PIV V2 – Particle Image Velocimetry Integration with the Bioengineering Devices Lab Benchtop Flow Model

Conceptual Design Report

Carley Barton – Project Manager/Test Engineer

Ryan Abelman – Logistics Manager

Clinton Nelson – Manufacturing Engineer

Blake Pottinger – CAD Engineer

Spring 2026 - Fall 2026

NORTHERN ARIZONA UNIVERSITY

Steve Sanghi College of Engineering

Project Sponsor: Dr. Tim Becker

Outside Sponsor: Western Component Sales

JB Industries

Sponsor Mentor: Jesse Wells

Instructor: Professor Carson Pete

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

The mission of the 2026 PIV capstone project is to design, manufacture, optimize, and validate a particle image velocimetry (PIV) phantom model. This project is a continuation of the 2025 PIV capstone project which focused on testing the cameras, lasers, particles, and software for the PIV setup. The goal of the 2026 PIV capstone is to seamlessly integrate the previously developed PIV system into the Bioengineering Devices Lab (BDL) benchtop flow model alongside the existing benchtop procedures. The new model must be able to easily convert between standard flow operations and the PIV enabled configurations. The initial task for the team is to develop a repeatable molding process that is designed to meet the required refractive index for a PIV phantom flow model. This process is to be documented in a comprehensive testing and validation plan which will then be executed by BDL lab students when testing medical devices. The phantom model will have a synthetic clot inserted for medical device testing for simulated endovascular applications. As of March 4, 2026, the team has constructed several different CAD models of blood vessels for preliminary testing of the silicone mold manufacturing process. Through extensive calculations, the team has opted to test a modified blood mixture that consists of HPMC and glycerin to match the refractive index of the silicone. This modified mixture allows for the silicone to remain clear and allows the team to use the donated Liquasil clear silicone. The casting process will require the use of the BDL vacuum chamber to degas the silicone and allow for a clear mold. The mold will be made of a PVA 3D printed core which is water soluble and allows for a clear finish. If the preliminary process leads to success, the team will manufacture more advanced models for higher accuracy when testing medical devices.

TABLE OF CONTENTS

Contents

DISCLAIMER 1
EXECUTIVE SUMMARY 2
TABLE OF CONTENTS 3
1 BACKGROUND 5
1.1 Project Description 5
1.2 Deliverables 2
1.3 Success Metrics 2
2 REQUIREMENTS 3
2.1 Customer Requirements (CRs) 3
2.2 Engineering Requirements (ERs) 4
2.3 House of Quality (HoQ) 5
3 Research Within Your Design Space 6
3.1 Benchmarking 6
3.2 Literature Review 8
3.2.1 Carley Barton 8
3.2.2 Blake Pottinger 9
3.2.3 Clinton Nelson 10
3.2.4 Ryan Abelman 11
3.3 Mathematical Modeling 13
3.3.1 HPMC Refractive Index – Carley Barton 13
3.3.2 Silicone RI Match – Carley Barton 15
3.3.3 PIV Spatial Resolution – Blake Pottinger 16
3.3.4 Change RI of HPMC – Blake Pottinger 17
3.3.5 Particle Density – Clinton Nelson 18
3.3.6 Minimum Wall Thickness – Clinton Nelson 19
3.3.7 Phantom Cost Analysis – Ryan Abelman 20
3.3.8 Revised Phantom Cost Analysis – Ryan Abelman 22
4 Design Concepts 24
4.1 Functional Decomposition 24
4.2 Concept Generation 25
4.3 Selection Criteria 31
4.4 Concept Selection 31
5 Schedule and Budget 37
5.1 Schedule 37
5.1.1 First Semester Gantt Chart: 37
5.1.2 Draft of Second Semester 38
5.2 Budget 39
5.2.1 Fundraising 40
5.3 Bill of Materials (BoM) 41
6 Design Validation and Initial Prototyping 42
6.1 Failure Modes and Effects Analysis (FMEA) 42
6.2 Initial Prototyping 47
6.2.1 Physical Prototype 1 47
6.2.2 Virtual Prototype 1 48
6.3 Other Engineering Calculations 50
6.3.1 Settling Velocity - Carley Barton 50
6.3.2 Revised Spatial Resolution – Blake Pottinger 51

6.3.3 Offset – Clinton Nelson 52
6.3.4 Relative Distortion – Ryan Abelman 55
6.4 Future Testing Potential 55
7 CONCLUSIONS 58
8 REFERENCES 59
9 APPENDICES 63

1 BACKGROUND

Chapter 1 takes an in-depth look at the PIV project description and the importance of the work that will be conducted. This chapter highlights the goals for the PIV project and what determines the success of the final design.

1.1 Project Description

Stroke is currently the second leading cause of death worldwide [1]. There are two types of strokes: ischemic and hemorrhagic. Ischemic strokes occur when a blood clot blocks blood flow from reaching distal parts of the brain [2]. Hemorrhagic stroke occurs when a section of a vessel in the brain has weakened, also known as an aneurysm, and ruptures, causing a brain bleed [3]. The Bioengineering devices lab (BDL) has a current simulated surgical suite with a benchtop flow model that tests novel medical devices that have the aim of treating both ischemic and hemorrhagic strokes. This current benchtop flow model only collects pressure and overall flowrate data but does not have the ability to see real time hemodynamic velocity in flows, or the stresses on medical devices and the vessel. This is where a particle image velocimetry (PIV) system can be incorporated to bridge the gap in this data collection.

PIV is used to evaluate fluid flow with outputs of velocity that can be derived to find stress and strains. This can be done by casting a phantom model, in this case the aim is to use silicone, and a flow loop going through it with an outside laser illuminating microscopic fluorescent particles within the fluid flow. By using high speed cameras these particles can be traced by recording their position between frame rates and analyzed using a data analysis system called PIVlab. PIVlab can display a map with vector arrows showing direction and magnitude of a flow as seen in figure 1.

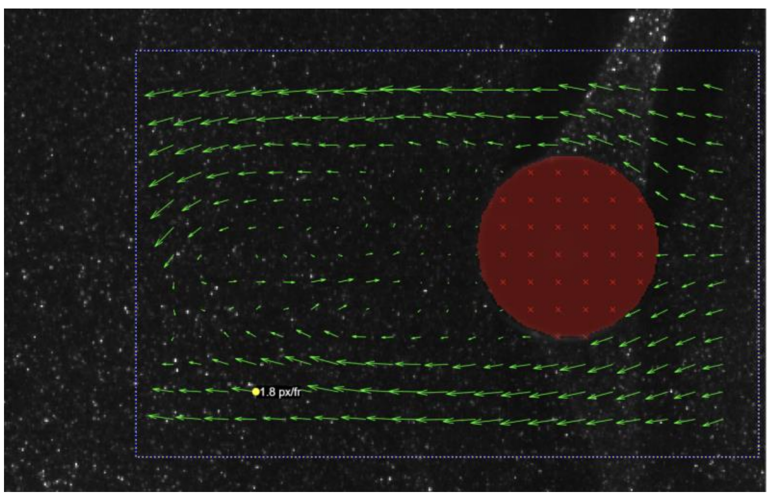


Figure 1: Flow analysis using PIVlab showing vectors

This capstone is a continuum of the previous Spring 2025 – Fall 2025 capstone group. Last year's team constructed a PIV setup that has a laser powerful enough to illuminate particles through thick silicone walls and project a laser sheet wide enough to capture the flow region to be studied. The next steps are to incorporate interchangeable phantom models that are physiologically relevant to the neurovascular anatomy and install it side by side with the BDL benchtop flow model to test medical devices on.

The PIV V2 team's research will be conducted during the Spring of 2026 and most of the manufacturing and testing will take place during the Fall of 2026. The project was given a budget from the Bioengineering Devices Lab of $3,000 to spend as the team sees fit. The team was also left with various materials from the previous capstone such as camera equipment, lasers, and testing equipment and other sources of equipment donations to the lab. The team was also required to produce $500 independently through fundraising. The team was able to complete this goal by receiving a generous donation of an eliminator series vacuum pump (Valued over $500) from Western Component Sales and JB Industries which will be used during the manufacturing process of the silicone phantom to help eliminate bubbles. A large portion of our budget is set aside to purchase a 3D printer that we will use to model the inner mold of the phantom. The rest of the money will be used to purchase testing materials such as PVA material, PIV particles, and silicone. A detailed budget can be found below in section 5.2.

1.2 Deliverables

Majority of the deliverables that will be produced throughout the PIV project are the course deliverables for ME-476C. Alongside the coursework for the class, the client only requests that we have this setup functioning by the end of fall 2026. Throughout this semester we are responsible for three presentations, two reports, two prototype demonstrations, a website, a CAD model, and a bill of materials for our final design. As of April 19th, 2026, the first and second report, three presentations, CAD model, and a bill of materials have been delivered and submitted.

Each of the customer's requirements will be tested for the best solution and will aim to satisfy the numerical engineering requirements. The acceptable range of the testing can be seen in section 2.3 and will all be validated both numerical and analytically if applicable through our engineering calculations and lab testing.

Our sponsor and main client, the Bioengineering Devices Lab, has listed several customer requirements found detailed in section 2.1. Our team then listed our engineering requirements that will be used to satisfy our customers and their requirements. All the deliveries submitted for the course are steps that have been taken to create a detailed solution for the customer requirements. Our other sponsors, Western Component Sales and JB industries, have requested credit for their donation in the reports and presentations as well as a video of the pump being used during the manufacturing process which they can use as advertisement.

1.3 Success Metrics

The overall goal for this capstone project is to integrate a PIV set up into the BDL lab's surgical suite. This could be having a switch in the already manufactured flow loop of the benchtop model that can switch between a 3D printed circle of Willis and a phantom silicone mold manufactured by this capstone or a separate flow loop next to the benchtop model using a different pump.

Our team has set technical requirement targets to help define our success metrics and give us an estimated goal during testing. These initial targets include a decreased time during flow conversion to 120 seconds, increasing the particle density of the blood analog to 0.1 particles per pixel, achieve a laser color value of 532 nm, achieve a minimum visibility through the silicone of 90%, match the refractive indices of silicone and HPMC, and finally have a testing success rate of 80%. Some of these values such as success rate and visibility are on the lower end as given to us by our client and we plan to surpass the expectations to provide a product that can be used repeatedly in the future. Many of the requirements listed above are calculated later in the report and are now needing to be tested numerically in the lab.

This project is seen as successful if the lab can retrieve hemodynamics (the study of the physical principles governing blood flow, pressure, and resistance within the cardiovascular system [4]) from a particle image velocimetry system by collecting data of the velocities of particles in a fluid flow. This data can be taken and derived to calculate the stresses on the medical products being tested, the synthetic blood clots, and the vessel walls. PIV will help the research and development field of medical devices and open up a new set of data that can be collected.

2 REQUIREMENTS

Chapter 2 is a discussion of the requirements for the final product. The PIV project was given specific requirements to meet by the client as seen in 2.1. The team then formulated various engineering requirements to quantify the requirements of the customers as seen in 2.2. Finally, the requirements are combined into a House of Quality (QFD) 2.3 to compare the customer requirements and engineering requirements.

2.1 Customer Requirements (CRs)

This list of customer requirements was brainstormed at a client meeting when discussing the project. Each of these requirements contain an aspect of the project and a PIV set up and when combined can lead to a successful outcome of our capstone.

- **Conversion Time**
  - To incorporate the PIV set up with the BDL benchtop model we will have two flow loops used by the same pump or side by side with different pumps. This conversion time will allow for easy set-up of the PIV system and the change between the two loops. The benchtop model must have a switch time between the PIV flow loop and standard benchtop model loop under 2 minutes.
- **Particle Selection**
  - Two particles are needed when collecting data, one saturating the fluid flow and another mixed in with the synthetic blood clot solution before they are cured. Each particle must be distinguished from the other to collect two data sets. We must choose a particle that is best for visibility as well as determine which particles will be used in the flow loop, and which particles will be used in clots.
- **Laser Wavelength (Color)**
  - The laser that illuminates the fluorescent particles can be set to different colors selected by the team where each color illuminates the particles differently. We must determine which laser color will best illuminate the particles.
- **Clarity of Silicone**
  - The clarity of silicone is important for data collection. This phantom silicone mold must be clear to collect the most accurate data. It is important for visibility when using cameras to capture the particles within the phantom.
- **Refractive Index Match**
  - When there is a differing refractive index between materials, in this case the HPMC blood analog fluid and the silicone, an offset can occur which creates a skew in the data collected. Matching the two refractive indexes will eliminate the offset and optimize data collection.
- **Validation**
  - This phantom model and PIV set up will be used by the BDL lab to test medical devices. Validating the Phantoms by molding a more intricate and physiologically accurate model will allow for testing of these novel medical devices. Validation will include performing medical procedures by aspirating synthetic blood clots with catheters in the phantom model.

2.2 Engineering Requirements (ERs)

- **Decrease time to convert between flows**
  - Being able to switch back and forth between two flow loops in under 2 minutes will increase the amount of time to focus on the experiments and we now have to wait for the set up to be complete.
- **Increase particle density in fluid**
  - Calculate the number of particles best fit for a certain volume of fluid so the visibility is 0.1 particles per pixel of an image. This will determine the seeding of the particles in the fluid.
- **Change laser color**
  - Find the best fit wavelength for laser color, should be around 532 nm for a green color. Test different wavelengths of the laser with different colored particles and analyze capture images in PIVlab to see best visibility.
- **Visibility of particles**
  - Selecting the best particle size and color to get the best visibility for analyzing images and calculate the particle density for seeding of the particles.
- **Visibility of silicone**
  - Prototype different methods for casting silicone including removal of male inner mold, eliminating bubbles, and preventing discoloration. This requirement can be calculated using the refractive index.
- **Match refractive index of all materials, silicone and synthetic blood mixture**
  - Change the properties of either the silicone or blood mixture to match each other. This will eliminate offsets in the images collected and have a clear view of the hollowed phantom model.
- **Success rate when testing on phantom**
  - An 80% success rate is ideal for a phantom under an aspiration test. Will we be able to track the flow around the catheter and clot? Will visibility be high? Will the software for PIV work accordingly? Will this process and set up be repeatable?

2.3 House of Quality (HoQ)

System QFD

Project: PIV
Date: 2/2/2026

	Decrease time to convert between flows	Increase particle density in fluid	Change laser color	Visibility of particles	Visibility of silicone	Match silicone to HPMC refractive index
Decrease time to convert between flows						
Increase particle density in fluid						
Change laser color						
Visibility of particles			9			
Visibility of silicone						
Match silicone to HPMC refractive index					9	
Success rate when testing on phantom	9			3		9

Legend	
S	Stomach
K	Kidney
B	Brain

		Technical Requirements							Customer Opinion Survey				
Customer Needs	**Customer Weights (Scale 1-5)**	Decrease time to convert between flows	Increase particle density in fluid	Change laser color	Visibility of particles	Visibility of silicone	Match silicone to HPMC refractive index	Success rate when testing on phantom	*1 Poor*	*2*	*3 Acceptable*	*4*	*5 Excellent*
Conversion time	4	10										B	
Particle selection	1		8	8									
Laser Wavelength (Color)	2			10									
Clarity of silicone	3				10					S		K	
Refractive index match	5				7	8	10			K			S
Validation	4	8			7	7	8	10	S				B
Technical Requirement Units		s	particles/ pixel	nm	color	%	Unitless	%					
Technical Requirement Targets		120	0.1	532		90	1.35	80					
Absolute Technical Importance		72	8	28	93	68	82	40					

Figure 2: House of Quality

3 Research Within Your Design Space

Chapter 3 is an in-depth review of similar designs that are currently available on the market as well as state-of-the-art methods used for manufacturing the intricate phantom models 3.1. This chapter also includes a review of the sources used during the research for this project 3.2. The final section of chapter 3 is a complete review of the mathematical modeling calculations that have gone into the project thus far and how they have informed our design.

