printer and Idea Lab were used to produce the physical models. Both the Idea Lab prints and the resin printer using ABS-like material posed several issues. However, after several failed iterations, the team successfully created the full three-part mold and the hollowed model for the idealized aneurysm. In the upcoming weeks, different methods of filling the three-part mold with silicone will be tested and refined before then printing the core with water-soluble material. Dissolving the water-soluble core to create a hollow model will be the final step in preparing the product for testing.

Though similar aneurysm rupture simulations exist, this project aims to focus on quick, cost-effective production. The \$1,000 budget will fund the manufacturing process and the various tests that will be conducted to understand how effectively the model simulates aneurysm behavior, and the rupture of the aneurysm itself. The client emphasized the necessity of easy replication in this project, which means that creating the most economic parts and methods is crucial to success.

Once the idealized model simulation is repeatable and predictable, the next step is to produce patient-specific models. Having a working model could help advance medical devices and treatments used for aneurysms. This could ultimately help prevent deaths caused by aneurysm ruptures.

TABLE OF CONTENTS

Contents

DISCLAIMER.....	1
EXECUTIVE SUMMARY (Amanda).....	2
TABLE OF CONTENTS.....	3
1 BACKGROUND (Anna).....	1
1.1 Project Description.....	1
1.2 Deliverables.....	1
1.3 Success Metrics.....	1
2 REQUIREMENTS.....	3
2.1 Customer Requirements.....	3
2.2 Engineering Requirements.....	3
2.3 House of Quality (HoQ).....	4
3 Research Within Your Design Space.....	5
3.1 Benchmarking (Anna).....	5
3.2 Literature Review (All).....	7
3.2.1 Anna Mellin.....	7
3.2.2 Caden Adams.....	9
3.2.3 Amanda Ortiz-Velazquez.....	11
3.3 Mathematical Modeling (all).....	12
3.3.1 Anna Mellin.....	13
3.3.2 Aneurysmal Wall Pressure and Shear Stress - Caden Adams.....	12
3.3.3 Amanda Ortiz-Velazquez.....	14
4 Design Concepts.....	16
4.1 Functional Decomposition (Caden).....	16
4.2 Concept Generation (All).....	17
4.3 Selection Criteria (Amanda).....	20
4.4 Concept Selection (All).....	20
5 CONCLUSIONS (Amanda).....	22
6 REFERENCES (all).....	23
7 APPENDICES.....	26
7.1 Appendix A: Descriptive Title.....	26
7.2 Appendix B: Descriptive Title.....	Error! Bookmark not defined.

1 BACKGROUND

This chapter highlights the general goals and direction of the aneurysm rupture modeling project. Two models will be created: idealized and patient-specific, which will be manufactured with the lost-wax casting method and high-resolution 3D printing. The project seeks to develop a realistic model within a budget of \$1000 and a fundraised \$100. With a functional model, teaching aneurysm anatomy and personalized treatment strategies may become more accessible to low-resource settings.

1.1 Project Description

This project focuses on the development of an aneurysm rupture model. The main objective of this project is to manufacture a model that mimics real-life rupture phenomena. The fluid flows will be measured with pressure sensors and a high-speed camera in order to verify the accuracy of the model. The end goal is to be able to create a model with high repeatability and a predictable burst. Manufacturing methods will consist of the lost-wax casting method and high-resolution 3D printing. These approaches were specified by the client as a means of cheap manufacturing. Our budget is \$1000, with the goal of fundraising 10% or \$100. If the model is both cheap and easy to remanufacture, it becomes more accessible to hospitals and clinics with smaller budgets. Not only would this create a perfect mechanism for teaching aneurysm anatomy and function in underprivileged areas, but patient-specific aneurysms may be quickly replicated, allowing for doctors to examine the aneurysm more thoroughly and determine the best treatment approach.

1.2 Deliverables

The major deliverables for this project are provided by our client Dr. Zhongwang Dou. The expected yields of this project are an idealized aneurysm model and a patient-specific model. The idealized model consists of a small sphere with two cylindrical legs that stick out at roughly a 120-degree angle. The patient-specific model is derived from a model given by Dr. Dou's laboratory. The lost-wax casting method and high-resolution 3D printing will be utilized to develop cheap and accurate models. The final models will be constructed of elastic silicone and must be easily tested with pressure sensors and a high-speed camera attached to a pump configuration. This pump setup will replicate the human cardiovascular system pumping blood into the aneurysm. The final deliverable is to make the aneurysm rupture.

1.3 Success Metrics

The project will be noted as a success when both idealized and patient-specific models are manufactured quickly and accurately. A current production timeframe is not set but will be defined once a working model is created. Once a working model has been produced, it must also be connectable to the pump configuration and accurately depict aneurysm blood flow. The aneurysm must be able to rupture, and the final metric of success will be forcing the rupture to occur within a minute.

To be more specific, the aneurysm walls must emulate the characteristics of human vessel walls. The current benchmarks prioritize geometry over behavior, which leads to less accurate simulations. This will be tested by comparing current data of blood flow and vessel wall behavior to that of the models. By using the high-speed camera setup, the flow can be analyzed. Additionally, wall characteristics may be assessed using a rheometer to understand the elastic silicone shear stress and strain threshold compared to a vessel wall. Equations such as Laplace's Law, Poiseuille's Flow, Navier-Stokes, and the equation for

arterial pressure—all explained further in a later section—will help with calculating the forces within the aneurysm and provide a prediction for when the aneurysm wall will fail. The Noyes-Whitney equation will allow the prediction of manufacturing times and assist in determining the most efficient means of production.

2 REQUIREMENTS

This chapter outlines the engineering and customer-specific requirements laid out for this project with the end goal of creating a cost-effective and easily reproducible aneurysm rupture model. The engineering requirements focus on parameters such as material strength, accurate simulation of aneurysm behavior ease of construction, and repeatability of vessel geometries. These criteria ensure that the aneurysm can produce consistent results. On the customer side, the primary needs include ease of use, affordability, and a different predictable geometry for patient-specific and idealized models. Meeting these requirements is critical to creating a substantial product capable of predicting aneurysm ruptures within 60 seconds of starting fluid flow.

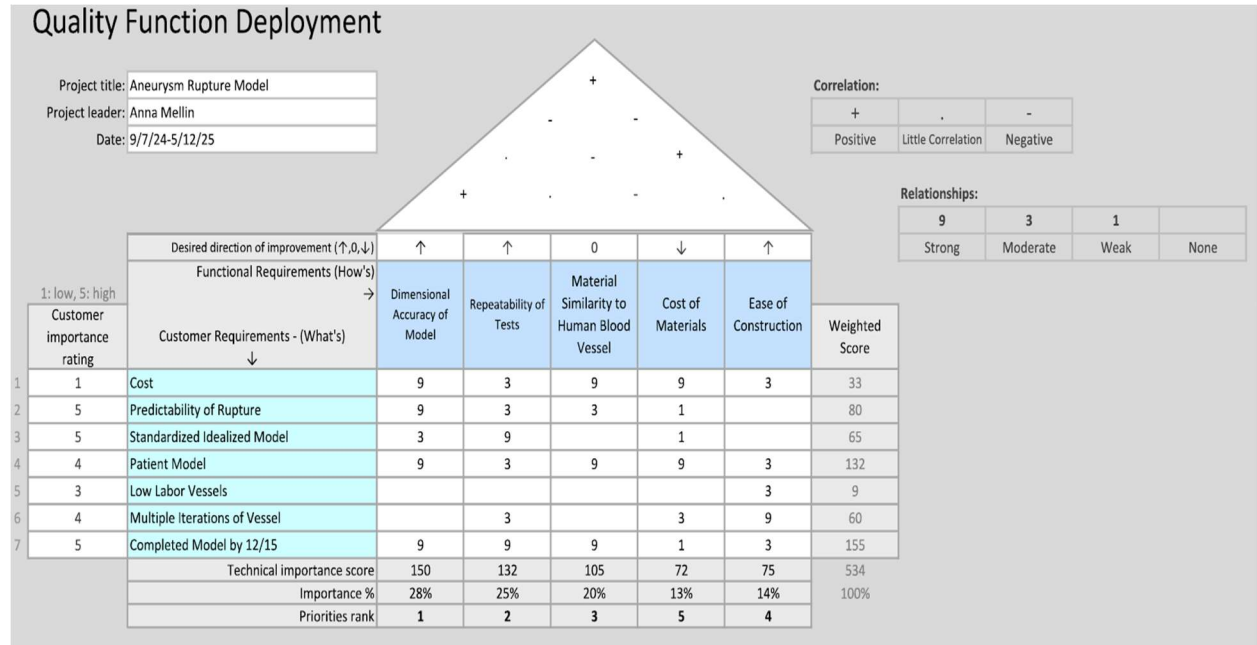
2.1 Customer Requirements

The customer requirements for this project are low cost, predictability of rupture, patient-specific and idealized rupture models, and low labor requirements. The customer laid this out in the first debrief, in which a budget of \$1000 was established. The requirement for rupture predictability stems from the project's need for data collection through an inlet and outlet, transparent vessels, and the targeted application of chemicals to create a thin wall in the aneurysm. This allows the direct observation of ruptures and deformations. Patient-specific and idealized models are required to give a broader testing basis than perfect geometry vessels every time. The patient-specific models are taken from the Vascular Model Repository [2] and when testing commences, the goal is to analyze at least 4 different patient-specific geometries. The low labor requirement ensures that rapid turnaround on new geometries is economically feasible and considers that each model can endure one test before rupture, so new model creation is imperative for a strong testing background.

2.2 Engineering Requirements

The engineering requirements for this project are dimensional accuracy of models, repeatability through model consistency, provision of both a wax cast and 3D printed soft material model for all specified geometries, material cost and availability, and ease of manufacturing. Dimensional accuracy requires the wall thicknesses to be within 0.15 mm of real observed aneurysms of large model geometries. Model consistency stems from the fact that the team needs accurate testing parameters, which begin with the model being tested. Providing both a wax cast and 3D printed model for all geometries creates a wider scope of potential methods moving forward and comparable results between two materials of the same dimensions. Material cost stems from the fact that most of the printing work done in this project is done with resin, primarily water-soluble resin, which is incredibly costly but required for the desired accuracy of the prints. Finally, ease of manufacturing is an important requirement as a rapid print turnaround on vessels will be necessary once testing begins.

2.3 House of Quality (HoQ)



3 Research Within Your Design Space

3.1 Benchmarking

Benchmarking is used to compare current designs to the ones in progress. The point is to take into account existing products and either find the faults that can be improved or use the strengths to incorporate them into the new design. The benchmark characteristics targeted for analysis were working models of aneurysms based on patient-specific geometry. Because the goal of this project is to create a replica of a cerebral aneurysm and test it with a fluid flow system, the best standards must also do the same. This section looks at the mode of production, cost, and general effectiveness. The first benchmark was the Kono Aneurysm shown in Figure 1 [5].



Figure 1: Kono Aneurysm Model

A 3D-printed vessel and aneurysm model is lain in a silicone block to create the desired geometry which is later dissolved to form the aneurysm-shaped cavity in the block. The process of development and testing took roughly two weeks to complete and cost a total of \$600. The actual creation timeframe is not given. One of the main issues with this model is that the walls of the aneurysm were much stiffer than those of an actual vessel wall. By not following the behavior of a real aneurysm, the ability to use this to simulate treatment is limited.

The capstone model is currently estimated to require two days for development: a day for printing and curing the molds, and a day for allowing the silicone to cure. Assuming numerous models of the same geometry are to be made, only the water-soluble core needs to be printed numerous times. Additionally, with less silicone, the curing time of the capstone model would be significantly lower than that of the Kono Model.

The second chosen benchmark was the Sugiu Model which is comprised of two parts, a rigid model, like the Kono Model situated in a block of silicone, and a soft model which only consists of the model walls, rather than floating in silicone (Figure 2) [6].



Figure 2: Sigiu Models: rigid model (left) and soft model (right)

The rigid model faced the same issues as the Kono Model, but the soft is closer to the objective of the capstone model. The main difference between the soft model and the capstone model is the method of production. The soft model was created via a lost-wax method and the silicone was applied by brushing on layers. This can lead to uneven wall thickness and striations left from the brush. The capstone model, with a uniform gap between the negative and positive molds, forces a uniform wall thickness, assuming the silicone is distributed without air bubbles. The capstone model is projected to require less labor and less attention to detail, making the model easier to manufacture and more geometrically accurate than the soft Sigiu Model.

The final benchmark chosen is the Liu Model, which is seemingly the most similar to the current capstone objectives [7]. Numerous models were made including a ruptured vessel, a collapsed vessel, a regular vessel, an uneven vessel, and a rigid vessel (Figure 3).



Figure 3: Liu Model- ruptured vessel, a collapsed vessel, a regular vessel, an uneven vessel, and a rigid vessel, respectively

The Liu Model is very cheap at under \$25 per model. The method of creation is similar to the soft Sigiu Model and uses a coating technique rather than a three-part mold. Additionally, the methods for

constructing the blister bulges shown in Figure 4 may be duplicated in the capstone model to examine different methods in reproducing aneurysms. The Liu Model uses both hard and soft silicone to allow the blister bulge to form, but it may also cause the vessel wall properties to stray from real-life characteristics.

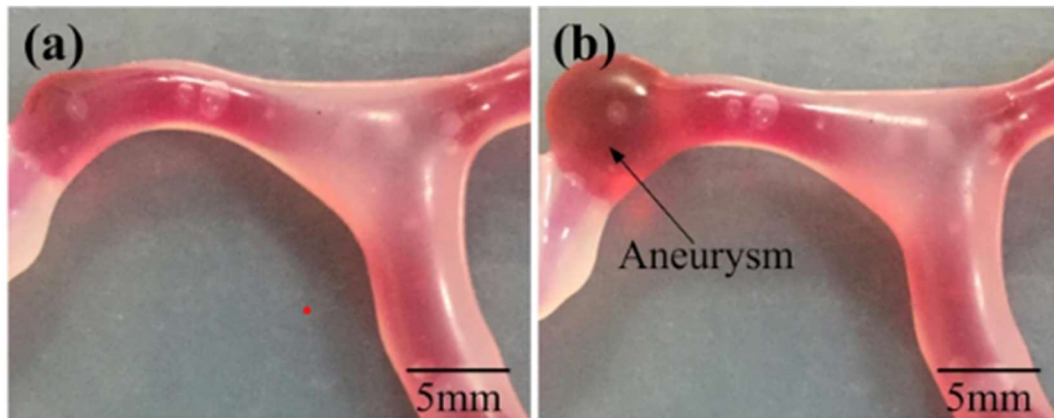


Figure 4: Blister bulge in Liu Model

These benchmarks construct a price range to aim for, as well as provide certain capabilities of aneurysm models currently on the market. By using a different technique than those already formulated, an easier, cheaper, and faster model may be developed to advance the medical field.

3.2 Literature Review

3.2.1 Anna Mellin

[2] “Vascular Model Repository,” *Vascularmodel.com*, 2024. <https://www.vascularmodel.com/index.html> (accessed Sep. 14, 2024).

This archive contains scans of real patient cardiovascular systems which can be used in further development of patient specific cerebral aneurysm models.

[3] R. Fox, A. McDonald, and J. Mitchell, *Fox and McDonald’s Introduction to Fluid Mechanics*, 10th ed. 111 River Street Hoboken, NJ: John Wiley & Sons, 2020.

This textbook is a reliable source of how fluid dynamics work which will be important for observing the behavior of fake blood flow within the capstone model.

[4] Mayo Clinic, “Brain aneurysm - Symptoms and causes,” *Mayo Clinic*, Mar. 07, 2023. <https://www.mayoclinic.org/diseases-conditions/brain-aneurysm/symptoms-causes/syc-20361483>

This medical website briefly defines a brain aneurysm and provides background information specifically useful for non-medical professionals.

[5] Kono K, Shintani A, Okada H, Terada T. Preoperative simulations of endovascular treatment for a cerebral aneurysm using a patient-specific vascular silicone model. *Neurol Med Chir (Tokyo)*. 2013;53(5):347-51. doi: 10.2176/nmc.53.347. PMID: 23708228.

A silicone model of an unruptured brain aneurysm is used to simulate treatment plans such as

balloon-assisted coil embolization. The model was based on a 3D image of a patient's aneurysm, 3D printed with acrylate photopolymer (light-activated resin) using the Vision Realizer RVS-G1. This model was then set in a block of silicone. When cured, the acrylate photopolymer was removed, leaving a cast of the aneurysm behind. This resulted in an easier application of treatment, with a significant difference noted: the real-life vessel was much more sensitive to catheter applications, causing slight differences between the simulation and the actual treatment. The main difference between this project and the capstone project is that the Kono Model only takes geometry into account rather than emulating the properties and reactions of the aneurysm.