3.1 Benchmarking

Benchmark #1: Cerebral Arteries Phantom

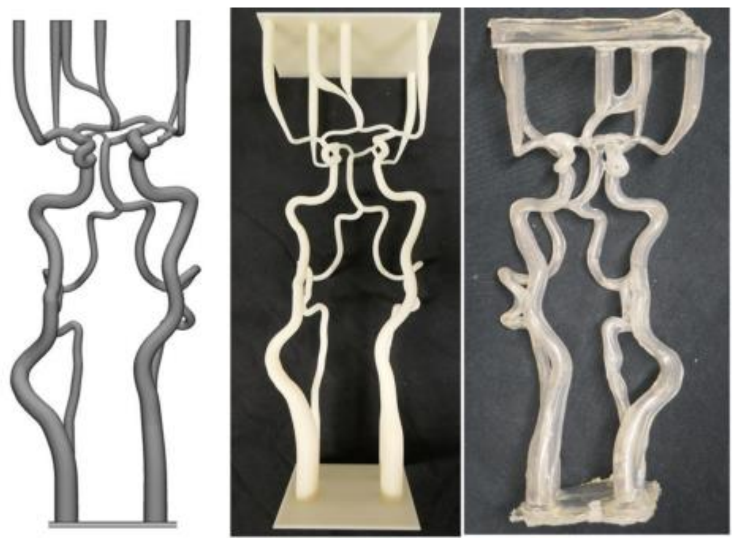


Figure 3: Cerebral arteries phantom [5]

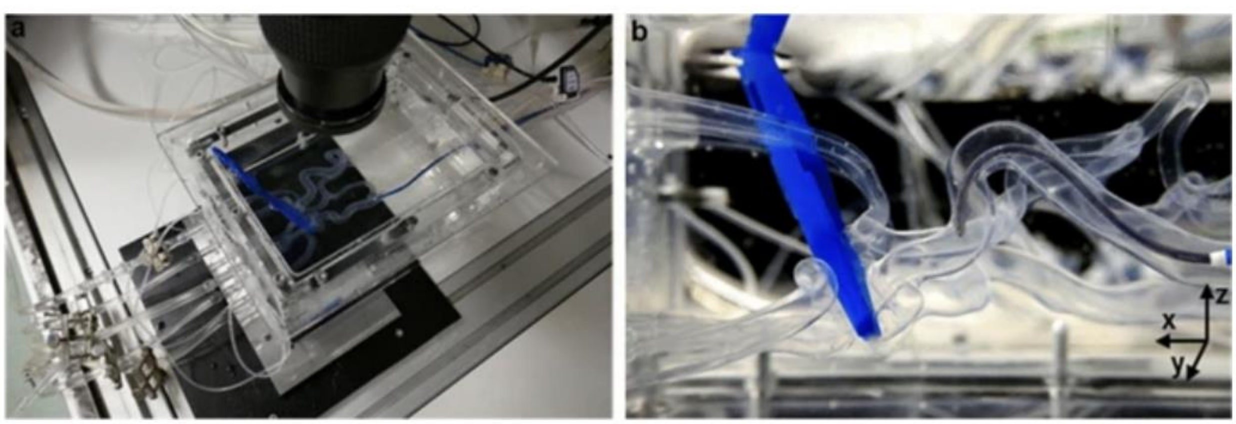


Figure 4: Flow set up with phantom model [5]

This model is an intricate system of the cerebral arteries in the brain, including the circle of Willis. The current testing system in the BDL lab has 3 inlet vessels and 8 outlet vessels. This model is a goal for our team in the future and something we can model our phantom after. The tests conducted on this model include performing aspiration thrombectomy, which is the removal of a blood clot via a suction pump or syringe pump to restore flow. This same test is what will be conducted in the BDL lab. The data that was produced from this journal article will likely be what we compare our data to. This benchmark will allow us to see the setup of the phantom, with the laser and camera as well as the whole flow loop with the pump and reservoir.

Benchmark #2: Molding Process

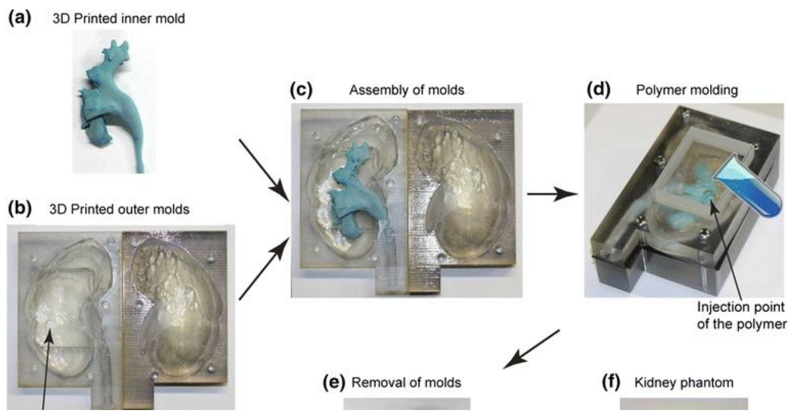


Figure 5: Kidney Phantom [6]

This benchmark is a phantom model (subsystem of PIV) of a kidney and although we are not modeling a kidney the process is a good benchmark. The inner mold was 3D printed in wax and the outer mold is 3D printed in photopolymer, once the liquid polymer is poured into the mold it is then degassed. Once solidified the outer mold is removed and the inner mold is dissolved in ethanol. This step by step is not a solid block of silicone like our plan but it is very similar. We will compare our materials to theirs and the process of molding.

Benchmark #3: PIV Set-up

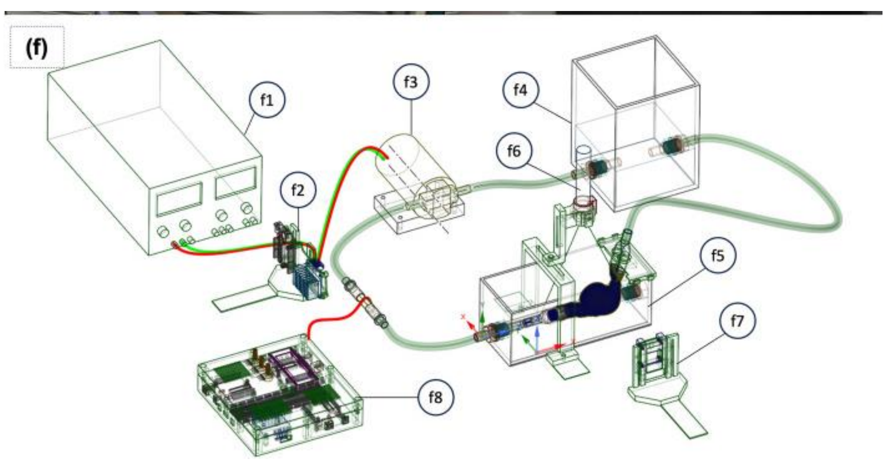


Figure 6: Abdominal aortic aneurysm phantom and PIV set up [7]

This last benchmark is for another PIV set up; this one is for an abdominal aortic aneurysm. This system has a silicone phantom that has a 2mm thick wall submerged in a tank of blood mimicking liquid, not a solid block of silicone. This PIV system has good imagery for the flow loop set up as seen in figure 5 This shows us the pump, reservoir, phantom pool, laser, and image sensor. It also shows the injection molding process to create a hollow tube that is then submerged in liquid.

3.2 Literature Review

3.2.1 Carley Barton

- **Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of light [8] (Book Ch 2.3)**

  In chapter 2.3 of this book titled Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of light the author explained how to solve for the refractive index of a mixture using the Lorentz-Lorenz equation. This source was used to inform our mathematical modeling section multiple times. For example, it was first used to calculate the refractive index of the HPMC blood analog mixture that is currently used in the BDL lab and has similar properties to blood. Once that refractive index was found we needed a way to change the refractive index of silicone to match that of the HPMC. Lastly, after finding out that the silicone refractive index could not be changed, we had to pivot and will have to change the blood analog mixture to have a higher refractive index matching to the silicone. This Lorentz-Lorenz equation from this book informed us through our mathematical modeling and validated our solutions.

- **Refractive index of Pharmacoat 606(Hydroxypropyl methylcellulose, HPMC) [9] (Website)**

  In order to solve for the refractive index of the HPMC blood analog mixture HPMC which is abbreviated for Hydroxypropyl methylcellulose is a polymer mixed with 90% water and about 10% ethanol in order to create a mixture with similar properties to blood. In order to solve for the total refractive index of this mixture the refractive index of the HPMC powder was needed along with water and ethanol. This website has a graph with equations and validations for many materials such as inorganic, organic, glasses, or miscellaneous materials.

- **Particle Image Velocimetry [10] (Book Ch. 10)**

  Chapter 10 of the book Particle Image Velocimetry is titled Practical Guidelines. This chapter goes over many questions about PIV and an experiment set up. When talking about the set up of PIV it brought light to variables that we were unaware of. For example, selecting the image density, surface flare, and test section cleanliness. Bringing light to these variables will help inform decisions later on in the manufacturing process.

- **Fabrication of deformable patient-specific AAA models by material casting techniques [11] (Journal)**

  This journal article highlights casting techniques for patient-specific AAA(Abdominal aortic aneurysm) models. Although our set up is not for AAA molds we can use the same techniques which are highlighted specifically in section 2.3. This section goes through the steps of lost core casting which is most likely what our manufacturing process of a phantom will look like. Their research also used PVA 3D printing filament for their core which is water soluble. In table 1 it also consists of multiple parameters when 3D printing such as layer height, nozzle diameter and temperature, support density, etc.

- **Evaluation of a desktop 3D printing rigid refractive-indexed-matched Flow Phantom for**

PIV measurements on cerebral aneurysms [12] (Journal)

This journal article explains the parameters for a refractive index matched flow through a phantom for PIV. They explain two set ups, a phantom consisting of a idealized model and a physiologically realistic model. The methods section explains the fabrication of the flow phantom. This phantom model was printed using a Formlabs Form 2 Desktop SLA printer using a clear photopolymer resin. The downside of using this resin is that the refractive index is closer to about 1.51instead of a silicone refractive index of 1.41. This higher refractive index is harder to match, and the printing process is a lot more expensive, informing us that this manufacturing process would not be the best for our set up.

- **Fabrication of low-cost patient-specific vascular models for particle image velocimetry [13] (Journal)**

This article is another source that highlights the lost core casting method of casting around a PVA 3D printed mold and removed after silicone is solidified around it. Their images are also good research to see how the fluid inside should look if the refractive index is matched correctly.

- **What is Hemodynamics? [4] (Website)**

This website informs us on what hemodynamics is and how blood flows through your arteries and veins. It talks about the effects of change in blood flow and what the causes are, for example a blood clot blocking flow.

- **Cospheric Microspheres - Precision Spherical Particles Globally [36] (website)**

Cospheric is the company that makes PIV particles. Doing some research about the particles brought me to learning about settling velocity which I calculated in section 6.3.1. The settling velocity calculation is based on Stoke's law, and this website gives good insight into the calculation of it and what it is.

- **"Rhodamine B polyethylene microspheres 0.98g/CC - 10UM to 1000um (1mm)," [37]**

From the same website of cospheric and reference #36 I looked into all of the different particles and landed on this one specifically because of the diameter and density of the particles. The diameter is small enough to flow through the vessel but large enough to still be seen by the camera. A potential good fit of our model or something close to it.

- **Imperative Care CDAT Checklist [38]**

Although this is not a published paper, this checklist displayed the set up of an aspiration test that has been done for many cases in the BDL lab. I have previously worked on testing of clot aspirations and that prepared me for what will come in the future with testing with PIV. I reviewed the SOP for the tests that were conducted over the summer to get a baseline of the steps and process of the procedure that will be implemented next semester.

3.2.2 Blake Pottinger

- **Optics and Lasers in Engineering, chapter 4.1. Spatial Resolution [14]**

This resource was important for calculating the spatial resolution needed for the camera to have a clear view of the particles. If done correctly the PIV program will display vectors on each of the particles, allowing the team to calculate the velocity and direction of the individual particle. Chapter 4.1 was particularly useful as it was used during section 3.3.3 for the first mathematical model.

- **Spatial Resolution and Dissipation Rate Estimation in Taylor—Couette flow for tomographic PIV, chapter 5.2.2. Effect of the size of the interrogation window [15]**

  Chapter 5.2.2 uses a 3D model to show how the interrogation window affects the accuracy of the estimations for the PIV vectors. This resource was also used for the mathematical model 3.3.3 in estimating the window size needed to clearly show the PIV particles.

- **Micro-PIV for the Analysis of Flow Fields near a Propagating Air-Liquid Interface [16]**

  This state-of-the-art PIV system is a similar medical set up to our product that measures the flow in the respiratory system. This source was important to our group as it gave an idea of what is available in the current medical field, giving us a goal to reach.

- **Ghost Cells as a Two-Phase Blood Analog Fluid [17]**

  This reference informed the group of a PIV system that uses artificial blood out of dead cells that created similar velocity fields to that of real blood. As calculated in mathematical model 3.3.2, the team needs to create a new analog blood mixture with a refractive index to match the silicone, and this type of fluid is a possible option.

- **Viscosity of Whole Blood [18]**

  This data chart shows the measurement data of blood viscosity based on temperature. This source gives us a target for how to create the most accurate model using the most accurate blood analog.

- **Modeling pipes / blood vessels in SOLIDWORKS [19]**

  This video series was used during the individual learning assignment to learn advanced skills in SolidWorks. The skills were specific to the PIV project since they taught how to make realistic blood vessels as well as how to run a flow simulation on any object.

- **Modeling blood vessel blockage in SOLIDWORKS [20]**

  This video was another advanced tutorial that showed a way to add a simulated aneurism blockage and run a flow simulation around it. This video was important as it gave the group a way to test velocity and stress on a model before manufacturing it.

- **Getting Started with Ansys Fluent [39]**

  This website was recommended by the professor as a website to use to learn Ansys for CFD modelling. This taught me how to run a CFD and extract data without having to physically model it.

- **Understanding Particle Image Velocity Techniques [40]**

  This is another source that was recommended by the professor that gave a lesson on how to use Ansys in the PIV setting. The resource was a free guide that took about 3 hours to learn.

- **JB Industries Vacuum Pump Catalog [41]**

  This source was used when reaching out to our sponsor JB Industries to help select a vacuum pump that would work best for our manufacturing process.

3.2.3 Clinton Nelson

- **Cardiovascular Hemodynamics, Flow in Arteries, (Book Chp.5) [21] –**In the Chapter, Flow in Arties, it talked about how particles reacted to different walls while in flow but more importantly how much the density matters to the adhesion of particles to the walls.

- **Cross-Correlation Digital Particle Image Velocimetry (Paper) [22] –** In this paper we gathered that particles have an interesting way of moving while in flow, most of the particles would be flowing in the same directions from heart to other regions in a, somewhat, constant velocity but a very few particles would be in the opposite direction in a lower velocity.
- **Density Marker Beads - 1.010g/Cc - Precision Microspheres, Beads, Microparticles for Creating Percoll Density Gradients (Website) [23] -** We used this website to get basic information of the particle we would be using while in test runs and to get a basic idea of the particle density we would be seeing in our calculations.
- **Investigation of Cerebral Hemodynamics during Endovascular Aspiration: Development of an Experimental and Numerical Setup (Website) [24] –** This Website gave us a theorical understand of the number of particles we would be seeing in our set up and how we should go about using the particle density equation we used in our mathematical model.
- **Structural Reconfiguration of Interacting Multi-Particle Systems through Parametric Pumping (Paper) [25] –** Helped in understanding particle behavior.
- **Particle Imaging in Electrohydrodynamic Pumps Operating at Several KV (Website) [26] –** In this reference it gave us a different perspective based on our results and the answer we would get. There is more to particle density than getting a numerical answer and that that numerical answer could be far off when looked at in different ways or without other known values or assumptions.
- **Cardiovascular Hemodynamics(Draft) (Book pg.1-25) [27] –** This draft book gave me the basic understanding of particle physics in a simulated or real scenario giving me basic equations, equations we've seen in fluid dynamics, as well as new equations and theories related to basic fluid dynamics. It also had different ideas of particle behaviors in different vascular regions of the body, how they flow, in the shape or direction they assume they flow.
- **Snell's law -- the law of refraction(Website)[42],** This website gave us the basic idea of Snell's Law and the insight of how to derive it from the standard Sine and index ratios to the linear equation related to the thickness of phantom models that may be used in experiments.
- ***Lecture 16: 2d and 3D Waves, Snell's law: Physics III: Vibrations and waves: Physics*.(Website)[43],** This source wasn't your typical written website, but a video lecture explaining Snell's law and how it related to optics used in field use. In the video lecture he explained how vibration and object moving in waves influence materials when observing them with Snell's Law in mind.
- **Snell's Law - Physics Book(Website)[44],** This site was another basic idea for Snell's Law but giving it not in relation to an object not moving but while in motion and taking the two velocities of the same material, turning it into a ratio and having it equal to the angles observing the objects.

3.2.4 Ryan Abelman

- **Fox and McDonald's Introduction to Fluid Mechanics [28] (Book)**

  In this book, the basic properties of fluids that affect their movement and flow are introduced. With our project centered around blood, a fluid with its own distinct properties, it is vital to know how to calculate and understand the meaning behind these values. Knowledge of concepts such as, velocity fields, streamlines, pressure, etc., will prove useful to apply these numbers to real life and further our project.

- **Mathematical Background of Statistical PIV Evaluation [29] (Book Ch. 3)**

  In this book reference, it reveals more ways to understand what is coming from the Particle Image Velocimetry. This is done through potential equations and ideas that we can extract from the images take with our Phantom set up. It also explains the main focus of process of PIV and how the tracking of particles and comparisons of images can give us information about the velocity of a fluid. Furthermore, it provides equations for the averaging of these displacements, along with considering uncertainty errors with the tools used.

- **Mechanical and adhesive properties of RTV silicone rubber blended with silicone polyurethane modified epoxy resin [30] (Journal)**

  The material used for our Phantom unit is very important as we need something to provide visibility to get the data we need from the blood vessel created. In this journal, the properties of a potential silicone are identified to see how it will interact with water, curing procedures, and durability. Using these properties, we can create the best blend of silicone for desired outcomes.

- **Soft 3D-Printed Phantom of the Human Kidney with Collecting System [31] (Journal)**

  Although it will not mainly be used in our realm of this project, this journal was used to understand more about Phantom units in general and their application. It also provided insight on how to print 3D objects that resemble actual tissue in the body. Employing strategies from the development of this effective "human kidney", can help us in our creation of something similar to a Circle of Willis further along into our testing.

- **Global Burden of Stroke [32] (Journal)**

  The ultimate goal of this project is to gather more information on the causes of strokes and solutions to them once they occur. The goal of this specific journal is for the group to remember the importance of why we are doing it and find more background facts to inform our project/decisions.

- **Silicone Website Cost [33] (Website)**

  This website provided the foundation for the Phantom cost analysis. Using the website, I was able to find values for a 5.5 kg amount of silicone which helped me find how much each pour would cost per volume. Other information about various properties for a specific type of silicone to see if this is what we would want.

- **Art of the Part, " SolidWorks: Core & Cavity Assemblies for Casting & Mold Making," [34] (Video)**

  Mainly utilized in the self-learning assignment, this video elaborates on the creation of molds in SolidWorks. This step-by-step video highlights various tools in SolidWorks needed to create an interactive version of a mold. One of these tools, "Cavity", gives our group representation of potential blood vessel shapes a mold could make without having to use materials. It could also give us the ability to potentially 3D print the mold.

- **Optimization of particle image distortion for PIV measurements [45] (Journal)**

  In order to conceptually understand my engineering calculation of relative distortion, I used this journal to see what is happening to cause distortion. Calculating values don't mean anything unless you know the meaning behind them. This journal gives different examples that help me make connections to our project.

- **Optimization of particle image velocimeters: II. multiple pulsed systems, "*Measurement Science and Technology"* [46] (Journal)**

  Furthermore, my calculations and understanding of how they will affect our testing. This article helped to verify the reliability of the offset and spatial resolution comparison. Now I can tell that the difference between the refractive index of the phantom unit and the fluid inside will not cause enough trouble to have to be dealt with.
- **A simple mechanical spring-driven rheometer for measurement of Newtonian and non-Newtonian fluids - design, validation, and input correction [47]**

  For upcoming individual analysis, I researched the tools to test viscosity that I will be using in the BDL lab. I wanted to have some previous knowledge of what I will be using to protect the equipment and to hopefully decrease troubleshooting time if anything occurs.

3.3 Mathematical Modeling

3.3.1 HPMC Refractive Index – Carley Barton

When running flows through a silicone phantom each material has a different refractive index. If these indexes don't match there will be an offset in the data collected. Just like how a straw looks cut when you put it in water.

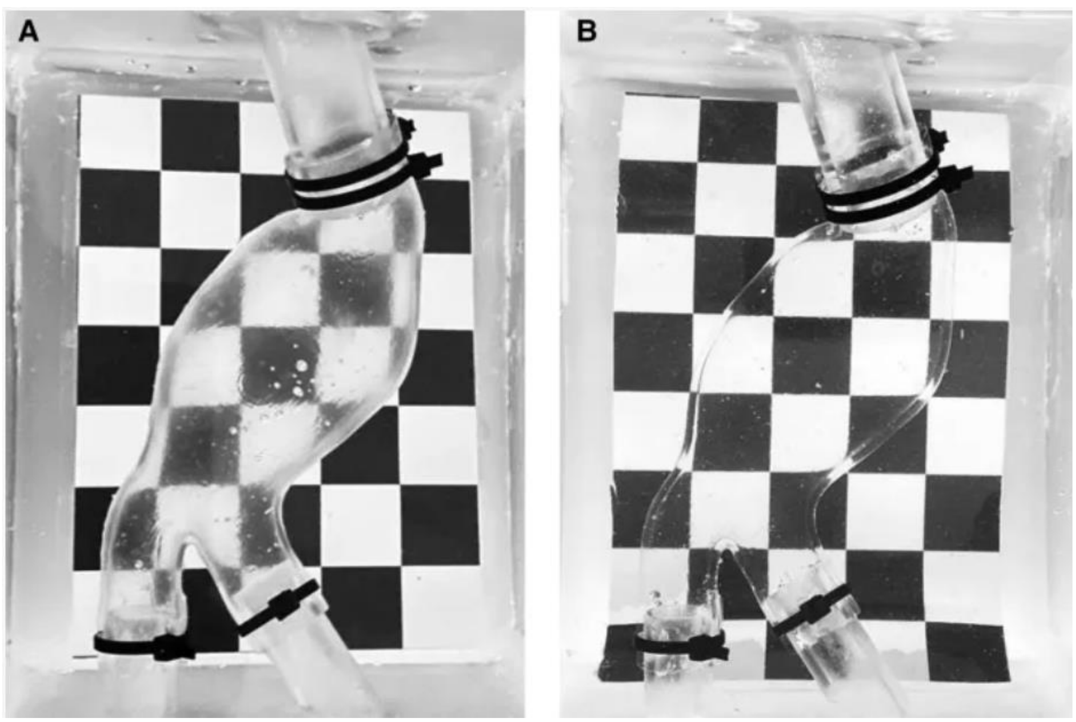


Figure 7: Left side (A) water flowing through model, right side (B) refractive index matched fluid [12]

As you can see in figure 1, the flow with water through it isn't as clear and the checkered board shown behind it has an offset. The section on the right has an index matched fluid that is also blood mimicking. This matched fluid has a much clearer visual and will have better success when collecting data.

Our client originally didn't want to change the components of blood mimicking fluid that will be going through the phantom, this fluid is known as HPMC which is comprised of a small amount of HPMC powder (Hydroxypropyl methylcellulose) mixed with ethanol and water. By taking these components and the known weight fractions and refractive index, we can solve for the overall refractive index of the fluid.

Lorentz-Lorenz equation [8]

$$\frac{n^2{}_{mix} - 1}{n^2{}_{mix} + 2} = \sum \emptyset_i \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

$$N_i = \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

Variable definition:

N_i= Lorentz-Lorenz parameter of component

$\emptyset_i$= Volume fraction

n_i= refractive index of component

Refractive index HPMC = 1.48 [9]

Volume fraction HPMC = 0.007

RI Water = 1.333

Volume fraction Water = 0.093

RI Ethanol = 1.361 [15]

Volume fraction Ethanol = 0.090

1st step is solving for the Lorentz-Lorenz parameter of each component, ethanol, water, and HPMC powder.

$$N_{water} = \frac{1.33^2 - 1}{1.33^2 + 2} = 0.204$$

$$N_{ethanol} = \frac{1.361^2 - 1}{1.361^2 + 2} = 0.221$$

$$N_{HPMC} = \frac{1.48^2 - 1}{1.48^2 + 2} = 0.284$$

2nd step: By multiplying the Lorentz-Lorenz parameter by each component's weight fraction we get the parameter for the mixture.

$$N_{mix} = (0.903 \cdot 0.204) + (0.090 \cdot 0.221) + (0.007 \cdot 0.284) = 0.206$$

3rd step: Plug in the N_{mix} to the equation below and you will get the refractive index.

$$n_{mix} = \sqrt{\frac{1 + 2N_{mix}}{1 - N_{mix}}} = 1.3335$$

HPMC blood analog mixture has a refractive index of 1.3335. We will now take this value and match the silicone refractive index to it.

Validation: These values were validated by using a Brix% refractometer on the HPMC fluid. This test includes placing a small drop of fluid on the refractometer and holding it up to light. This value matched the calculated value above.

3.3.2 Silicone RI Match – Carley Barton

In order to lower the refractive index of a substance you can mix another material with it that has a lower refractive index. After some research, the best option that is low cost and has a low refractive index would be water. After solving for the refractive index of HPMC in section 3.3.1 the value was found to be 1.334. This is the index we will bring the silicones refractive index of 1.41 down to.

Using the same Lorentz-Lorenz equation we will re-arrange to solve for the weight fraction of water to be added.

Lorentz-Lorenz equation [8]

$$N_i = \frac{n^2{}_i - 1}{n^2{}_i + 2}$$

$N_{mix} = \emptyset_s N_s + \emptyset_w N_w$

N_i= Lorentz-Lorenz parameter of

component

$\emptyset_i$= Volume fraction

n_i= refractive index of component

Known:

RI Water = 1.333

RI Silicone = 1.41

RI of HPMC from section 3.3.1 = 1.334

1st step: find the Lorentz-Lorenz parameter for each component, silicone, water, and the final silicone mixture.

For silicone

$$n_s = 1.41 \implies n_s{}^2 = 1.988$$

$$N_s = \frac{1.988-1}{1.988+2} = 0.248$$

For water

$$n_w = 1.333 \implies n_w{}^2 = 1.777$$

$$N_s = \frac{1.777-1}{1.777+2} = 0.206$$

Target silicone mixture (after adding water)

$$n = 1.334 \implies n^2 = 1.7796$$

$$N = \frac{1.7796-1}{1.7796+2} = 0.2063$$

2nd step: Then by multiplying the weight percentage by parameter we can rearrange to solve for the weight fraction of water.

$N_{mix} = \emptyset_s N_s + \emptyset_w N_w$ Since $\emptyset_s + \emptyset_w = 1$; rearrange this and plug in

$\emptyset_w = 1 - \emptyset_s$ along with the corresponding values for each variable

$0.2063 = \emptyset_s$ (0.248) + (1- $\emptyset_s$)(0.206)

Solve for $\emptyset_s$ and $\emptyset_s = 0.00714$

Therefore, the volume fractions would be 0.71% silicone and 99.29% water which is not possible.

Since this is not possible to have a silicone mixture of 0.71% silicone and have it cure, as a group we will have to pivot and come up with a solution with the client. Most likely having to change the fluid going through the model.

Validation: This was validated by the source the Lorentz-Lorenz equation came from [8], there were many examples of this equation being used and since there were a lot of known variables there isn't that much variation within the answer.

3.3.3 PIV Spatial Resolution – Blake Pottinger

When filming the microscopic PIV particles, it is important to get a clear picture to collect the data efficiently. To do so the correct camera equipment is needed as well as the proper software. The previous capstone had bought the correct camera equipment, but it was up to us to determine the ideal factors such as the interrogation window size and particle diameter. When plugged into a computer program, the particles' information is tracked using vector arrows (figure 8). These arrows return crucial information such as particle velocity, direction, and stress on the walls and around aneurisms.

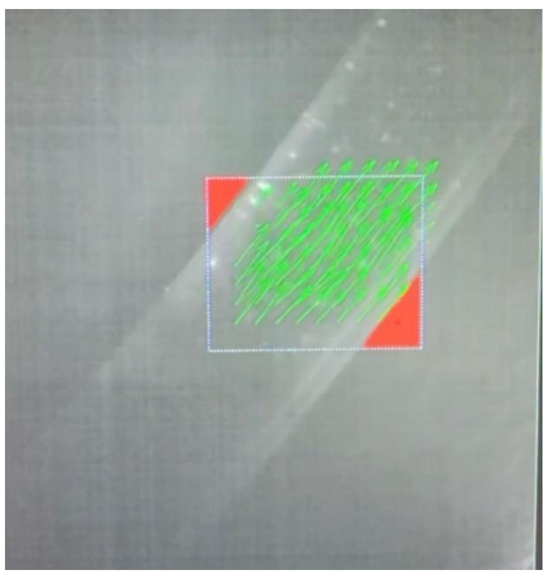


Figure 8: PIV particle vectors

The information below will be validated once testing has commenced. The team will begin with a resolution of about 4.33 mm, and we will adjust the resolution of the specific camera as needed. But this calculation gives our team an amazing starting estimation and future resolutions will be listed below.

PIV Spatial Resolution Equation [14]

$$RES = (D_1 + D) \cdot \frac{S}{M}$$

Variable Definition

RES: The resolution in physical space represented by a velocity vector.

$\mathbf{D_1}$: Interrogation window size

D: Particle Image Diameter

S: Camera sensor pixel spacing

M: Optical Magnification

Solution

$$RES = (32\ [pixels] + 8\ [pixels]) \cdot \frac{6.5 \times 10^{-6}\ [m]}{0.06}$$

$$RES = 40 \ \cdot 1.083 \times 10^{-4}$$

$$RES = 0.00433\ [m]$$

$$RES = 4.33\ [mm]$$

3.3.4 Change RI of HPMC – Blake Pottinger

Following the calculations done in mathematical modelling section 3.3.2, the team needed to calculate a new blood analog to fit the refractive index of the silicone. To do so, the current HPMC mixture could be mixed with glycerin to match the target refractive index of the silicone which was 1.41. The calculations below show the new mixture needs to be comprised of 56% glycerin and 44% of HPMC.

To validate the new mixture composition, the team needs to compare the properties of the mixture to that of 100% HPMC as well as to the properties of blood. If the client deems the analog blood to be suitable for the current benchtop model, we will then need to test the refractive index of the mixture to that of the silicone. Once both crucial criteria are met, we can move forward with the rest of the product testing.

Lorentz-Lorenz equation [8]

$$N_i = \frac{{n^2}_i - 1}{{n^2}_i + 2}$$

$N_{mix} = \emptyset_G\, N_G + \emptyset_H N_H$

N_i= Lorentz-Lorenz parameter of component

$\emptyset_i$= Volume fraction

n_i= refractive index of component

Known:

RI HPMC = 1.334

RI Silicone= 1.41

RI Glycerin = 1.473 [6]

- **For glycerin**

$$n_G = 1.473 \Longrightarrow {n_G}^2 = 2.17$$

$N_G = \frac{1.988-1}{1.988+2} = 0.281$

- **For HPMC**

$$n_w = 1.334 \Longrightarrow {n_w}^2 = 1.78$$

$N_w = \frac{1.78-1}{1.78+2} = 0.206$

- **Target silicone mixture**

$n = 1.41 \Longrightarrow n^2 = 1.988$

$N = \frac{1.988-1}{1.988+2} = 0.248$

$N_{mix} = \emptyset_G N_G + \emptyset_H N_H$ Since $\emptyset_G + \emptyset_H = 1$ we can plug in

$\emptyset_H = 1 - \emptyset_G$ and solve

$0.248 = \emptyset_G (0.281) + (1 - \emptyset_G)(0.206)$

Solve and $\emptyset_G = 0.56$

In order for out fluid mixture to have a refractive index of 1.41 it needs to be comprised of 56% glycerin and 44% HPMC

3.3.5 Particle Density – Clinton Nelson

Particle density is an important aspect of PIV because it will determine the seeding concentration of particles for good velocity measurements. These equations of an output of the percentage of the image is occupied by particles.

$$A_{Particle} = \pi \left(\frac{d}{2}\right)^2 = 95\mu m^2 = 9.5 * 10^{-11} mm^2$$

$$A_{Phantom} = w * h = 1.3225 mm^2$$

$$n_{Particles} = \frac{m_{Total} * N_A}{M} = 15.63 * 10^7 \text{particles}$$

$$d = 11\mu m$$

$$\rho = 1.06 \left(\frac{g}{mL}\right)$$

$$w = 1.15m$$

$$h = w$$

$$m_{Total} = 0.1g$$

$$N_A = \text{Avogadro's Number}$$

$$PD(\%) = \frac{(n_{particle} * A_{particle})}{A_{phanom}} = 0.011\%$$

Through the calculations above and the assumptions of what is going into the system we found that 0.011% of particles will be seen within the camera.

This calculation will be validated and updated in the future when a raw PIV frame is captured. We will count the visible particles in the image either manually or using PIVlab. We will then compare the same equation of $PD(\%) = \frac{(n_{particle} * A_{particle})}{A_{phanom}}$ with the new $n_{Particles}$ number and areas to this mathematical modeling and see what changed and how to adjust.