[6] Sugiu K, Martin JB, Jean B, Gailloud P, Mandai S, Rufenacht DA. Artificial cerebral aneurysm model for medical testing, training, and research. *Neurol Med Chir (Tokyo)*. 2003 Feb;43(2):69-72; discussion 73. doi: 10.2176/nmc.43.69. PMID: 12627882.

Two models were created using the 'lost wax' technique, one hard and one soft. The hard model was created out of a solid silicone block where the aneurysm structure was melted out leaving behind the impression of the aneurysm. The soft model was made via painting 4-6 layers of silicone on the wax model and then melting the wax leaving behind the phantom model that replicated the properties of the vessel walls better.

[7] Liu, Y. *et al.* Fabrication of cerebral aneurysm simulator with a desktop 3D printer. *Sci. Rep.* **7**, 44301; doi: 10.1038/srep44301 (2017).

Numerous models were made using the same techniques. The main process included 3D printing a core with PVA and using a coating technique to cover the model in silicone. Both hard and soft silicones were used in order to replicate a bulge to simulate aneurysm formation. The PVA was then dissolved leaving behind a hollow model perfect for flow analysis.

[8] J. R. Ryan, K. K. Almefty, P. Nakaji, and D. H. Frakes, "Cerebral Aneurysm Clipping Surgery Simulation Using Patient-Specific 3D Printing and Silicone Casting," *World Neurosurgery*, vol. 88, pp. 175–181, Apr. 2016, doi: <https://doi.org/10.1016/j.wneu.2015.12.102>.

Not discussed in the main three benchmarks as a more accurate model was found. An anatomically correct model was created via 3D printing using photopolymer (Objet500 Connex multimaterial printer) and 2-part silicone casting (used for the skull). This was developed to assist medical students in becoming familiar with cerebral anatomy and aneurysm clipping. A skull model was created to incorporate the brain aneurysm to familiarize the medical students with a non-isolated aneurysm. Although used for aneurysm clipping procedural practice, to the best of the team's understanding, there is no mention of simulating the aneurysm properties (although the skull is meant to replicate its respective properties) but rather this method is focused on helping students with anatomy identification. This may help the capstone model in correcting patient specific geometry.

[9] N. Hopkinson, Richard Hague, and Philip Dickens, *Rapid Manufacturing An Industrial Revolution for the Digital Age*. The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ England: John Wiley & Sons, Ltd, 2006.

This book is a great source for understanding additive manufacturing and standards.

[10] “Flow Diversion with Stents for Brain Aneurysms,” Dec. 28, 2022.
<https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/flow-diversion-with-stents-for-brain-aneurysms#:~:text=What%20is%20flow%20diversion%20for>

This website illustrates flow diversion with a stent treatment plan for brain aneurysms. Brain stents are a common form of treatment for cerebral aneurysms.

[11] “Endovascular Coiling,” *John Hopkins Medicine*, 2019.
<https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/endovascular-coiling>

This website describes another treatment plan involving coils of platinum metal being inserted into the aneurysm to promote clotting and take pressure off the weakened wall.

[12] “Microsurgical Clipping and Endovascular Coiling for Brain Aneurysm,” *www.hopkinsmedicine.org*.
<https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/microsurgical-clipping-and-endovascular-coiling-for-brain-aneurysm>

This website provides information about clipping as a means of treatment for brain aneurysms.

3.2.2 Caden Adams

[13] R. G. Nagassa, P. G. McMenamin, J. W. Adams, M. R. Quayle, and J. V. Rosenfeld, “Advanced 3D printed model of middle cerebral artery aneurysms for neurosurgery simulation,” *3D Printing in Medicine*, vol. 5, no. 1, Aug. 2019, doi: <https://doi.org/10.1186/s41205-019-0048-9>.

This article depicts a simple wax-casting method to create a vascular model with a defined aneurysm neck. The process entails the creation of a 3D print of a CAD aneurysm model which is then cast in wax, and painted in several layers of silicone, allowing the wax to be melted through evacuation points leaving a hollow silicone model. This approach allows for a realistic simulation of neurosurgical procedures.

[14] M. S. Pravdivtseva *et al.*, “3D-printed, patient-specific intracranial aneurysm models: From clinical data to flow experiments with endovascular devices,” *Medical Physics*, vol. 48, no. 4, pp. 1469–1484, Feb. 2021, doi: <https://doi.org/10.1002/mp.14714>.

This study delves into the creation of 3D-printed models of intracranial aneurysms specific to patients' aneurysm geometries. The models can be produced within 15-30 hours, allowing for a relatively quick risk analysis and optimal cure procedure.

[15] J. R. Cebra *et al.*, “Aneurysm Rupture Following Treatment with Flow-Diverting Stents: Computational Hemodynamics Analysis of Treatment,” *American Journal of Neuroradiology*, vol. 32, no. 1, pp. 27–33, Nov. 2010, doi: <https://doi.org/10.3174/ajnr.a2398>.

This research investigates the velocity and pressure changes in aneurysms following the implementation of flow-diverting stents using computational fluid dynamics. The use of CFD software is helpful for identifying factors that can lead to both reduced and increased flow rates.

[16] L.-D. Jou and M. E. Mawad, “Analysis of Intra-Aneurysmal Flow for Cerebral Aneurysms with Cerebral Angiography,” *American Journal of Neuroradiology*, vol. 33, no. 9, pp. 1679–1684, May 2012, doi: <https://doi.org/10.3174/ajnr.a3057>.

This article looks at aneurysmal flow using contrast injection. This method allows for non-invasive blood flow analysis through the observation of luminescent particles on the micron level in the blood stream.

[17] W. C. Merritt, H. F. Berns, A. F. Ducruet, and T. A. Becker, “Definitions of intracranial aneurysm size and morphology: A call for standardization,” *Surgical Neurology International*, vol. 12, p. 506, Oct. 2021, doi: https://doi.org/10.25259/SNI_576_2021.

This article goes over the definitions of intracranial aneurysm size. The authors advocate for the standardization of measurements and suggest that wide-neck aneurysms should be the norm for further study.

[18] K. W. Yong, M. Janmaleki, M. Pachenari, A. P. Mitha, A. Sanati-Nezhad, and A. Sen, “Engineering a 3D human intracranial aneurysm model using liquid-assisted injection molding and tuned hydrogels,” *Acta Biomaterialia*, vol. 136, pp. 266–278, Dec. 2021, doi: <https://doi.org/10.1016/j.actbio.2021.09.022>.

This article shines light on a method for engineering 3D intracranial aneurysm models using liquid- injection molding and specialized hydrogels. The process allows for the creation of models that resemble the properties of human tissue, opening the door to a more realistic simulation environment.

[19] C. Patel, “Acquiring Data from Sensors and Instruments Using MATLAB.” Available: <https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/solutions/automotive/files/in-expo-2012/acquiring-data-from-sensors-and-instruments-using-matlab.pdf>

This document along with the MathWorks website gives readers a guide on using MATLAB for gathering data from sensors and instruments. It covers the fundamental methods for connecting and collecting data, which gives the team a good option for when flow sensors are added into the testing phase.

[20] L. Boussel *et al.*, “Aneurysm Growth Occurs at Region of Low Wall Shear Stress,” *Stroke*, vol. 39, no. 11, pp. 2997–3002, Nov. 2008, doi: <https://doi.org/10.1161/strokeaha.108.521617>.

This study looks at the relationship between wall shear stress and aneurysm growth, finding that regions of low shear stress are more likely to expand and rupture. The findings suggest that wall shear stress may be a strong factor in predicting aneurysm risk.

[21] The Engineering Toolbox, “Dynamic Viscosity of common Liquids,” *Engineeringtoolbox.com*, 2019. https://www.engineeringtoolbox.com/absolute-viscosity-liquids-d_1259.html

This online resource provides a comprehensive list of dynamic viscosity values for various liquids, used primarily for hemodynamic analysis in this project.

[22] F. M. White, *Fluid Mechanics*, 7th ed. McGraw Hill, 2011.

This textbook was used in the team’s fluid dynamics class, offering a wealth of fluid mechanics principles. It is a valuable resource for understanding the fluid mechanics taking place in this project, in a digestible setting as the team has experience with the textbook.

[23] A. Mardston, “SimVascular,” *SimVascular Docs*, 2024.
<https://simvascular.github.io/documentation/quickguide.html> (accessed Oct. 20, 2024).

This source comes from the SimVascular’s github page that describes the process for setting up problems for the computational fluid dynamics solver. Detailing common issues, user guides, and more. Providing a useful tool for modeling the team’s geometries in an idealized space.

3.2.3 Amanda Ortiz-Velazquez

[24] Á. Ugron, “Flow Simulation in Intracranial Aneurysms,” ProQuest Dissertations & Theses, 2015.

This dissertation discusses the use of flow simulation to comprehend the hemodynamics involved in brain aneurysms and their ruptures. The author examines how different flow-modeling techniques can be utilized to better understand aneurysms and help improve patient-specific diagnoses and outcomes. The team chose this article because the ultimate goal of their project is to make patient-specific models that can be used to fix aneurysms. Ways of modeling flow would be incredibly useful when creating the patient-specific aneurysms models.

[25] D. M. Sforza, C. M. Putman, and J. R. Cebral, “Computational fluid dynamics in brain aneurysms,” *International journal for numerical methods in biomedical engineering*, vol. 28, no. 6–7, pp. 801–808, 2012, doi: 10.1002/cnm.1481.

This paper focuses on the use of computational fluid dynamics to study how blood flow and wall geometry contribute to the formation and ultimately the rupture of brain aneurysms. This source was used because the team’s current project aims to do a similar thing. However, unlike in the dissertation which is mostly mathematical model based, this project will be heavily based on experimentation. However, the use of computational fluid dynamics might prove to be useful when the team enters the replication phase of the project.

[26] P.-C. Chen et al., “Engineering additive manufacturing and molding techniques to create lifelike willis’ circle simulators with aneurysms for training neurosurgeons,” *Polymers*,
<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7761873/> (accessed Sep. 9, 2024).

This source explores the use of 3D printing to create a life-like model of the willis circle. The author discusses how the properties of certain filaments can actually do a very good job in replicating the properties of brain tissue. Ideally this method could be utilized in training future neurosurgeons and perfecting or inventing new techniques for brain surgery. The team considered this article important while choosing which materials to create their own models out of.

[27] ochxlzwiz, “electric circuits 11th edition nilsson pdf.” Zenodo, Jun. 10, 2024, doi: 10.5281/ZENODO.12364277.

This book provides a detailed explanation of basic electrical circuits and components. The team utilized this source to do some preliminary calculations concerning the pump that will be used later in the project.

[28] H. E. A. Baieth, "Physical parameters of blood as a non - newtonian fluid," International journal of biomedical science : IJBS, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3614720/> (accessed Sep. 9, 2024).

This article explains the properties of blood and how it acts as a non-newtonian fluid. The paper highlights how shear rate and viscosity affect the behavior of blood in the circulatory system and therefore, are extremely important in flow simulations and analysis. The article also emphasizes that understanding the physical properties of blood is crucial in making medical devices that are compatible in the body and effective. The team looked at this article because understanding the properties of blood will be useful when ensuring that their simulation is as realistic as possible.

[29] "Blood flow - CFD simulation CFD software tutorial," Blood Flow CFD Simulation Software, <https://help.sim-flow.com/tutorials/blood-flow> (accessed Sep. 16, 2024).

The above source is software available that allows for computational fluid dynamics simulation as well as provides a tutorial on how to do so. This source is important because it allows the team to test out different aneurysm types and get an idea of how they will rupture without having to create actual models which are time consuming and expensive.

[30] M. R. Harreld, "Brain aneurysm blood flow: Modeling, simulation, VR visualization," ProQuest Dissertations & Theses

This source analyzes the use of virtual reality to better understand the behavior of cranial aneurysms and their ruptures. The author hopes to use VR alongside other advanced modeling techniques in order to improve risk assessments for patients as well as create better ways to map out surgery or other treatment plans. This source was useful for the team to understand brain aneurysms better.

3.3 Mathematical Modeling

3.3.1 Aneurysmal Wall Pressure and Shear Stress - Caden Adams

The first engineering calculation completed for this section was pressure at the walls of the aneurysm through the usage of mean arterial pressure, calculated by adding systolic pressure to two times the diastolic pressure, which are taken from standard blood pressure readings. Then the results were plugged into Bernoulli's Equation 2. Assuming viscosity of the fluid to be one, the calculation follows.

Mean Arterial Pressure:

$$MAP = \frac{SBP + 2 \times DBP}{3}$$

SBP = Systolic Blood Pressure

DBP = Diastolic Blood Pressure

$$\text{Type 2 Hypertension: } \frac{SBP}{DBP} = \frac{140}{90} > \frac{140+2 \times 90}{3} = 106.67 \text{ mmHg}$$

$$P_1 = 15 \text{ mmHg (Static Pressure from Brain)}$$

$$S = 0.192 \text{ mm (Aneurysm Tube Diameter)}$$

$$V_1 = 8.3 \text{ ml (Per pump, based on Becker setup of } 0.5 \frac{\text{L}}{\text{min}})$$

$$\rho = 1$$

$$P_1 + \frac{1}{2} \rho V_1^2 = P_2 + \frac{1}{2} \rho V_2^2 + \rho g h_2 \text{ (Equation 2: Bernoulli's Equation)}$$

$$V_2 = 0: \text{ blood flow near top of aneurysm stagnates}$$

$$h_2 = 0: \text{ Start and end height the same}$$

$$15 \text{ mmHg} + \frac{1}{2} \left(\frac{MAP}{Rv \times \pi * r^2} \right)^2 = P_2$$

$$P_2 = 49.445 \text{ mmHg} = 6592.106 \text{ Pa}$$

The second calculation performed for this section is to determine wall shear stress in an aneurysm through the usage of Poiseuille Flow (assuming laminar flow) [22].

$$\tau_w = \frac{4\mu Q}{\pi R^3} \text{ (Equation 3: Poiseuille Flow for WSS)}$$

- μ = Dynamic Viscosity (of fluid $\text{Pa} \cdot \text{s}$) [21]
- Q = Volumetric flow rate of blood ($\frac{\text{m}^3}{\text{s}}$) = $342 \frac{\text{mL}}{\text{min}}$ [21]
 - R = Blood Vessel Radius (m)

$$\tau_w = \frac{4 \times 0.0035 \text{ Pa} \cdot \text{s} \times 5.713 \times 10^{-6} \frac{\text{m}^3}{\text{s}}}{\pi \times (0.005195 \text{ m})^3}$$

$$\tau_w = 0.182 \text{ Pa}$$

- Areas with low shear stress ($\tau_w < 0.4 \text{ Pa}$) are more prone to enlargement and potential rupture. [20]

3.3.2 Anna Mellin

In the first presentation, the Navier- Stokes equation shown in Equation 4 describes fluid movement which can be used to help characterize the flow in the model artery and compare its behavior to that of a real-life aneurysm [3].

$$\rho \left[\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} u + \frac{\partial u}{\partial y} v + \frac{\partial u}{\partial z} w \right] = - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \rho g_x$$

Another equation to characterize the model is Laplace's Law (Equation 5), which describes the tension in the wall of the aneurysm [1].

$$T = \frac{PR}{2} \text{ (Equation 5 Laplace's Law)}$$

T = tension

P = internal pressure

R = radius

If P = 12443.3784 Pa (using Equation 6), and R = 0.010 m for a large aneurysm, the tension is

$$T = \frac{12443.3784 \text{ Pa} * 0.010 \text{ m}}{2} = 124.43 \text{ Pa} * m \text{ (Equation 6)}$$

Which if compared with the tension the aneurysm wall can withstand, will tell us if the aneurysm will burst or not.

The next equation, also based on Laplace's Law, demonstrates the stress within the wall of the aneurysm.

$$\sigma = \frac{Pr}{2w}$$

The variables in these equations represent the following:

σ = wall stress

P = Internal Pressure

r = radius

2 = wall thickness

$$\sigma = \frac{12443.3784 \text{ Pa} * 0.01 \text{ m}}{2 * 0.75 \text{ m}} = 165.91 \text{ Pa}$$

This equation will help dictate where the aneurysm is most likely to burst (by examining wall thickness) and again, whether the silicone will be able to withstand the stress inflicted upon it.