3.3.6 Minimum Wall Thickness – Clinton Nelson

When manufacturing a silicone phantom we asked the question, is there a minimum thickness between the outside of the phantom and the hollow inside vessel as seen in figure 9. This thickness could influence the strength of the silicone and if the minimum happened to be large, how does the thickness effect data collection that will be uploaded to PIVlab.

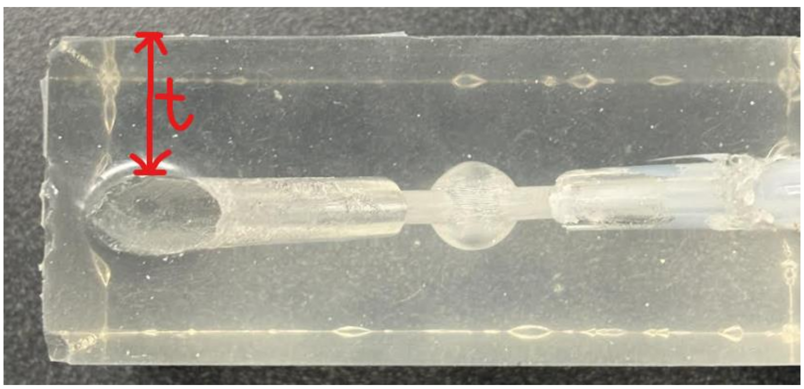


Figure 9: Side view of example phantom

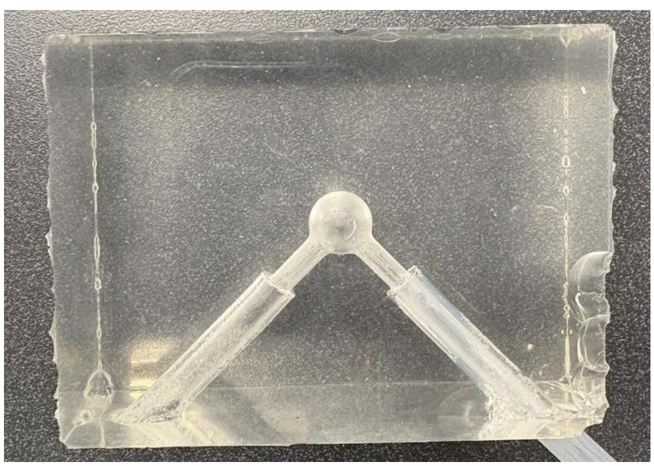


Figure 10: Front view of example phantom

$$\textbf{Hoop Stress}: \boldsymbol{\sigma} = \frac{\mathbf{Pr}}{\mathbf{t}} \ [35]$$

$$P = \text{Internal Pressure} = 0.015995\left(\frac{N}{mm^2}\right) = 120\text{mmHg}$$

The internal pressure was taken from physiological pressure of 120 mmHg, this was then converted to N/mm^2 or MPa.

$$r = \text{Radius} = 2.5\text{mm (average vessel radius)}$$

$$\sigma_{allowable} = 1.5\text{MPA (given from silicone properties [33])}$$

We then rearranging the hoop stress equation we solved for t-thickness

$$t = \frac{Pr}{\sigma_{allowable}}$$

When plugging in corresponding values we get a thickness of

$$t = 0.0262\text{mm}$$

From the Hoop Stress equation, we used dimensions of a vessel to model our phantom as well as the internal pressure. We then took the properties of silicon to get the allowable stress to then be plugged into the Hoop equation to get a thickness of 0.0262mm.

By getting a minimum thickness of 0.0262mm, we found that the pressure on the inside of the phantom model does not affect the silicone enough to cause it to break. This informed our design because now we can focus on the visibility of the silicone and what thickness is best for data collection without having to worry about a rupture in the model because of a high internal pressure.

This mathematical model was validated via textbook problems and applying lessons taught in mechanics of materials and machine design. We will further validate the thickness with testing the physical model and fitting it best to the refractive index of our blood analog mixture.

3.3.7 Phantom Cost Analysis – Ryan Abelman

In the first analysis of the Phantom Cost, the team took a broad approach without knowing the specifics of the materials, process, or size of the object.

$$PPU = \left(\frac{C_f}{n}\right) + C_v + t(C_L)$$

The variables involved in this initial equation are as follows:

$$PPU - Price\ Per\ Unit$$

$$C_f - Fixed\ Costs$$

$$n - Quantity$$

$$C_v - Variable\ Costs$$

$$t - Labor\ time\ (hours)$$

$$C_L - Hourly\ Labor\ Cost$$

Without actual numbers early in the project, the team had to assume numbers that were believed to be in the realm of what we could use. The initial calculations were also done relative to the whole 5.5

Quantity (n)	Cost of Normal Cure Time (7-8hrs)	Cost of Faster Cure Time (1-2hrs @ 120F)
1	366.25	273.25
5	206.25	113.25
10	186.25	93.25
20	176.25	83.25
25	174.25	81.25
50	170.25	77.25
100	168.25	75.25
150	167.58	74.58
200	167.25	74.25

kg of silicone to be purchased. These values included:

$$C_f = \$200.00$$

$$n = 1, 5, 10, 20, 25$$

$$C_v = \$50.00$$

$$t = 7.5\ hrs\ or\ 1.5\ hrs$$

Table 1: Analysis #1 of Phantom Cost

$$C_L = 15.5 \frac{dollars}{hr} (minimum\ wage\ at\ NAU)$$

After Presentation 1, some concerns with validation of these values and how they would be applied in the project were brought forth in feedback. How high the costs were depending on the time and curing did not completely make sense and the quantity produced was not plausible. To account for these concerns, a revised calculation of the analysis was completed.

3.3.8 Revised Phantom Cost Analysis – Ryan Abelman

With a greater understanding of how the process for the Phantom unit would be created, the actual size of it, and the feedback in mind, adjustments were made to the values and the PPU equation itself.

$$price\ per\ unit\ (PPU) = \left(\frac{C_f}{n}\right) + C_v$$

This equation was adjusted with the assumptions that we did not need to incorporate the hourly labor cost because the team would not be paid during the process of making the unit. Also, if a heating mechanism was incorporated, the cost would be in the Fixed Cost rather than having the actual time the curing takes affect the cost.

$$C_f = \$5.00\ (non - heated)\ or\ \$7.00\ (heated)$$

Furthermore, after studying more about the Fixed and Variable cost, we decided to consider the Variable cost to come from the volume of a unit produced. This was done through dividing the total milliliters available in the 5.5 kg silicone order (5500mL) by the volume of 392 mL to find the number of units we could produce.

# of units available to produce = 14

Then using the total cost of one order, we could find the price per volume:

$$price\ per\ unit\ volume = \frac{\$196.25}{14} = \$14.02$$

Using that value, we could then assume the Variable cost.

$C_v = \$17.06$ (includes another \$3.00 for miscellaneous items)

Now applying these new values to the new equation, we found more accurate and appliable results for our group, seen in Table 2 below.

Quantity (n)	Normal Curing at Room Temperature	Faster Curing(1-2hrs @ 120°C)
1	$22.02	$24.02
2	$19.52	$20.52
3	$18.69	$19.35
5	$18.02	$18.42
10	$17.52	$17.72

Table 2: Analysis #2 of Phantom Cost

With the feedback, we developed a more reasonable cost with reasonable quantities that we could produce and validate. These values show that if we have the time to wait early on in production, then we can save a couple of dollars, once we increase quantity though the prices begin to even out. In validating, these numbers come from actual values and ultimately make sense when thinking about the size of the object being created, compared to the values found in 3.3.8.

4 Design Concepts

Chapter 4 details the extensive process our group underwent to select the best designs and methods to be used for our first manufactured prototype. This process was completed using functional decomposition charts 4.1, concept generations 4.2, and the methods we used to select the best design 4.3 and 4.4.

4.1 Functional Decomposition

Figure 11 depicts a black box model for manufacturing a single silicone phantom model. The black box model is a useful tool for simplifying a decomposition model by only showing the inputs and outputs of the process. The arrows on either side of the black box represent the specific method of the input with materials represented by a thick black arrow, energy represented by a thin arrow, and electronic signals represented by a dashed line. The paths can be seen in more detail in figure 11. The black box model was important when generating our preliminary bill of materials as we can see every item needed to create a single silicone phantom.

Figure 11: Black Box design

Figure 12 is a detailed plan for manufacturing a singular silicone phantom. Unlike the black box model, the decomposition model shows the entire manufacturing process in detail. This model is useful to the team as it provides a detailed flow chart of the processes and tools needed to manufacture a model. The decomposition model was also useful in helping the team identify ways for improving the manufacturing method. For example, the team was informed of the importance of having the silicone be both pressurized and degassed to produce the clearest silicone possible. It informed the team that we need to get a vacuum pump which made us reach out and get sponsorship from Western Component Sales and JB Industries. The decomposition model also helped with a revision to our concept generation as the team pivoted to adding a 3D printer to create a water-soluble core. Future iterations of the decomposition model will show this change.

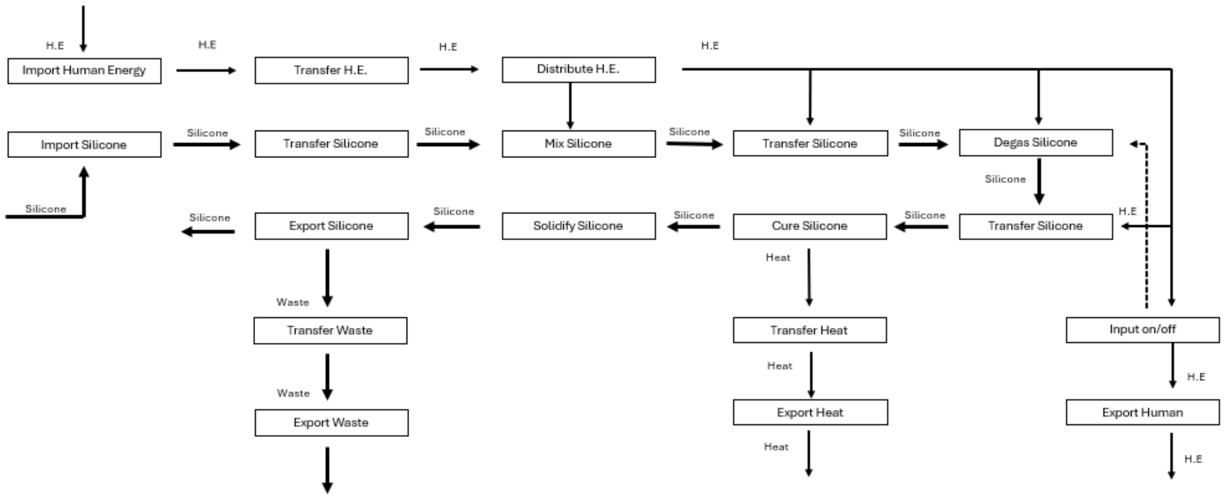


Figure 12: Decomposition Model

4.2 Concept Generation

A. **Face shape of silicone block –** This is the shape of the final silicone phantom block. For example, in figure 9, the phantom shape is rectangular. This is an important aspect to see which shape decreases the use of unnecessary material, and which affects visibility of the hollowed inner vessel model.

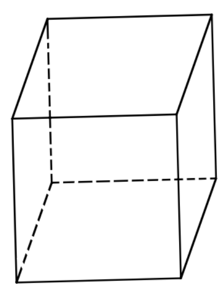


Figure 13: Square phantom shape

The concept design for the face shape of the silicone phantom block was a square. This model works well for smaller phantoms but if we had to increase the length of the vessel inside the model then we would also have to increase the height of the phantom to match the square shape.

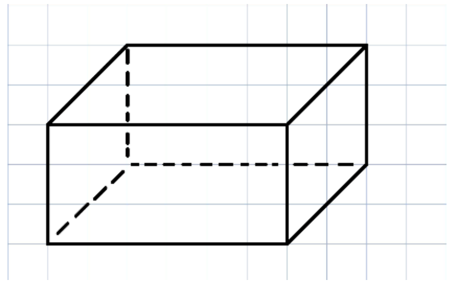


Figure 14: Rectangle phantom shape

We have the rectangle next which will also be used as a shape for our phantom model. This design will roughly be the same dimensions as a phone but a bit thicker. This is the likely model we want for both the phantom and vessel model because it optimized the size of the vessel model and decreasing cost on material used.

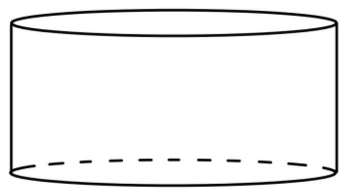


Figure 15: Oval face phantom shape

The oval shaped model will have a cylindrical body and will have the vessel model run along the length in the center. There will likely be less material needed for this model, but we believe this would be difficult to observe unless viewed from above with the molding process being inefficient as well.

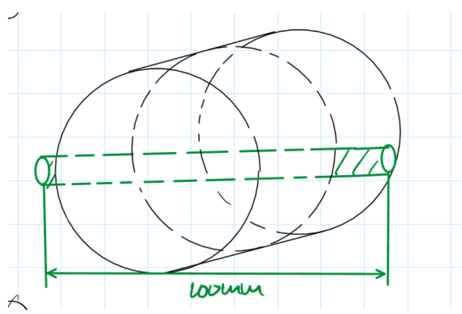


Figure 16: Circle phantom shape

Lastly, we have a shape with a circular cross section and a cylindrical body. The vessel model will run along the length of the model in the center. Similar to the oval design, it may be difficult to cast and observe. The vessel inside would have extra length added onto the inlet and outlet to combat the curvature of the face, typically the vessels have a hard cut off line of the inlets and outlets.

B. **Material of outside silicone mold –** One of the steps in the silicone molding process is to cast silicone around an inner core model, once the silicone has cured it will be removed. The material of this outside mold is important because it needs to hold the silicone in a shape long enough for it to cure and not leave any texture on the silicone.

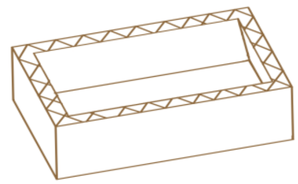


Figure 17: Cardboard material

For this concept we have cardboard being the housing for the silicone model as it cures from pouring. This would likely be the cheapest option, and we can always buy more if needed. However, we believe it would provide poor-quality housing for our mold. Leakage may also be a problem with casting, and the removal process may leave cardboard residue on the silicone.

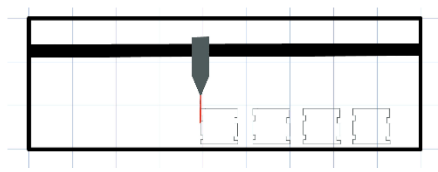


Figure 18: Laser cut acrylic

Next, we have Laser cut acrylic which will be acrylic cut into desired lengths and thicknesses to then be assembled to house the curing silicone. This will most likely be the best option to make the housing and get precise results. This method may be the most expensive due to the machines and materials needed. However, we would be able to reuse the mold if the length of the phantom stays the same. Unfortunately, if the length is altered, we would have to have another laser cut acrylic made which increases the cost.

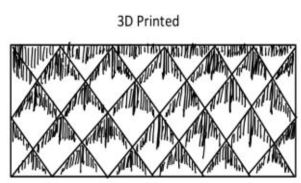


Figure 19: 3D Printing

As seen in figure 19, the 3D Printed mold will be a polymer-based material which will be printed to lengths needed to house our silicone. 3D printing is another likely option and not as expensive as other options allowing the team to get as good of results but with the risk of being melted by the heat of the poured silicone.

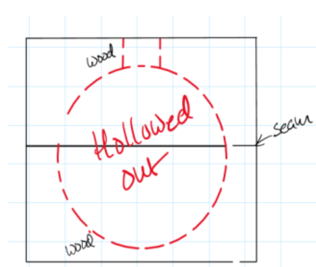


Figure 20: Wood material

Now we have wood being the housing for the silicone which will be milled or hand carved from two solid blocks of needed lengths and thickness to then be assembled at the seam. Wood is not expensive, but it is also not as cheap as some other options. It would be good housing for the poured silicone but with the temperature of the silicone once poured and the grain of the wood it will likely burn the wood and melt into the grain and may cause the wood to be replaced often. The wood will have to be very smooth as the goal is to have smooth outside of the silicone.

C. Male mold material – The male inner mold is probably the most variable aspect of this design. Each material has pros and cons of using it, varies in prices, and are all removed in a different way. This material will allow the inner vessel model to be more intricate, which is important for the model to be physiologically accurate. The ease of removal of this core will ultimately determine how repeatable this manufacturing process is and how fast a phantom can be made.