3.3.3 Amanda Ortiz-Velazquez

The last calculation performed was the Noyes-Whitney Equation shown below. This equation provides an estimation for how long it will take for the water-soluble resin to completely dissolve in water.

$$dM/dt = (DA(C_s - C))/L$$

The variables in these equations represent the following:

DM/dt = rate of mass dissolved per unit time
D = diffusion coefficient
A = Surface area
Cs = saturation concentration
C = concentration of solute in solvent at time
L = thickness of boundary layer

In order to conduct the calculations using this equation, a few assumptions were made. Diffusion coefficient and saturation concentration are not listed for the exact type of resin that we will be using so the team had to take the average numbers for these factors for other available water-soluble resins.

$$dM/dt = ((1 \times 10^{-5} \text{ cm}^2) \times (5.52 \text{ cm}^2) \times (0.5 \text{ g/L})) / 0.01 \text{ cm} = 2.76 \times 10^{-3} \text{ g/s}$$

With 6 grams of resin and a surface area of 5.52 cm²:

$$(6 \text{ g}) / (2.76 \times 10^{-3} \text{ g/s}) = 2174 \text{ seconds}$$

$$2174 \text{ seconds} = 36.2 \text{ minutes}$$

According to the calculations, it would take about 36 minutes for the water-soluble resin to completely dissolve with room temperature water (78 degrees Fahrenheit) and no agitation.

4 Design Concepts

4.1 Functional Decomposition

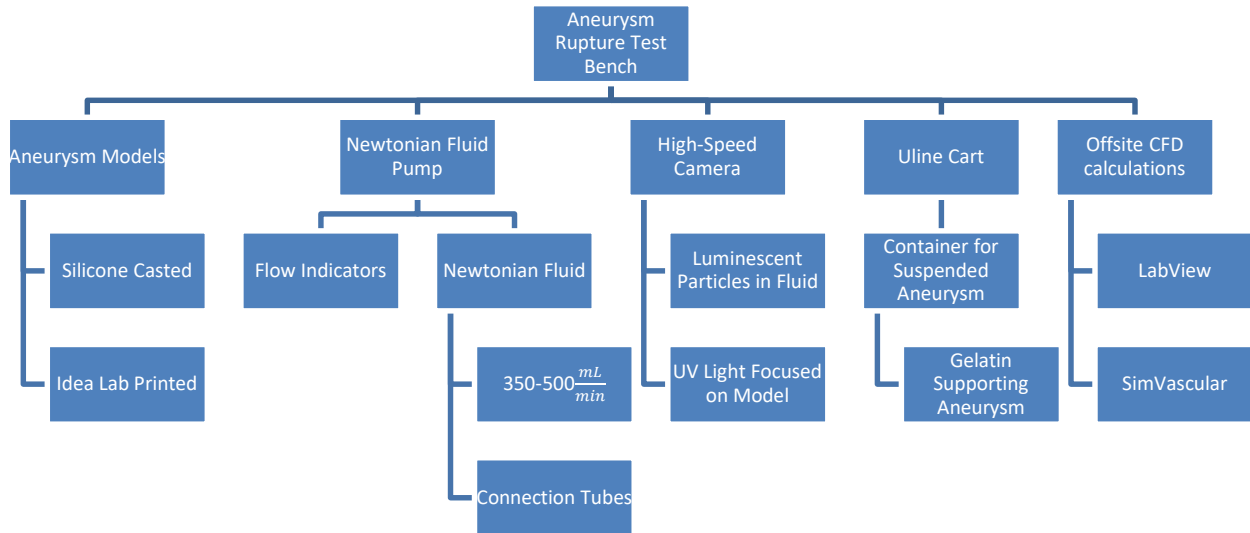


Figure 5: Functional Decomposition

Pictured above is the functional decomposition for this project, starting with the end goal of a moving operation aneurysm test bench. This decomposition is important project as the client needs and mentor instructions are not as finite or linear as other projects. A lot of this work is up to interpretation, so having a model that lays out all the required pieces of each part is extremely important for the success of the project.

This decomposition breaks down the complex tasks of the project into manageable subtasks, in which all aspects of the project are accounted for, guiding the direction of the project with the overarching goal of creating a realistic simulation environment for aneurysm treatment procedures.

4.2 Concept Generation

4.2.1 Support System

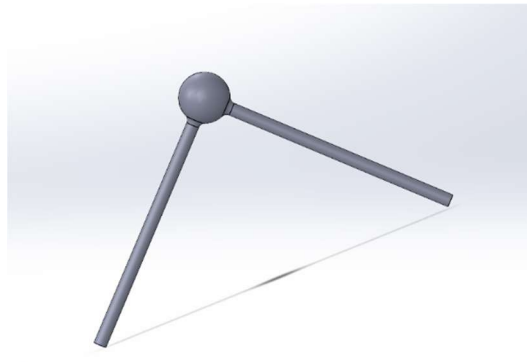


Figure 6: No Support System

Figure 6 above depicts the original design which has no supports. This design was not chosen because it did not meet the necessary requirements. Without supports, the structure would move once the silicone was inserted and the walls of the mold would not be uniform. However, this design was the easiest to create and did have the lowest production cost.



Figure 7: Cylindrical Support System

The second design shown in the figure above had two cylindrical supports on either end of the structure. While this design did use less material than some of the other designs, it would not provide adequate support, and silicone would leak out of mold through the ends.



Figure 8: Cylindrical Supports along structure

This above design shows cylindrical supports along the structure on one side. This design provided the most support as every area of the structure had a support. However, not only did this design use the most amount of material which made it difficult to design and would increase manufacturing cost, it would also create issues in the postproduction of the model. When the mold would be filled with silicone, the silicone would harden around these cylinders creating holes in the structure. It would then be necessary to find a way to cover these holes after the model hardened and ensure that the patches were even. Due to this, the design shown in the figure above was chosen as it did not meet the requirements for the project.

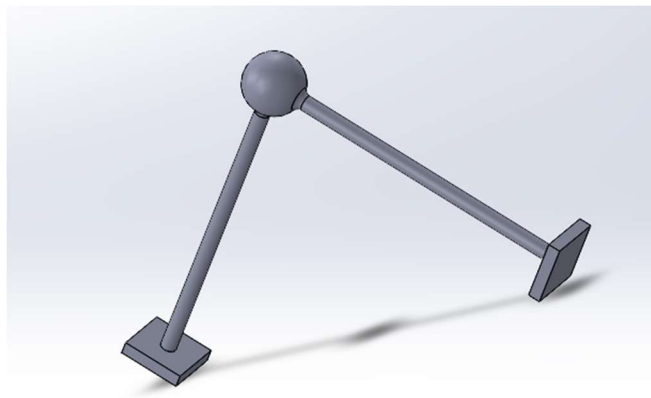


Figure 9: Square Supports

Figure 9 shows the final design with square supports on both ends of the structure. This design would provide the needed support without compromising the structure. The square ends would slot into holes in the mold which would keep the silicone from leaking out of the sides. Despite having a slightly higher production cost than some of the other designs, this design was chosen as it would be the simplest while still satisfying the other criteria.

4.2.2

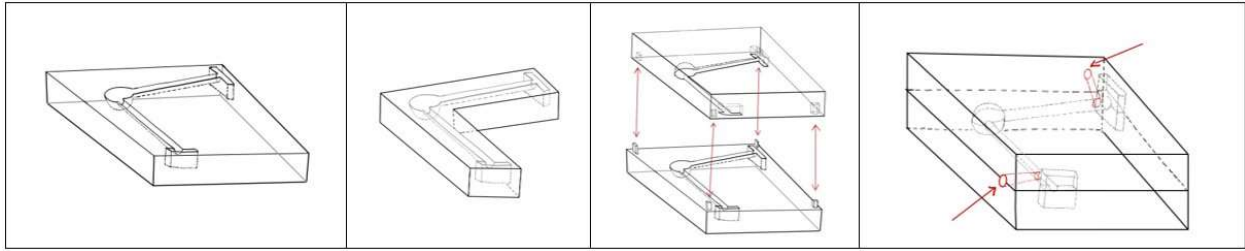


Figure 10: Negative mold concepts, from left to right: Idea 1: basic square negative, Idea 2: negative without excess, Idea 3: with keys, male and female parts, Idea 4: with holes for silicone injection.

Idea 1 was the generic concept. It fulfilled the basic requirements of creating a cavity with a space of 0.75 mm for wall thickness while keeping the silicone in place. Idea 2 was formulated as a means of reducing cost. By removing unnecessary material, the expenses are reduced. Idea 3 was developed as a potential means of reducing error. By creating keys with male and female parts for the two sides of the negative mold to fit together, the parts will not be able to slide around and there is less of a risk of deformity. Idea 4 was produced to increase accuracy of the anatomical model. By injecting silicone through holes, the parts are again less likely to slide (as they will be adhered to each other before injection) and deformity is again less likely to occur.

4.2.3 Negative Mold Conception

When producing the hollow models, there was not much leeway in terms of development. The various methods included SolidWorks attempts with various methods of hollowing out the complex geometries, but this failed multiple times as the files used primarily were mesh STL files, which SolidWorks has a very difficult time working with. After these trials and errors, the focus was shifted to Mesh Mixer, in which the body could be hollowed out with specified parameters providing a much simpler way to model. Mesh mixer was also a crucial tool for smoothing and changing the size of the models as it was designed to work with the mesh bodies used in this project. The team plans to use more SolidWorks in the mold generation previously stated.

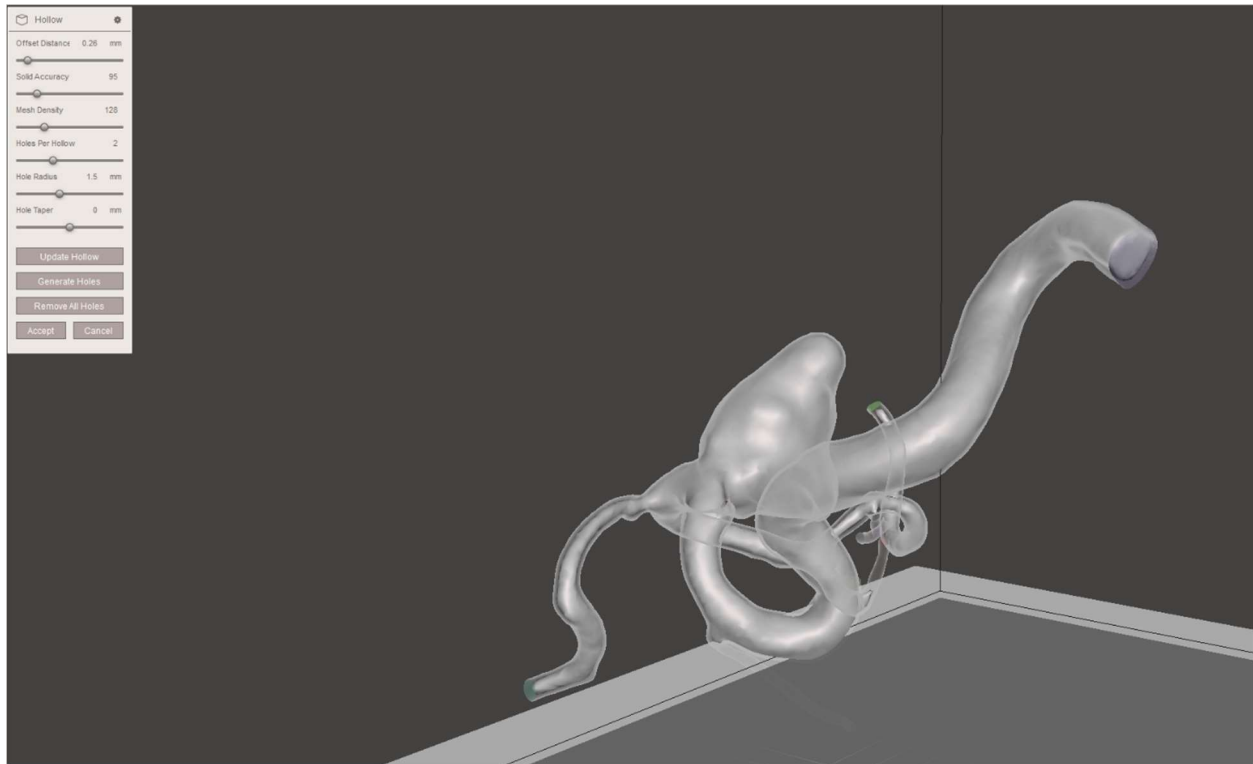


Figure 11: Meshmixer Hollow Feature

4.3 Selection Criteria

After meeting with the client, Dr. Zhongwang Dou, a list of criteria was provided which entailed the concepts that the project must meet. Additional requirements were also added as the project progressed. These customer requirements and criteria included cost, simplicity, user-friendliness, reusability, precision, and effectiveness. The material being used for the resin printer costs approximately \$50 per bottle, due to this, the team decided that the concepts that utilized the least amount of material would be preferred. For precision the team needed the dimensional accuracy to be within 0.15 mm. For the final design the product must be within 0.10mm. The reusability aspect refers mainly to how easy the design is to reprint; this came down to how big the design was and how many fragile parts were included in each concept. This requirement is almost directly correlated to the cost. The smaller the part, the easier it is to print and the lower the cost. User-friendliness is measured by how much time it took to create the design and how much time it will take to make the silicone model. Effectiveness depends on how well the blood-like fluid is able to flow through the material. Lastly, simplicity will be measured by how much time it takes from the moment the design begins printing to when the hollow silicone model is finished.

4.4 Concept Selection

The team created two Pugh charts as shown below, in order to analyze which concept would best satisfy the requirements. The first Pugh chart shown in figure 12 was created for the selection of the support type for the solid model. In this chart the design with no support was chosen to be the reference as it was the most straightforward of the design choices. As can be seen below in figure 12, the square supports were

best. The cylinder support along the structure was not chosen because it would have been too costly and was not effective nor simple. The team also decided against the other cylinder support system because while it was not necessarily a bad design, it did not have more advantages than the square supports.

Criteria	Weight	No supports	Cylinder Support	Cylinder supports along structure	Square supports
Cost	4	0	-	--	-
Simplicity	2	0	-	--	-
User Friendly	3	0	0	-	0
Reusability	5	0	0	0	0
Precision	5	0	0	--	++
Effectiveness	5	0	0	-	++
Plus			0	0	2
Minus			2	5	2
Zero			5	2	2
			-2	-5	0

Figure 12: Positive Solid Models Pugh Chart

For the concept selection of the negative mold, a Pugh chart, shown in Figure 13 was created to demonstrate how the concepts compared to Idea 1, the base design. Idea 1 was chosen to be the reference as it was the simplest of the models.

Criteria	Weight	Basic Square	Excess removed	With keys	Silicone injection holes
Cost	4	0	++	-	+
Simplicity	2	0	+	-	-
User Friendly	3	0	0	+	-
Reusability	5	0	0	0	0
Precision	5	0	0	+	0
Effectiveness	5	0	0	0	0
Plus			2	2	1
Minus			0	2	2
Zero			4	2	3
			2	0	-1

Figure 13: Negative mold Pugh chart

According to the chart, Idea 2 was the best. Idea 1 was eliminated simply because it added nothing that Idea 2 cannot produce, and it is more costly. Idea 3 was eliminated because it was assumed that it may create complications with silicone removal. Plus, high levels of printing accuracy are required to ensure that not only are the cavities printing correctly but that the keys fit smoothly and snugly together as well. Essentially it was a lot of unnecessary labor that may have become a complex issue in the future.

5 CONCLUSIONS

Dr. Zhongwang Dou assigned our team with a project to find an effective way of recreating an aneurysm rupture simulation that could be adjusted for patient-specific cases. This model would be connected to a pump and suspended in gelatin with a blood-like fluid pumping through it in order to create the most realistic conditions. This project must be effective, predictable, and measurable.

The report above describes in detail the design process as well as the final concept. Section one discusses the goals and direction for the aneurysm rupture project. The model will be made with both 3D printing and wax casting techniques which will both be tested to discover which one yields better results. The model will need to replicate the real-life phenomena of an aneurysm rupturing. This will be recorded using a high-speed camera as well as flow and pressure sensors. The next section of the document describes the requirements which were given to the team by the client. These requirements include but are not limited to repeatability, consistency, and effectiveness. To gauge a good starting point, the team did research on existing models which were similar as a way to get a benchmark. These benchmarks are the Kono Aneurysm model, Sigiui model, and the Lui model which are all further detailed in section three. The team then continued to do more research and compiled a list of resources which were beneficial to the project and are summarized in section 3.2. The mathematical models are included later in the document and provide a description of which equations were used and why they are important. The next section depicts the concept generation as well as the selection process of mentioned concepts. The concepts were split into three main components. These were the hollow versions of the aneurysms, the solid versions, and the mold. Several concepts were generated and then inserted into a Pugh chart to help the team make a decision. In the end, the team chose to make the square supported structure and the mold that will require the excess silicone to be removed.