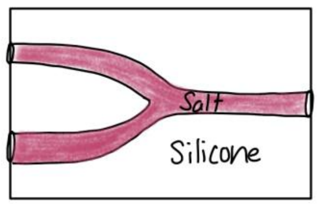


Figure 21: Inner core material, salt

For the vessel model inside the vessel will chose a salt core as one of the male molds which will be dissolved once the silicone has cured fully around the core. A salt core is good and inexpensive material but to mold it and keep it structured to then pour around it may be difficult. Another con is that the salt may cause porous indents along the inside of the silicone where we want it to be smooth. These indents will cause variation in the flow data which is not wanted.

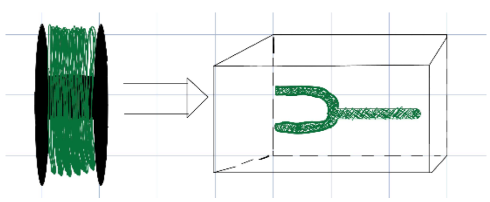


Figure 22: Inner core material 3D printing with PLA

Next, we have PLA which will be 3D printed and placed inside the housing before pouring the silicone. It will be dissolved using an ethyl acetate solution. This option is a good precise way to get a detailed vessel model within in the phantom but the need for a special solution to dissolve the PLA is expensive and proper safety measures are needed when handling ethyl acetate.

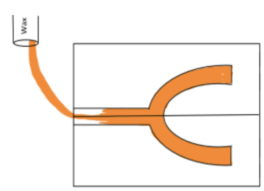


Figure 23: Inner core material, wax

We have Wax as another male model which will be modeled to desired diameters and length before phantom use, once silicone is poured and cured around the wax it can be broken up and melted out using a heat gun. This is a decent option to use but it comes with extra costs of having to create a mold just for the wax and then the wax will be used inside the phantom. Creating the molds for the wax will be difficult once the vessel models become more intricate and wax may not be as strong as it needs to be in order to pour the silicone around it.

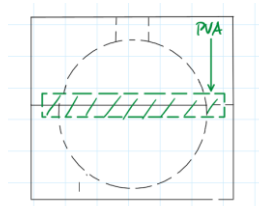


Figure 24: Inner core material 3D printing with PVA

Lastly, we have PVA, PVA is a 3D printing material that stands for Polyvinyl alcohol. This material is water soluble which is a low-cost option for removing the inner male mold from the phantom. By using 3D printing, we can model intricate vessels that are very precise and easy to remove. The only downside to this material is that it is the most expensive to purchase but there are no other expenses when using it.

D. Outside box mold assembly – The outer box assembly corresponds with how the outer mold of the silicone casting shape will hold together. It is important that the silicone does not leak and this outer mold is easily able to be disassembled.

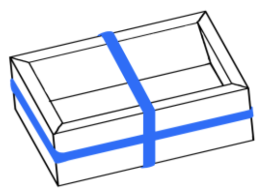


Figure 25: Rubber band hold

For what will be holding our assembly together we have rubber bands as an option which means we have several rubber bands wrapped around each side of the housing holding it all together to cure. Once the silicone has cured the bands will be released and the housing pulled apart. The rubber bands are a good and inexpensive option that are reusable, but they do not allow for precision when holding the silicone housing together and may not be able to hold enough pressure to prevent leakage when the silicone is curing.

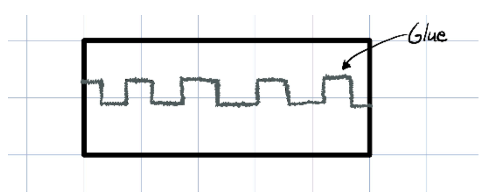


Figure 26: Outer box adhesive with glue

Next, we have Glue. The glue will be applied on the seams of the housing walls. Once curing is complete, heat will be applied to loosen the glue, and the walls will be pried apart to release the mold. Glue is another inexpensive option, but it depends on the structure of the outside housing of the assembly, and the temperature of the silicone may cause the glue to melt or not adhere correctly.

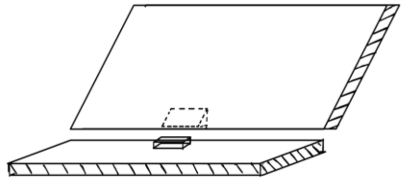


Figure 27: Pins to hold outer box together

We now have pins which will most likely be a part of the 3D printed housing. Extrusions and extruded cuts on parts of the wall will piece together and hold the housing together during silicone curing. Once cured the walls can be pried apart and reused again and again. Downside to this is that overtime the cuts may wear down and become loose, therefore leading to leaks and there is a chance of the walls breaking if too much force is needed to pry apart the pieces.

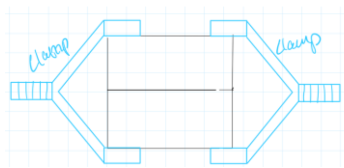


Figure 28: Clamps to hold outer box together

Last in the concept generation we have clamps, depending on the housing design clamps will be placed on the corners of the housing to hold the seams tightly for the silicone to cure. Once done clamps will be released and the mold pulled from the housing. With the clamps it's a good option to hold everything together of varying housing sizes over time but the housing will have an open top making it difficult to clamp each side of the wall together.

Concept Generation Table

	1	2	3	4
A Shape of silicone block	Square	Rectangle	Oval	Circle
B Material of outside silicone mold	Cardboard	Laser cut acrylic	3D printed	Wood
C Male mold material	Salt	PLA	Wax	PVA
D Outside box mold assembly	Rubber band	Glue	Pins	Clamps

Table 3: Compiled Concept generation denoting each concept with a letter (based on row) and number (based on column)

4.3 Selection Criteria

This selection process was only based on the subsystem of the manufacturing of the silicone phantom model. Based on the engineering requirements the only two that involve this process would be the clarity of the silicone after casting and the validation process at the very end. Clarity of the silicone is very important so the removal of the inner male mold or the outer housing must not leave any material residue or yellow the silicone. Validation involved the process of testing medical devices on the model; this involves having a smooth inside to the phantom model and an intricate vessel design that is physiologically similar.

Other requirements include ease of core removal and material usage. The hardest part of this manufacturing process is the removal of the inner male mold. This must include leaving no damage to the inside of the silicone during removal and the removal that takes the least amount of time to make this process more repeatable. Material usage is also important to cut down on costs. There will already be material usage for the housing of the silicone casting process and the inner male mold, if there is any way to not add another material or step to the process that would cut down on costs and time.

Based on the engineering requirements, the team needed to carry out this process while maintaining 90% visibility. The PVA being soluble with water will ensure there is no staining from another solution while also leaving behind a smooth model of the artery. The team also will choose to select a PIV particle that reacts best to a laser color of 532 nm and has a particle density within the fluid of 0.1 particles per pixel. This selection will be made after the concept generation, but it is still important to take into consideration. The final selection criteria during our concept generation that is important is ensuring the manufacturing process works a minimum of 80% of the time. The team needs to ensure the silicone is constantly being poured clear with minimal bubbles while also having the inner core be easily removable with no internal residue being left behind. This will be confirmed post concept generation during numerical testing.

4.4 Concept Selection

After the concept generation table was created, four designs were put together, one by each member of this team. Each design consists of one concept from each of the four categories including, shape of silicone block, material of outside silicone mold, male mold material, and outside box mold material.

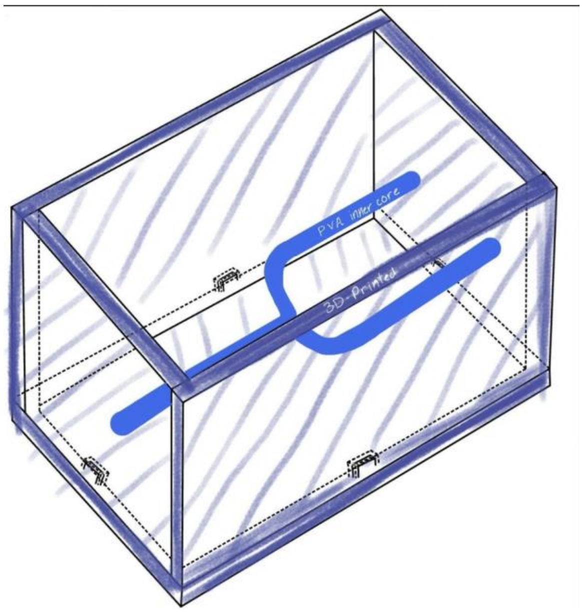


Figure 29: Design 1

Design 1 consists of a rectangle silicone shape, 3D printed outer mold material, PVA 3D printed inner male mold, and pins to hold the outer mold together. A2, B3, C4, D3

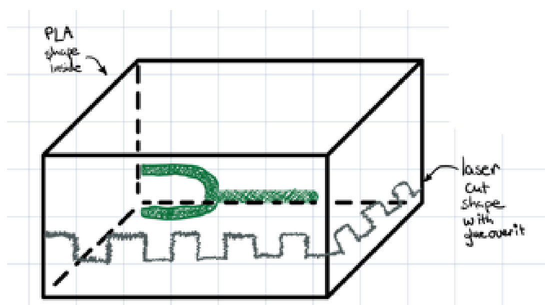


Figure 30: Design 2

Design 2 consists of a square shaped box for silicone casting, laser cut acrylic material of the outer mold, PLA 3D printed inner male mold, and glue to hold the box together. A1, B2, C2, D2

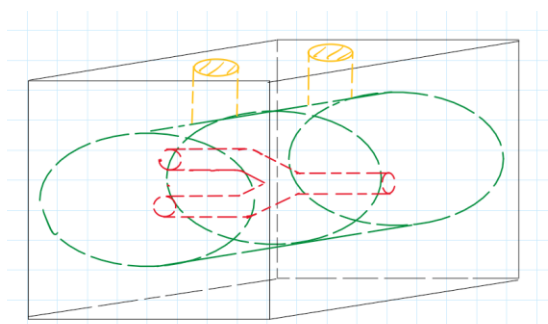


Figure 31: Design 3

Design 3 consists of a circle face shape of the silicone with the rest of the mold being a cylinder, Wood outer mold material during silicone casting, a wax inner male mold, and clamps to hold the outer mold together. A4, B4, C3, D4

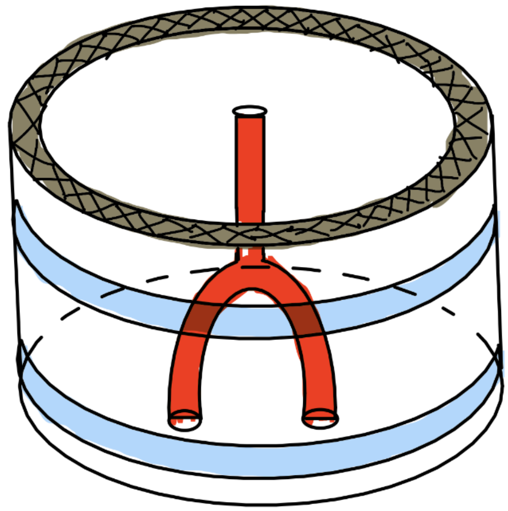


Figure 32: Design 4

Design 4 consists of an oval face shape silicone mold, the outer mold will be made of cardboard, a salt inner male core, and outer mold will be held together via rubber bands. A3, B1, C1, D1

Each design was put into a Pugh chart with one design being denoted as the datum. Design 3 was selected as the datum because it was the middle ground with each of the concepts and felt the rest could compare as either better or worse based on the selection criteria to this design.

Pugh Chart

Concept/ Criteria	Design 1	Design 2	Design 3	Design 4
Clarity Of Silicon	S	S	Datum	S
Validation	+	+		+
Ease of Core Removal	+	-		-
Material Usage	S	+		-
Sum +	2	2	Datum	1
Sum -	0	1	Datum	2
Sum S	2	1	Datum	1

Table 4: Pugh chart, comparing each design to the datum with an S meaning it compares similarly, + being positively or better than, or – as negatively

Each design was then put into a decision matrix with a weight relating to each of the criteria. Then each design was rated on a scale of 1-100, 100 being it fulfills that criteria fully. The rating, shown in the unweighted column, would then be multiplied by the weight of the criteria, as shown in the weighted column, and each weighted value would be summed to get the total value for that design. The design with the highest value scored the best according to the criteria and is now the selected design.

Decision Matrix

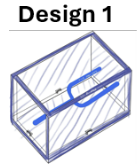
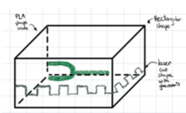
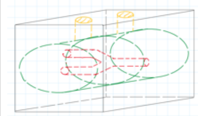
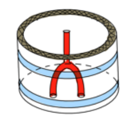
Criteria	Weight	Design 1 		Design 2 		Design 3 		Design 4 	
		Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
Clarity Of Silicon	0.3	90	27	70	21	60	18	90	27
Validation	0.2	90	18	70	14	90	18	60	12
Ease of Core Removal	0.4	90	36	80	32	70	28	50	20
Material Usage	0.1	90	9.0	40	4.0	90	9.0	40	4.0
Total:	1.0	Sum:	90	Sum:	71	Sum:	73	Sum:	63

Table 5: Decision Matrix

According to the decision, matrix design 1 scored the best based on the four criteria. Design 1 consists of a rectangle silicone shape which decreases the amount of silicone used in the model, 3D printed outer mold material which has a smooth finish and low-cost option, PVA 3D printed inner male mold easiest core to remove, and pins to hold the outer mold together.

In the future multiple designs may be tested and each process will be evaluated when prototyping to truly see which one is the most repeatable and easy to assemble.

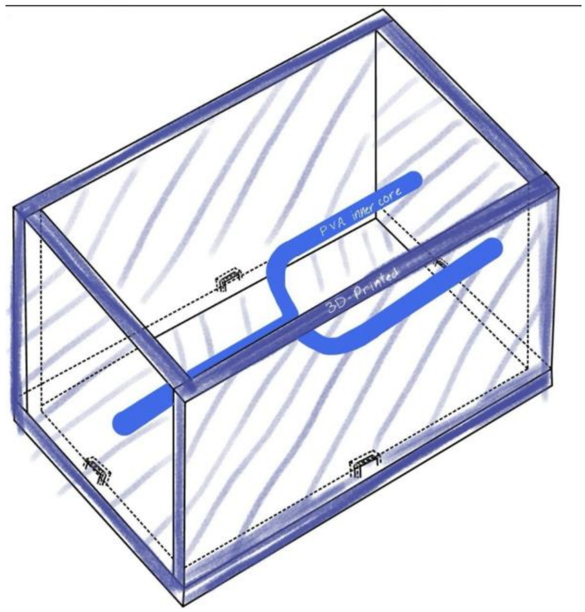


Figure 29: Design 1

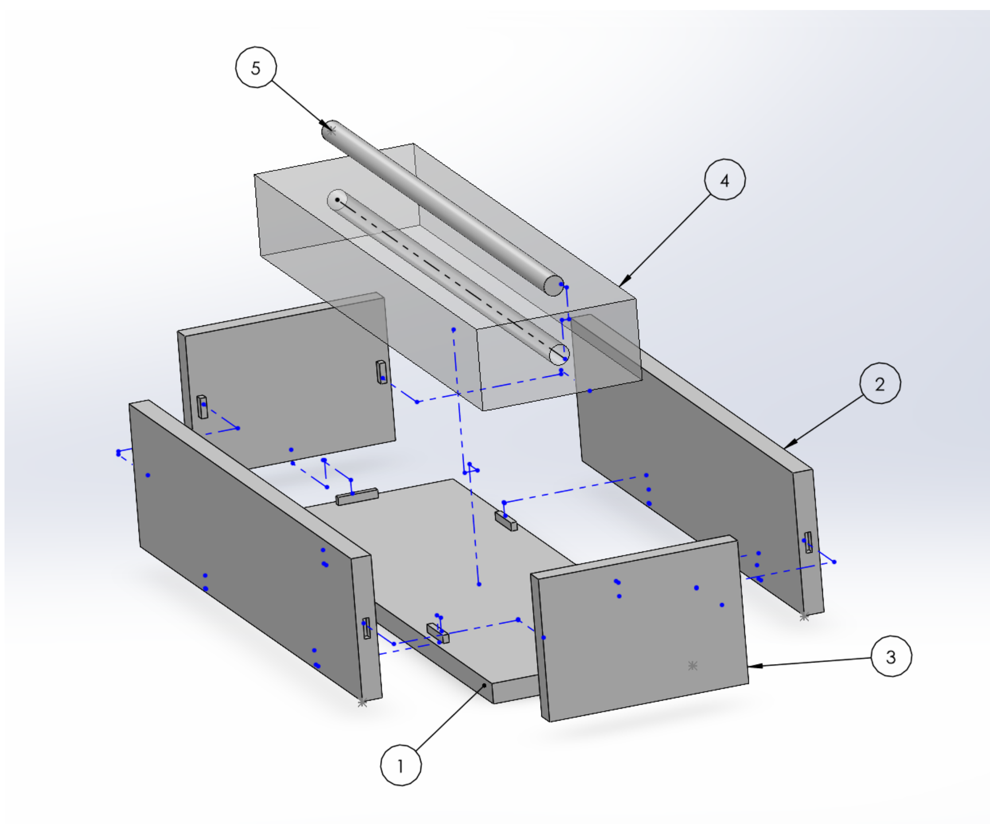


Figure 33: CAD model of final design with balloons and leader-lines

CAD design balloon labels:

1. Bottom plate made of 3D printing material with extruded pins.
2. Long side wall made of 3D printing material with extruded cut for pins to fit into.
3. Short Side wall made of 3D printing material with extruded cut on bottom and extruded pins on front face to fit with long side wall.
4. Rectangular clear silicone block (the phantom model).
5. PVA 3D printed inner core that will be dissolved out with water leaving a hollow inside of the phantom.