In the previous weeks the team has successfully created a mold for one of the types of aneurysms. They plan to test this mold soon and have a working prototype within the next three weeks. The next steps are to successfully print the molds for the other aneurysms and proceed with testing. Once testing begins the team hopes to have a working model that will be capable of advancing the medical devices available to prevent or fix aneurysms, thus resulting in a decreased loss of life due to aneurysm ruptures.

6 REFERENCES

- [1] “Pressure,” *hyperphysics.phy-astr.gsu.edu*. <http://hyperphysics.phy-astr.gsu.edu/hbase/ptens.html>
- [2] “Vascular Model Repository,” *Vascularmodel.com*, 2024. <https://www.vascularmodel.com/index.html> (accessed Sep. 14, 2024).
- [3] R. Fox, A. McDonald, and J. Mitchell, *Fox and McDonald’s Introduction to Fluid Mechanics*, 10th ed. 111 River Street Hoboken, NJ: John Wiley & Sons, 2020.
- [4] Mayo Clinic, “Brain aneurysm - Symptoms and causes,” *Mayo Clinic*, Mar. 07, 2023. <https://www.mayoclinic.org/diseases-conditions/brain-aneurysm/symptoms-causes/syc-20361483>
- [5] Kono K, Shintani A, Okada H, Terada T. Preoperative simulations of endovascular treatment for a cerebral aneurysm using a patient-specific vascular silicone model. *Neurol Med Chir (Tokyo)*. 2013;53(5):347-51. doi: 10.2176/nmc.53.347. PMID: 23708228.
- [6] Sugiu K, Martin JB, Jean B, Gaillood P, Mandai S, Rufenacht DA. Artificial cerebral aneurysm model for medical testing, training, and research. *Neurol Med Chir (Tokyo)*. 2003 Feb;43(2):69-72; discussion 73. doi: 10.2176/nmc.43.69. PMID: 12627882.
- [7] Liu, Y. *et al.* Fabrication of cerebral aneurysm simulator with a desktop 3D printer. *Sci. Rep.* 7, 44301; doi: 10.1038/srep44301 (2017).
- [8] J. R. Ryan, K. K. Almefty, P. Nakaji, and D. H. Frakes, “Cerebral Aneurysm Clipping Surgery Simulation Using Patient-Specific 3D Printing and Silicone Casting,” *World Neurosurgery*, vol. 88, pp. 175–181, Apr. 2016, doi: <https://doi.org/10.1016/j.wneu.2015.12.102>.
- [9] N. Hopkinson, Richard Hague, and Philip Dickens, *Rapid Manufacturing An Industrial Revolution for the Digital Age*. The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ England: John Wiley & Sons, Ltd, 2006.
- [10] “Flow Diversion with Stents for Brain Aneurysms,” Dec. 28, 2022. <https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/flow-diversion-with-stents-for-brain-aneurysms#:~:text=What%20is%20flow%20diversion%20for>
- [11] “Endovascular Coiling,” *John Hopkins Medicine*, 2019. <https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/endovascular-coiling>
- [12] “Microsurgical Clipping and Endovascular Coiling for Brain Aneurysm,” [www.hopkinsmedicine.org. https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/microsurgical-clipping-and-endovascular-coiling-for-brain-aneurysm](https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/microsurgical-clipping-and-endovascular-coiling-for-brain-aneurysm)
- [13] R. G. Nagassa, P. G. McMenamin, J. W. Adams, M. R. Quayle, and J. V. Rosenfeld, “Advanced 3D printed model of middle cerebral artery aneurysms for neurosurgery simulation,” *3D Printing in Medicine*, vol. 5, no. 1, Aug. 2019, doi: <https://doi.org/10.1186/s41205-019-0048-9>.

- [14] M. S. Pravdivtseva *et al.*, “3D-printed, patient-specific intracranial aneurysm models: From clinical data to flow experiments with endovascular devices,” *Medical Physics*, vol. 48, no. 4, pp. 1469–1484, Feb. 2021, doi: <https://doi.org/10.1002/mp.14714>.
- [15] J. R. Cebal *et al.*, “Aneurysm Rupture Following Treatment with Flow-Diverting Stents: Computational Hemodynamics Analysis of Treatment,” *American Journal of Neuroradiology*, vol. 32, no. 1, pp. 27–33, Nov. 2010, doi: <https://doi.org/10.3174/ajnr.a2398>.
- [16] L.-D. Jou and M. E. Mawad, “Analysis of Intra-Aneurysmal Flow for Cerebral Aneurysms with Cerebral Angiography,” *American Journal of Neuroradiology*, vol. 33, no. 9, pp. 1679–1684, May 2012, doi: <https://doi.org/10.3174/ajnr.a3057>.
- [17] W. C. Merritt, H. F. Berns, A. F. Ducruet, and T. A. Becker, “Definitions of intracranial aneurysm size and morphology: A call for standardization,” *Surgical Neurology International*, vol. 12, p. 506, Oct. 2021, doi: https://doi.org/10.25259/SNI_576_2021.
- [18] K. W. Yong, M. Janmaleki, M. Pachenari, A. P. Mitha, A. Sanati-Nezhad, and A. Sen, “Engineering a 3D human intracranial aneurysm model using liquid-assisted injection molding and tuned hydrogels,” *Acta Biomaterialia*, vol. 136, pp. 266–278, Dec. 2021, doi: <https://doi.org/10.1016/j.actbio.2021.09.022>.
- [19] C. Patel, “Acquiring Data from Sensors and Instruments Using MATLAB.” Available: <https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/solutions/automotive/files/in-expo-2012/acquiring-data-from-sensors-and-instruments-using-matlab.pdf>
- [20] L. Bousset *et al.*, “Aneurysm Growth Occurs at Region of Low Wall Shear Stress,” *Stroke*, vol. 39, no. 11, pp. 2997–3002, Nov. 2008, doi: <https://doi.org/10.1161/strokeaha.108.521617>.
- [21] The Engineering Toolbox, “Dynamic Viscosity of common Liquids,” *Engineeringtoolbox.com*, 2019. https://www.engineeringtoolbox.com/absolute-viscosity-liquids-d_1259.html
- [22] F. M. White, *Fluid Mechanics*, 7th ed. McGraw Hill, 2011.
- [23] A. Mardston, “SimVascular,” *SimVascular Docs*, 2024. <https://simvascular.github.io/documentation/quickguide.html> (accessed Oct. 20, 2024).
- [24] Á. Ugron, “Flow Simulation in Intracranial Aneurysms,” ProQuest Dissertations & Theses, 2015.
- [25] D. M. Sforza, C. M. Putman, and J. R. Cebal, “Computational fluid dynamics in brain aneurysms,” *International journal for numerical methods in biomedical engineering*, vol. 28, no. 6–7, pp. 801–808, 2012, doi: 10.1002/cnm.1481.
- [26] P.-C. Chen *et al.*, “Engineering additive manufacturing and molding techniques to create lifelike willis’ circle simulators with aneurysms for training neurosurgeons,” *Polymers*, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7761873/> (accessed Sep. 9, 2024).
- [27] ochxlxzwiz, “electric circuits 11th edition nilsson pdf.” Zenodo, Jun. 10, 2024, doi:

10.5281/ZENODO.12364277.

[28]H. E. A. Baieth, “Physical parameters of blood as a non - newtonian fluid,” International journal of biomedical science : IJBS, <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3614720/> (accessed Sep. 9, 2024).

[29] “Blood flow - CFD simulation CFD software tutorial,” Blood Flow CFD Simulation Software, <https://help.sim-flow.com/tutorials/blood-flow> (accessed Sep. 16, 2024).

[30] M. R. Harreld, “Brain aneurysm blood flow: Modeling, simulation, VR visualization,” ProQuest Dissertations & Theses

7 APPENDICES

7.1 Appendix A: Computational Fluid Dynamics Research

This project's data collection will primarily take place through the usage of LabView monitoring several flow meters that the team will have on the inlet and outlet connection points of the vessels. However, the team believes that it is beneficial to the project to compare results to computational fluid dynamics results gathered through setting up the same vessels through SimVascular.