5 Schedule and Budget

5.1 Schedule

5.1.1 First Semester Gantt Chart:

Figure 34: Phase 1

Tasks: In the first phase of our project this semester, as a group we focused on the team charter and Presentation 1. In the team charter we laid out how we wanted to attack problems as a group and make sure we continued to progress consistently throughout the semester. We also defined roles to make sure that we complete tasks on time and in an efficient manner. For Presentation 1 the group worked on research, mathematical modeling to inform our design, described the project, and began creation of the Gantt chart and budget.

Figure 35: Phase 2

Tasks: In Phase 2, the group took on self-learning in tools like Solidworks and PIVlab along with preparing for Presentation 2. In Presentation 2, we added a more thorough breakdown of our design with concept generations, decision matrix, and a bill of materials. Then compiling everything we had up to date we created Report 1. In the website check, we started the foundation of our website so we could also start putting information there as well. In the Analysis Memo, we informed the teacher what our client recommended we test and research more to help make the design of our project more streamlined and realistic.

Figure 36: Phase 3

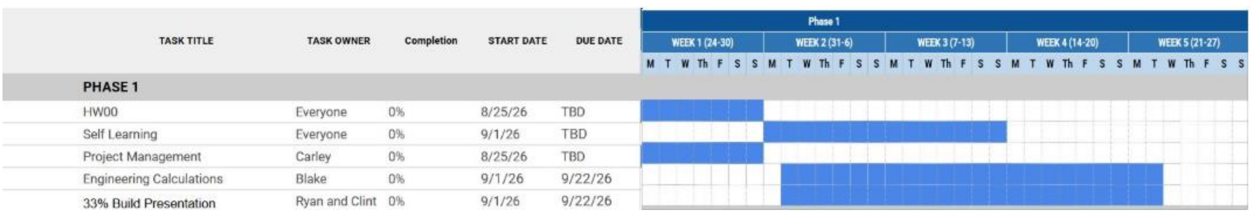
Tasks: In Phase 3, some of our research and data came to fruition in our first prototype demo. Presentation 3 included how our design and testing would fulfill our customer and engineering requirements and ultimately how those would correlate to one another. It also highlighted potential failures that could occur so we could plan ahead and have solutions to potentially dangerous situations. Furthermore, Report 2 compiles everything we have done to this point of the year and shows wear we plan to go. Next, the CAD model of our final system will be finished so next semester actual building and testing will be focused on.

Phase 4				
2nd Prototype Demo	Blake and Clint	20%	4/21/26	4/27/26
Project Management	Everyone	10%	4/21/26	5/1/26
Website Check 2	Ryan and Carley	15%	4/28/26	5/3/26

Figure 37: Phase 4

Tasks: Finally, Phase 4 finishes up the semester with a more in-depth prototype to build on for next semester and planning as well demonstrated by the draft of second semester to stay on time.

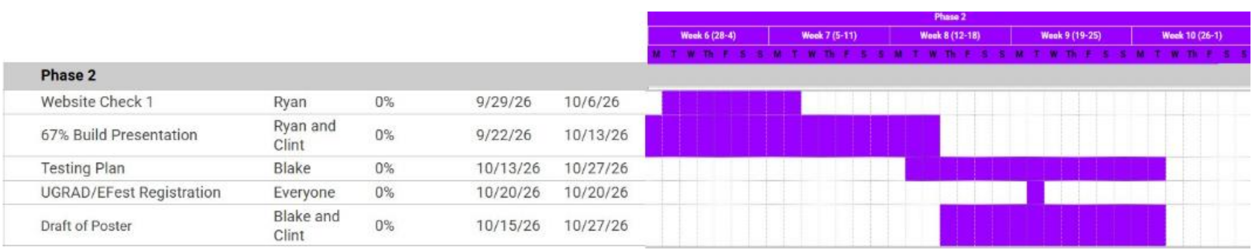
5.1.2 Draft of Second Semester



TASK TITLE	TASK OWNER	Completion	START DATE	DUE DATE
PHASE 1				
HW00	Everyone	0%	8/25/26	TBD
Self Learning	Everyone	0%	9/1/26	TBD
Project Management	Carley	0%	8/25/26	TBD
Engineering Calculations	Blake	0%	9/1/26	9/22/26
33% Build Presentation	Ryan and Clint	0%	9/1/26	9/22/26

Figure 38: Phase 1 Second Semester

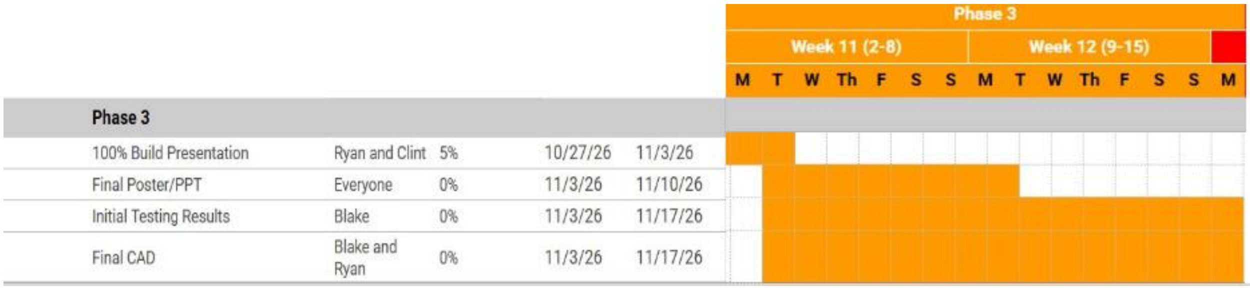
Tasks: Phase 1 in the second semester entails similar task that have already been mentioned in the first semester schedule. This phase will deal with more advanced calculations and testing to produce a model that is 33% complete of our total goal.



Phase 2				
Website Check 1	Ryan	0%	9/29/26	10/6/26
67% Build Presentation	Ryan and Clint	0%	9/22/26	10/13/26
Testing Plan	Blake	0%	10/13/26	10/27/26
UGRAD/EFest Registration	Everyone	0%	10/20/26	10/20/26
Draft of Poster	Blake and Clint	0%	10/15/26	10/27/26

Figure 39: Phase 2 Second Semester

Tasks: In Phase 2, the website will continue being updated on a regular basis and building, along with testing, the phantom units will begin. Taking some of our data and compiling it into a poster for our presentations at end of semester will also start.



Phase 3				
100% Build Presentation	Ryan and Clint	5%	10/27/26	11/3/26
Final Poster/PPT	Everyone	0%	11/3/26	11/10/26
Initial Testing Results	Blake	0%	11/3/26	11/17/26
Final CAD	Blake and Ryan	0%	11/3/26	11/17/26

Figure 40: Phase 3 Second Semester

Tasks: In Phase 3, we expect to have our full system completely finished and all of data put into the poster and presentation. With more testing and modeling, the Final Solidworks build of our system will be completed.

Phase 4				
Final Report	Carley and Blake	0%	11/17/26	11/24/26
Final Website	Ryan	0%	11/17/26	11/24/26
Final Testing	Blake	0%	11/17/26	11/24/26
Practice Efest	Everyone		12/1/26	12/6/26
Efest	Everyone			12/6/26

Figure 41: Phase 4 Second Semester

Tasks: Finally, in Phase 4 the dates will need to be pushed forward because of the acceleration of our schedule due to our final presentation being a week or two sooner. All these dates may be subject to change, as this is a rough schedule to make sure, we hit the ground running next semester and stay ahead.

5.2 Budget

Projected budget			
Item	Cost	Quantity	Purchased?
PVA material	39.99	1 roll	Yes
PLA material	14.94	1 roll	Yes
1/8"IDx3/16"OD Tubing	7.26	25 ft	No
1/4"IDx3/8"OD Tubing	3.28	10 ft	No
Vial of particles color #1	200	1 vial	No
Vial of particles Color #2	200	1 vial	No
Bambu Lab H2D 3D printer + Accessories	2533.25	1 Printer	Yes
Vacuum Chamber	100	1 Chamber	No
Liquasil clear silicone	196.25	5.5 kg	No
Projected Total:	3294.97	Actual Total:	2588.18
Remaining Budget:	-294.97	Remaining Total:	411.82

Table 6: Projected Budget

This is the projected budget of this PIV project. Only a few things have been purchased including the 3D printer which will be used by the lab on many other projects and for the future to come. The rest of the materials will most likely be purchased next semester when the flow loop with a phantom model will be created. We included particles and silicone into the budget in case we needed to buy more but the lab has been given silicone and particles from a previous lab so those costs may not be needed.

Next semester a full flow loop model will be manufactured but will most likely be comprised of materials already purchased by the lab.

5.2.1 Fundraising

As a part of this project, the team was required to fundraise a minimum of $500 to be put towards the project. The PIV V2 team would like to extend a special thanks to Western Component Sales who partnered with JB industries to donate a JB Industries Eliminator Vacuum Pump which is valued over our fundraising goal.

The Eliminator Vacuum Pump is a top-of-the-line pump that the team will use to power a vacuum chamber to degas the silicone phantom. This will help complete the customer requirement of providing clear silicone by eliminating any air pockets leading to a clean pour.

5.3 *Bill of Materials (BoM)*

Part	Part Number	Quantity	Vendor	Manufacturer	Manufactured or Purchased	Lead Time	Part Material	Manufacturer Location	Part Status	Price
PVA 3D printing matieral	N/A	1	Amazon	TRONXY	Purchased	N/A	PVA	N/A	To be Purchased	35.99
PLA 3D printing material	N/A	1	Bambu	Bambu	Purchased	N/A	PLA	N/A	To be Purchased	22.99
1/8"IDx3/16"OD Tubing	N/A	25 ft	Home Depot	Home depot	Purchased	N/A	PVC	N/A	To be Purchased	7.26
1/4"IDx3/8"OD Tubing	N/A	10 ft	Home Depot	Home depot	Purchased	N/A	PVC	N/A	To be Purchased	3.28
Vial of particles color #1	N/A	1	Cospheric	Cospheric	Purchased	N/A	N/A	N/A	To be Purchased	200
Vial of particls color #2	N/A	1	Cospheric	Cospheric	Purchased	N/A	N/A	N/A	To be Purchased	200
Liqualsil clear silicone	N/A	5.5 kg	Castaldo	Castaldo	Purchased	N/A	Silicone	N/A	Donated	196.25
Mount for Lens	N/A	1	N/A	N/A	Purchased	N/A	N/A	N/A	Purchased	######
Breadboard	M45B612	1	ThorLabs	ThorLabs	Purchased	N/A	N/A	N/A	Donated	$0.00
Laser	NPL52C	1	ThorLabs	ThorLabs	Purchased	N/A	N/A	N/A	Purchased	######
Function Generator	9520	1	Quantum Composers	Quantum Composers	Purchased	N/A	N/A	N/A	Purchased	######
Camera	CR21-1.0-32M-FNL	1	TBD	TBD	Purchased	Up to 4 weeks	N/A	N/A	Purchased	######
Cylindrical Lens	LG1629L1-A	1	ThorLabs	ThorLabs	Purchased	N/A	N/A	N/A	Purchased	######
Articulating Arm Base	1530N11	2	McMaster Carr	McMaster Carr	Purchased	1 Week	N/A	N/A	Purchased	$42.83
Articulating Arm Connector	1530N12	2	McMaster Carr	McMaster Carr	Purchased	1 Week	N/A	N/A	Purchased	$48.68
Articulating Arm Links	1530N15	1	McMaster Carr	McMaster Carr	Purchased	1 Week	N/A	N/A	Purchased	$24.04
Articulating Arm Links	1530N16	1	McMaster Carr	McMaster Carr	Purchased	1 Week	N/A	N/A	Purchased	$27.45
Articulating Arm Mount Plate	1530N24	1	McMaster Carr	McMaster Carr	Purchased	1 Week	N/A	N/A	Purchased	$35.22
Articulating Arm Locking Levers	1530N14	2	McMaster Carr	McMaster Carr	Purchased	1 Week	N/A	N/A	Purchased	$25.63
Safety Shroud	N/A	1	N/A	Chris	Manufactured	1 Day	VeroCyan	BDL	To be manufactured	$0.00
Lens for Camera		1			Purchased		N/A	N/A	To be Purchased	######
Camera Filter		1			Purchased		N/A	N/A	To be Purchased	$300.00

Table 7: Bill of Materials

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

In our group's FMEA there were not many new potential failures to our additional modeling compared to the last PIV team, but there are some parts and failures too those parts that are relevant to our project. The part that is new to the system is the phantom model made of a silicon mixture that creates a vessel to allow flow and it being able to be monitored thankfully through the clear material. The risks we saw potential happening was Leakage and Rupturing. For the Leakage there is always the risk with any system involving pipping and connections where the fluid being contained and transferred happens to seep through causing pressure to drop, flow rate to change, un-uniform velocity, and many other causes depending on the systems. As for Rupturing it could be caused by the leaking, but it could also come from other causes within or outside the containment like being over-pressurized, vapor bubbles, and outside problems putting strain or damage on the system. These failures seemed most likely to occur, but we came up with countermeasures to make it less occurrent. We found out that looking at the pressures likely to be experienced inside that we were able with Hoop's Law to determine a minimum thickness which for us seemed a great base thickness to work off a slowly build thicker without distorting the look of the vessel, this will help by giving mold a more stronger stance to pressures that may exceed the values we used in our mathematical modeling, another is stronger adhesives and gaskets at all connections to prevent leaking, there are many other countermeasures we can take to prevent theses failures these are just the measures we believe to be enough based on the current status of the system.

Product Name: Particle Image Velocimetry Set Up		Development Team				Page No of			
System Name: PIV System						FMEA Number			
Subsystem Name: Phantom Unit and Flow Loop						Date 3/27/2026			
Component Name									
Part Name and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Phantom Mold: creates a vessel for fluid to flow through and allow images to be taken through the clear material.	Leakage	Loss of flow control, effects pressure data and flowrates.	9	Poor sealing of tubing coming in and out of the phantom. Failures of adhesive or connectors.	2	Visual inspection of bubbles in system. Monitor changes in pressure during experiments.	7	126	Select the correct connectors/luers to connect tubing to the phantom. Increase wall thickness at inlets and outlets.

	Fluid Overload/rupture	Decreases Lifespan, would need to be replaced if ruptured	9	Improper pressures exceeding material strengths, repeated pressure cycles, used particles can coat tubing and inside of phantom leading to the need for replacement.	3	Run the mold with body-like Pressures to best replicate a human vascular system, and not over exceeding max 44ressure of the silicone	5	135	Regulate pressures of the system during testing and have back up options in case the system experiences an increase in pressure to then lower it or shut the system down
Laser (NPL52C): produces a uniform light source used to form the laser sheet.	Diode Overheating	Laser failure, needs warranty repair.	9	Failure of electronic monitoring components inside laser, significant increase in ambient temperature bringing it outside of laser TEC threshold.	3	Test laser system in work area for long cycles before system integration.	6	162	Consider adding additional active cooling to laser enclosure.
	Diode Overcurrent	Laser failure, needs warranty repair.	9	Failure of electronic protection inside laser.	1	Test laser system in work area for long cycles before system integration.	3	27	Investigate Thorlabs existing longevity data for maintenance/replacement schedule.