The process for setting up the experiment in SimVascular is tedious, and not mandatory for the success of the project, landing itself in the appendix section, but is worth mentioning in case further research and work goes into it. The process begins the same way as our solid body models, by refining and meshing with MeshMixer.

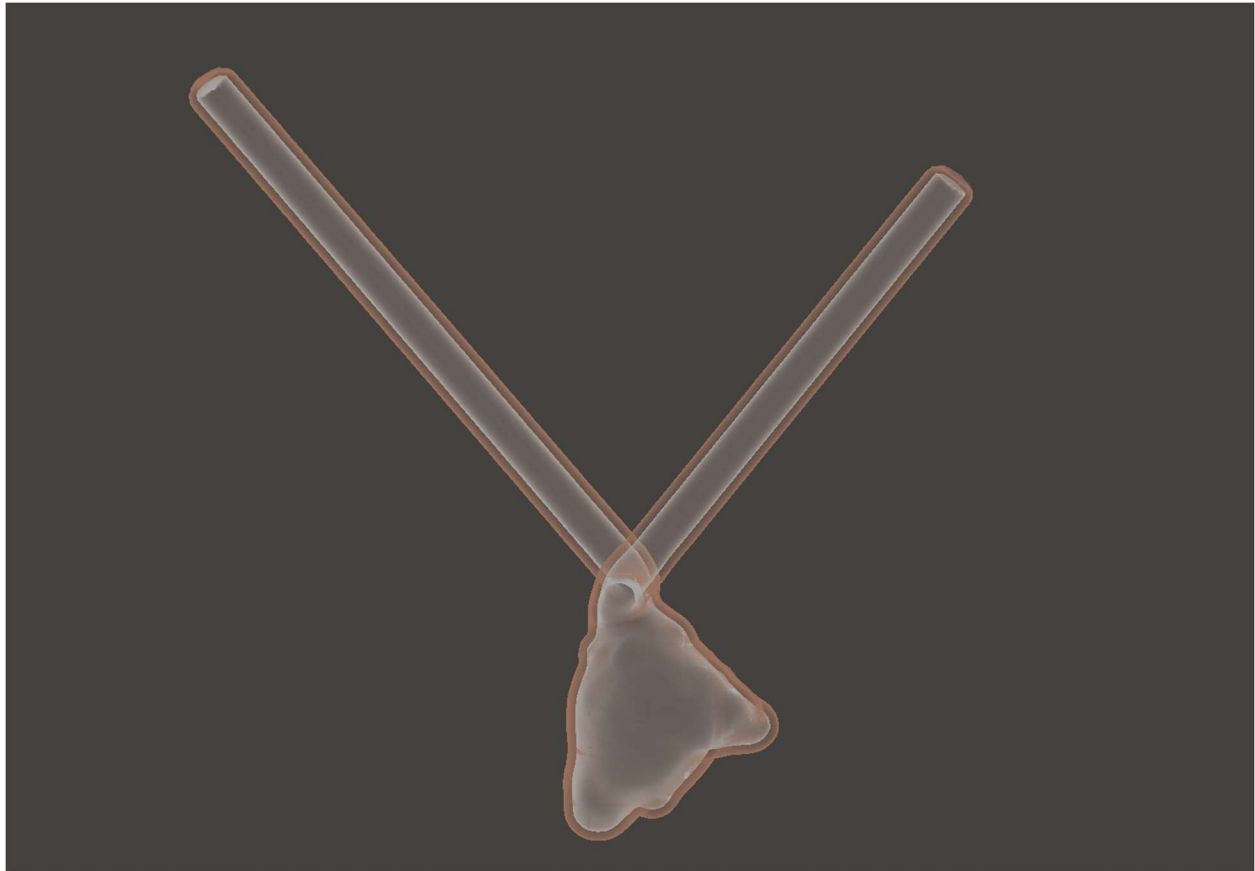


Figure 14 Refining in MeshMixer

Then the model needs to be segmented through a program called 3D slicer, in which the model is imported and paths for fluid flow can be established. This is an extremely straightforward step as exporting a hollow body can be opened directly as a segment in 3D slicer. Once the model is segmented it is exported to SimVascular as a STL body. In SimVascular, the mesh can be pathed out with their path tool, adding specific flow points through the model, and a reduced order motion simulation can be started.

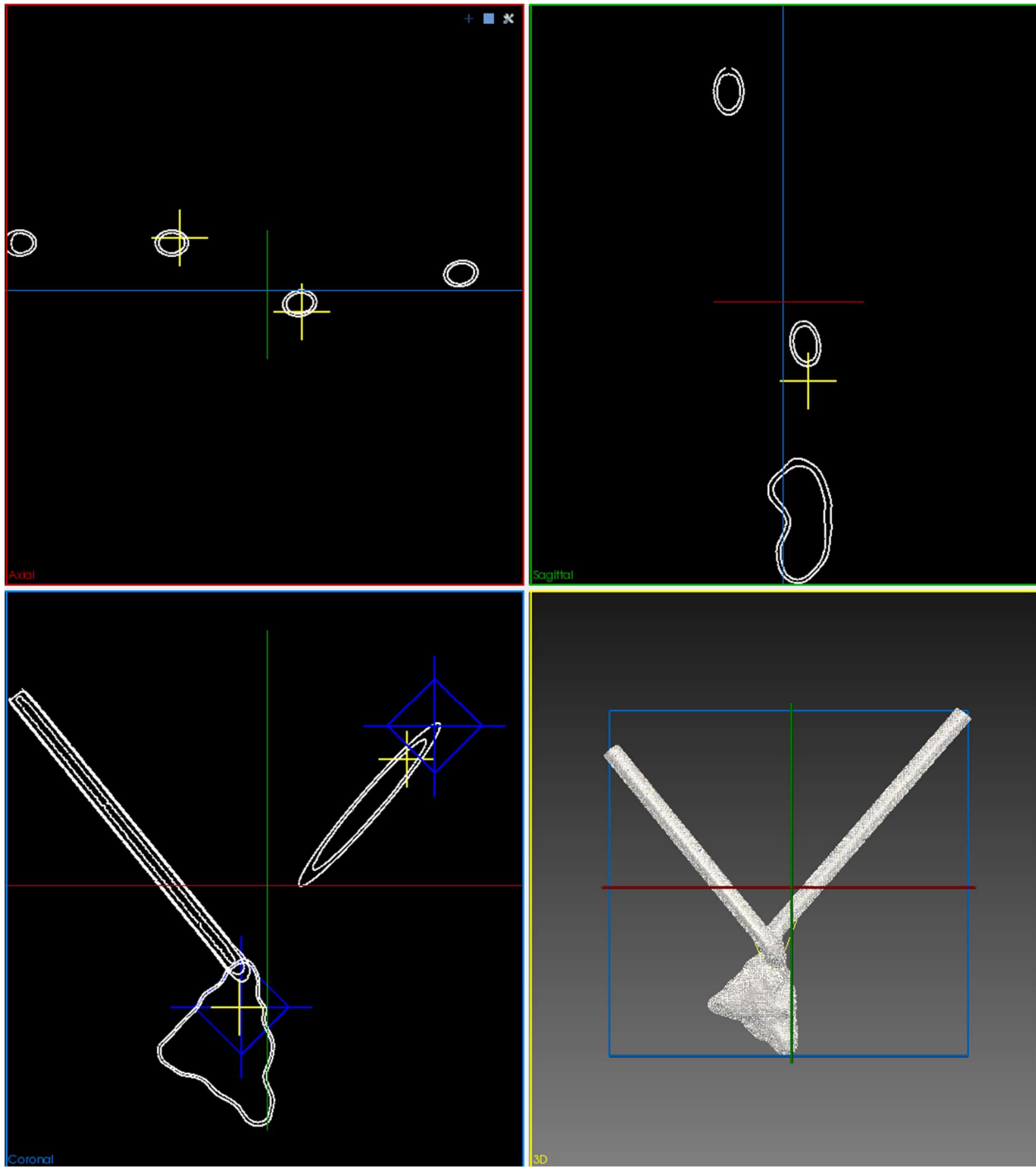


Figure 15: Path creation in SimVascular