	Electrostatic Discharge (ESD)	Laser failure, needs warranty repair, possible paid repair.	9	Operator handling laser electronics inside enclosure.	2	Incident based, cannot be tested effectively.	10	180	Outline operator procedure for grounding and use of anti-ESD wrist strap in case need to open laser enclosure arises.
	Beam Viewing Incident	Possible permanent blindness.	10	Failure to use provided and rated PPE, failure of light sheet generator, failure to enact proper LOTO-TO procedures before maintenance /adjustments to optical train.	1	Attempt to replicate any sequence of unsafe actions and procedures in engineering testing environment before delivery to customer.	5	50	Bring in outside testing personnel to interact with system to ensure no procedural blind spots.
Function Generator (9520): signals the laser to start and when pictures are taken	Overheating	Function generator failure, needs warranty repair.	8	Exceedingly high ambient temperature.	3	Test synchronization system in work area for long cycles before system integration.	3	72	Investigate need for additional active cooling for function generator.

	Output Drift	Poor laser/ camera timing, need to repeat trials / discard results.	5	Electronic failure.	1	Test synchronization system in work area for long cycles before system integration.	4	20	Contact manufacturer for mitigation strategies.
Camera (CR21-1.0-32M-FNL): takes pictures of the fluid flow to input into PIVlab	Overheating	Camera failure, needs warranty repair.	8	Exceedingly high ambient temperature, very high load duty cycles.	2	Test imaging system in work area for long cycles before system integration.	6	96	Investigate need for additional active cooling for camera sensor.
	Sensor Laser Exposure	Possible camera failure / damage.	6	Misalignment of light sheet generator / component in optics train.	3	Investigate potential damage based on lens configuration and optical power output of laser at max duty cycle.	4	72	Educate operators on risks of camera exposure to direct beams and powerful specular reflections.
Articulating Arm: holds the laser and camera in place to produce repeatable results.	Locking Handle Failure to Engage	Impact damage to laser and optics train.	9	Fatigue and wear due to use.	2	Buy additional locking handles and test	2	36	Inform customer of potential for random failures as well.

						them over a very high number of cycles- replace before delivering to customer.			
Sheet Generator (N/A): turns the laser into a planar sheet for us to see the vectors	Thermal Shift	Laser beam misalignment, poor beam quality.	5	High temperature fluctuations inside optics train enclosure.	2	Test laser system in work area for long cycles before system integration. Actively vary ambient temperature during trials.	4	40	Research computational simulations for thermal expansion with selected lens mounts.
	Vibrational Shift	Laser beam misalignment, poor beam quality.	5	Vibrations generated by other equipment in testing room.	1	Test laser system in work area for long cycles before system integration.	7	35	Determine options for ground isolation mounts for laser-optics system.

Table 8: FMEA

6.2 Initial Prototyping

6.2.1 Physical Prototype 1

1. What question was answered with the prototype?

Is this process repeatable, is there anything that needed to be changed about the process?

Physical prototype 1 was molding a phantom using a pin as the inner mold that was snapped once cured and removed leaving a hollow inside of the silicone. This pin was not made out of PVA (a water-soluble material that was selected from our decision matrix) because a 3D printer that can use PVA had not been ordered yet.

The process that was used to create this phantom was as follows:

1. 3D print inner core
2. Piece together acrylic box and sealed with hot glue
3. Mix 2-part silicone mixture in a cup of container that can hold 300% mixture volume
4. Place cup in vacuum chamber and apply vacuum for 5 minutes
5. Once removed from vacuum pour silicone around 3D printed core inside the assembled acrylic box
6. Place the filled mold into vacuum chamber again and apply vacuum for 2-3 minutes
7. Place filled mold into pressure chamber and apply pressure for 7-9 hours or until fully cured
8. Removed outer acrylic mold by applying heat to hot glue and disassembled box
9. Twist inner pin until it snaps into two pieces
10. Pull the two pieces out of the mold, trim and clean off excess silicone from block

2. What was the answer?

This process proved to be very repeatable. Two molds were made with some minor cosmetic issues.

3. How did this inform our design and what will future iterations include?

The first mold that was created did not cure as a perfect block. This was because there was a working time with the silicone of 45 minutes where it needed to be poured into the mold before that time or else it would not pour evenly and spread out. A second iteration was made, including that working time and the process became a lot easier. This second prototype cured a lot cleaner with little cosmetic issues. This process included a previous acrylic block used by the BDL lab with dimensions of 101.6x37.75x33.02mm. The acrylic box was not cut with precision leaving lots of space between each piece which was then sealed using hot glue. For the future this was not a good material to seal with because of the residual glue once heated and removed. In the next prototype we will 3D print the box to be assembled and will be printed with much more precision.

6.2.2 Virtual Prototype 1

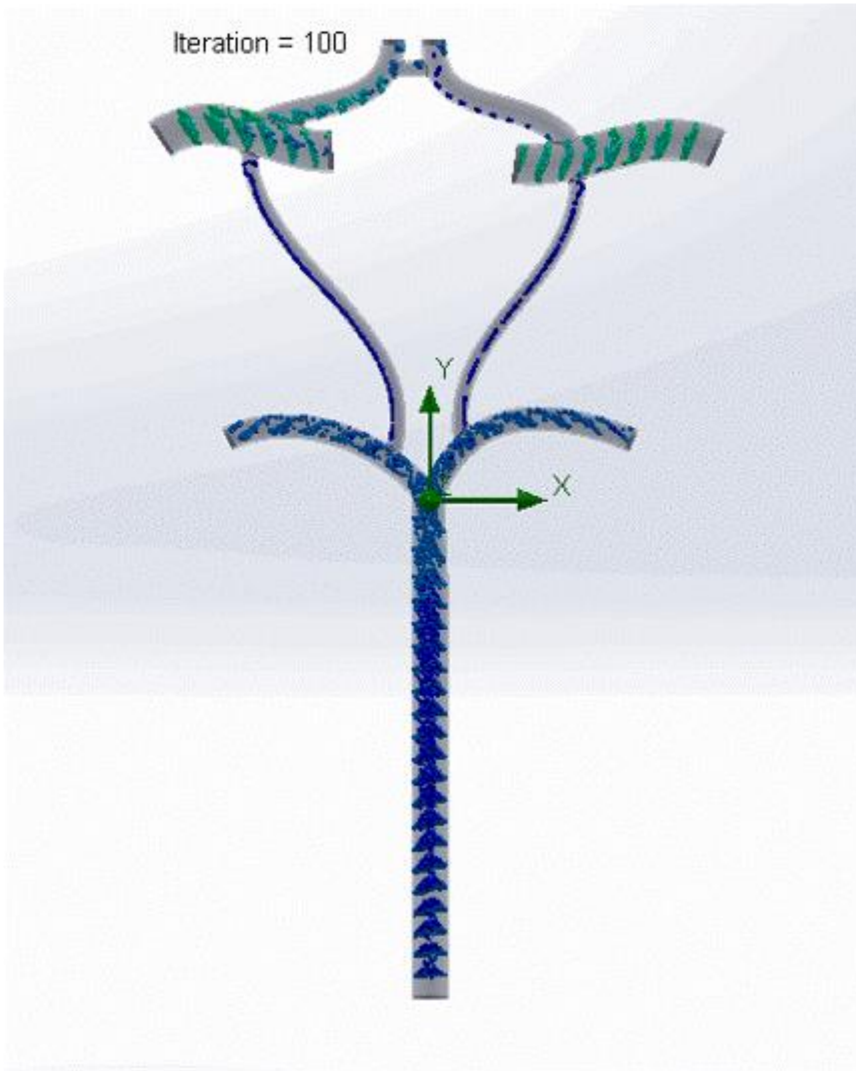


Figure 42: CAD Model of the Circle of Willis

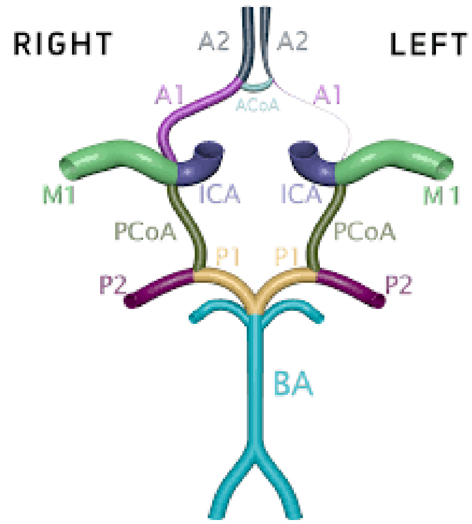


Figure 43: Labelled Circle of Willis

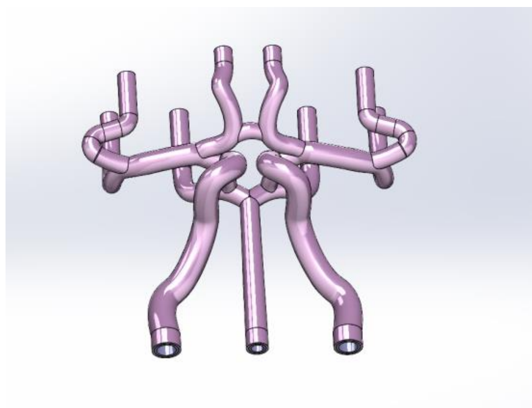


Figure 44: BDL CAD Model of Circle of Willis

1. What question is trying to be answered?

How does flow behave through the Circle of Willis, and is the planned PIV setup sufficient to accurately capture the flow velocity distribution?

2. What was the answer?

The CFD model shows that flow through the Circle of Willis is not uniform throughout, it depends on where the bifurcations are, the vessel diameter, and length. Some of the features in the flow occur at scales either comparable to or smaller than the special resolution of about 3mm that Blake solved for in section 6.3.2. This means that certain fine details may not be fully captured in PIV data.

3. How did this inform our design and what will future iterations include?

This informed our design by showing key places to position the laser sheet and camera to best capture regions with relevant flow information. This also brought awareness of the spatial resolution of our set up and how small-scale features may be missed so an iteration of the spatial resolution may be needed. In the future we will iterate on this CFD model to make it more alike to how our circle of Willis model will look and do a more in-depth analysis using CFD in Ansys.

6.3 Other Engineering Calculations

6.3.1 Settling Velocity - Carley Barton

Settling velocity is the velocity that the particles will either sink or rise within a fluid. This is important to calculate because during experiments the particles need to be evenly distributed within the fluid but if there is a difference in density between the particle and fluid the particles will either rise or fall. This equation was found from the website that the particles will come from. [36]

$$V_t = \frac{g * d^2(\rho_p - \rho_m)}{18\mu}$$

Where, V_t is the settling velocity that will be solved for.

g = 9.81 $\frac{m}{s^2}$, acceleration of gravity

d = $\frac{27-45}{2}\mu m = 36\mu m = 3.6\ x\ 10^{-5}\ m$, average particle diameter in a vial

$\rho_p = 0.98\ \frac{g}{mL} = 980\frac{kg}{m^3}$, particle density [37]

$\rho_m = 0.982\frac{g}{mL} = 982\frac{kg}{m^3}$, medium/fluid density, this is the density of HPMC which is slightly lower than water because of the adding of ethanol

$\mu = 0.004\ \frac{N}{m^2}$, viscosity of medium/fluid, this is the viscosity of HPMC which is matched to be very close to the viscosity of blood.

Then all of the variables are plugged into the equation above leaving,

$$V_t = \frac{(9.81) * (3.6 * 10^{-5})^2 * (980 - 982)}{18(0.004)} = -3.5\ x\ 10^{-7}\frac{m}{s} = -0.00035\frac{mm}{s}$$

This number means that every second a particle will rise 0.00035 mm. This equation solved for Vt to be negative but normally particles will sink in the fluid which would be a positive number, since this is negative that means the particles will be rising due to the difference in density. The particle type that was used in this equation was one that had a density closest to that of HPMC and a diameter that is small enough to flow through the vessel but large enough to still be seen and captured by the camera. When prototyping next semester, we will either purchase this particle or find one close to this one.

This process helped select a particle best fit for our fluid and model. By matching the density of the particle to the fluid and diameter the particles will not sink or rise in the fluid enough to affect the data.

This analysis was validated by the website, Cospheric, which is where the particles will be purchased from. This website provided a lot of information about each particle, and equations that are helpful for experimenting and gaining knowledge about how their particles behave. On this same website they also have a calculator for each equation where you can plug in different values and select the particle you will be using. I first solved this equation by hand and then I confirmed my answer with the calculator on the website.

6.3.2 Revised Spatial Resolution – Blake Pottinger

As stated above in section 3.3.3, Spatial Resolution is important in a PIV system as it is one of the main components to collect accurate data efficiently. A proper spatial resolution will make it easy for PIVlabs and the camera to collect the velocities, directions, and stresses on individual particles. The camera that will be used during the testing is the X-Stream XS-4 High-Speed Camera.

X-Stream XS-4 High-Speed Camera

512 x 512 [pixel] resolution

16 x 16 [μm] pixel size

$$512 \text{ x } 16\ [\mu m] = 8192\ [\mu m] = 8.192\ [mm]$$

$$8.192\ [mm] \text{ x } 8.192\ [\text{mm}]\ \mathit{sensor\ width} \text{ x } \mathit{height}$$

Set Values

Focal length of camera f = 50 [mm] (Dependent on Lens)

Distance of lens to laser sheer working distance (WD) = 300 [mm]

Calculations

$$FOV = \frac{Sensor\ Size * WD}{f} = \frac{8.192 * 300}{50} = 49.152\ [mm]$$

$$Image\ Scale = \frac{mm}{pixel} = \frac{49.152\ [mm]}{512\ Pixels} = 0.096 \left[\frac{mm}{Pixel}\right]$$

$$Spatial\ Resolution = 32\ [Pixels] * 0.096 \left[\frac{mm}{Pixel}\right] = 3.072\ [mm]$$

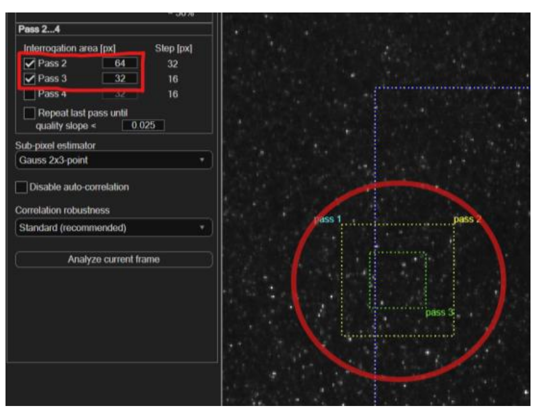


Figure 45: PIVlab Analysis

Figure 45 is a simulated analysis in PIVlabs to show how the system can view the particles in a certain number of pixels. PIVlabs analyzes per frame allowing you to see each individual particles movements throughout the duration of the flow.

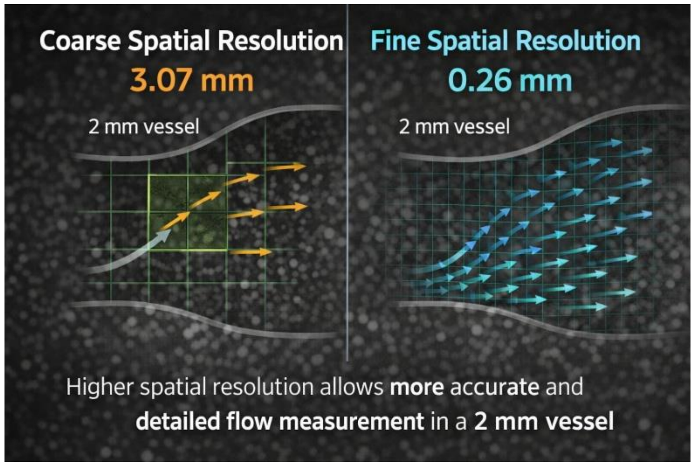


Figure 46: Comparison to Cerebral Arteries Benchmark

This image was generated using ChatGPT to show a visualization between our benchmark on the right, and our current set-up on the left. The spatial resolution is very important as with better equipment, you can see how many more particle vectors are visible and able to be analyzed. After some research, we found there to be several ways to decrease the spatial resolution such as increasing the focal length of the lens which would require a higher quality lens or by decreasing the distance of the camera to the PIV phantom while remaining in focus.

6.3.3 Offset – Clinton Nelson

In our project one problem we believe we can run into is the offset of particles. We based this on Snell's Law, the relationship between the ratio of Sine angles given to us based on the phantom model thickness and the ratio of different refractive indexes. We take that general equation, and we simplify it to where we can use it alongside the change in thickness of the phantom. Another change to equation is taking the difference in refractive indexes and dividing it by the average we can multiple it by the thickness to understand the offset depending on the thickness.

Snell's Law [44]:

$$\frac{sin\theta_1}{sin\theta_2} = \frac{n_2}{n_1}$$

Simplify it into a linear relationship without trig functions

$$\Rightarrow sin\theta \approx \theta$$

$$\Rightarrow n_1\theta_1 = n_2\theta_2$$

We then:

$$= \theta_2 = \frac{n_1}{n_2}\theta_1$$

But instead of solving for change in angles, we can derive Snell's Equation from angles too:

$$\Delta\theta(Change\ in\ Angles) \propto \frac{\Delta n(Difference\ in\ Indexes)}{n(Average\ of\ Indexes)}$$

$$\delta(Offset) = t * \Delta\theta = t * \frac{\Delta n}{n}$$

Using this derived equation, we were able to get chart solving for the offset based on different thicknesses:

Silicone Refractive Index	1.41
Fluid Refractive Index	1.334
Difference	0.076
Average	1.372
Slope(Difference/Average)	0.05539359

Table 9: Input values to equation

Thickness(mm)	Offset(mm)
0.5	0.02769679
1	0.05539359
1.5	0.08309038
2	0.11078717
2.5	0.13848397
3	0.16618076
3.5	0.19387755
4	0.22157434
4.5	0.24927114
5	0.27696793
5.5	0.30466472
6	0.33236152
6.5	0.36005831
7	0.3877551
7.5	0.4154519
8	0.44314869
8.5	0.47084548
9	0.49854227
9.5	0.52623907
10	0.55393586

Table 10: Offset based on thickness

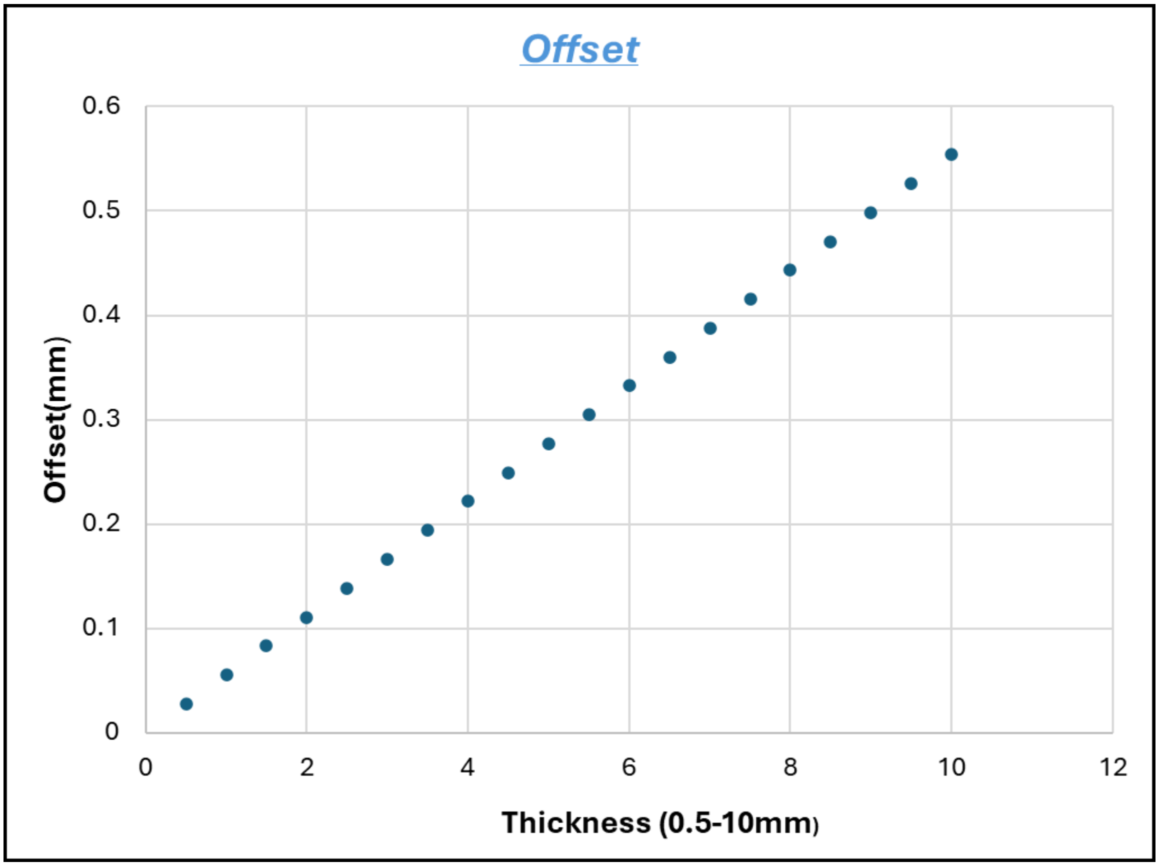


Figure 47: Graph of offset vs thickness

Based off this graph we see a linear relationship between offset and thickness, meaning the greater the thickness is of the phantom model, as seen in figure 9, the greater the offset of particles will be. This offset is the difference between where the particle actually is and where the camera will pick it up in the images captured. The offset is also not the same for every particle, and the direction of the offset is not the same as seen in figure 47.

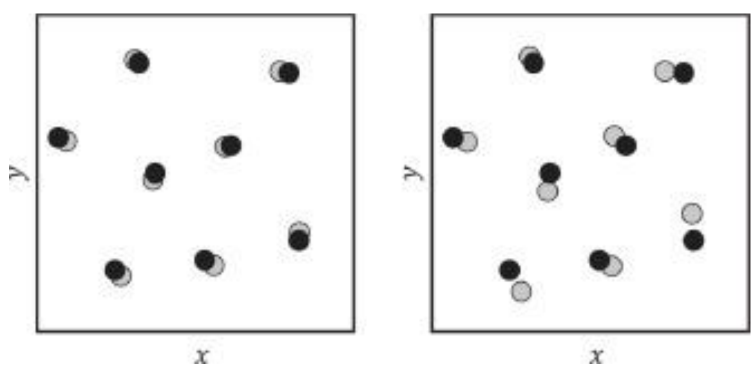


Figure 48: Display of offset

The validity of this is that snell's law is a basic textbook problem and an easy relationship to see. We will take this information into consideration when casting the phantom and trying to decrease the thickness of the silicone to prevent an offset based on thickness, but this also brings up the estimated offset if the refractive indices between the silicone and fluid.

6.3.4 Relative Distortion – Ryan Abelman

Comparing the revised spatial resolution and the offset values previously calculated, I computed the relative distortion—how much of a notable difference there will be in the photos of the flow taken and where the actual particles sit. Calculating the relative distortion allows the team to see how accurate and effective the data obtained will be and if it can still be used. To begin with, the offset is estimated using the thickness (t), the difference between the refractive index of the substances (Δn), and the average between the two ($\overline{n}$).

$$offset = t \cdot \frac{\Delta n}{\overline{n}}$$

Now, plugging in the values specific to our substances, the offset for 10 mm thickness comes out as:

$$10mm \left(\frac{1.41 - 1.334}{\frac{1.41-1.334}{2}} \right) = 0.554\, mm$$

Continuing to find relative distortion, spatial resolution is needed as well. This value comes from Blake's calculation done in 6.3.2.

$$relative\ distortion = \frac{0.554\, mm}{3.072\, mm} = \text{ 18\% of the resolution will be distorted}$$

From this value, the team can infer that the results produced from the camera and our substances used will give us fairly reasonable and acceptable data to apply. Although the images will be slightly shifted from where the actual particles will be, they will not be severe enough to cause changes to our phantom unit. In fact, our camera will not be strong enough to catch this 18% difference that occurs. If we really needed even more accurate results, we could potentially decrease the total thickness of the phantom unit itself to decrease the offset.

The values in this calculation come from validated procedures through research and passed down from my groupmates.

6.4 Future Testing Potential

Testing plans for the future include performing a clot aspiration in the model. A clot aspiration, also known as thrombectomy aspiration is a medical procedure used to remove blood clots (thrombi) from vessels by applying negative pressure through a catheter to suck out a clot. This procedure is performed in the BDL lab simulated surgical suite to provide new information towards stroke research.

The current benchtop model only gathers pressure data and minimal flow data, for example only flow information at outlets not real time data in the vessel model during the procedure. PIV testing while performing the clot aspiration will give real time data in the vessel model/phantom to see how the fluid is behaving around the clot and catheter as well as the vessel walls. A simplified testing procedure is displayed below and will be executed next semester. This procedure will be shown through images from the current BDL benchtop model that does not have PIV, but the testing will be very similar and will be standardized later.

Steps include:

1. Deploy a synthetic blood clot through a catheter into a specified part of the silicone phantom.

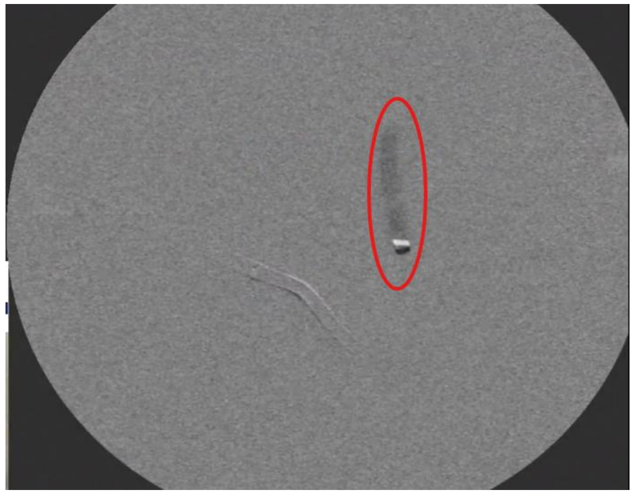


Figure 49: Clot deployment

2. Insert an unused catheter and navigate it until the tip is touching the face of the clot.

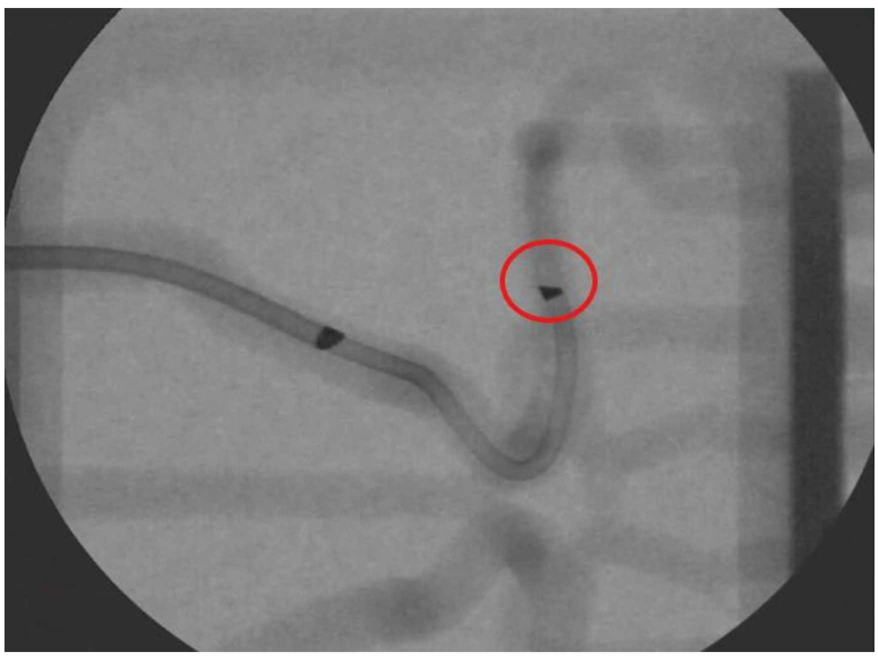


Figure 50: Navigation of catheter to clot

3. Turn on aspiration pump or syringe (the suction) which is attached to the end of the catheter in order to fully engage the tip with the blood clot.

4. Slowly pull back on the catheter with the clot still engaged until removed from the model/flow

system.

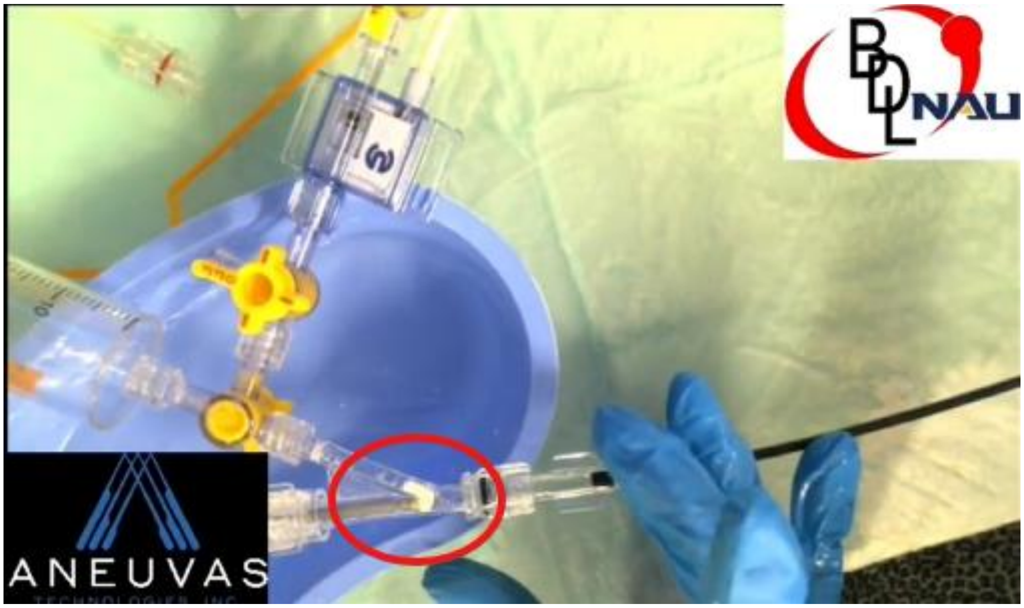


Figure 51: Clot fully removed from model

During this experiment the fluid going through the model will have PIV particles and the camera will be angled at a section capturing data during the experiment. The data will then be exported to PIVlab and analyzed to find flow rates during the aspiration

7 CONCLUSIONS

In this project we are trying to simulate interchangeable phantom models to be used alongside the BDL benchtop flow system. Our capstone is the second version of the NAU’s PIV project where the last team was able to design and construct a PIV set up with the necessary device to illuminate particles in thick silicone models and be able to capture flow regions to be studied. Building upon the previous capstone’s work, which established a functional PIV setup with a camera and laser, this project will now advance the system to include a physiologically accurate circle of Willis phantom. This will enable the collection of necessary data like velocities and stresses to gain information on the medical procedures that combat strokes.

Through the application of customer and engineering requirements the team evaluated multiple design concepts using a Pugh Chart and Design Matrix. From the list of designs, we chose Design 1, Figure 29 and 30, as the best fit for all the requirements, while the others compared to design 3, our datum. From then on, we approached different failure points in our chosen design and have come up with countermeasures to rule out failures and pitch prevention methods, all of which can be seen in our Failure Modes and Effects Analysis (FMEA). Our Ghantt chart outlines what the rest of this spring semester will look like for our team and the tasks due in the next couple weeks as well as a schedule for the next fall 2026 semester.

The selected design provides a strong foundation to build off of for future testing and validation. The next phase of the project will involve fabrication of the physical phantom model, experimental validation using the testing procedure in section 6.4, and iterative refinements based on results. Successful implementation of this system will allow the Bioengineering Devices Lab to capture detailed hemodynamic data, ultimately contributing to improved testing and development of medical devices for the treatment of strokes.

8 REFERENCES

[1] M. Katan and A. Luft, "Global burden of stroke," Seminars in Neurology, vol. 38, no. 02, pp. 208–211, Apr. 2018. doi:10.1055/s-0038-1649503

[2] C. Hui, P. Tadi, M. Z. Khan Suheb, and L. Patti, "Ischemic Stroke," in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2025. http://www.ncbi.nlm.nih.gov/books/NBK499997/

[3] A. K. A. Unnithan, J. M. Das, and P. Mehta, "Hemorrhagic Stroke," in *StatPearls*, Treasure Island (FL): StatPearls Publishing, 2025. Available: http://www.ncbi.nlm.nih.gov/books/NBK559173/

[4] C. C. medical professional, "What is hemodynamics?," Cleveland Clinic, https://my.clevelandclinic.org/health/body/24013-hemodynamics

[5] C. A. Luisi *et al.*, "Investigation of cerebral hemodynamics during endovascular aspiration: Development of an experimental and numerical setup," *Cardiovascular Engineering and Technology*, vol. 14, no. 3, pp. 393–403, Feb. 2023. doi:10.1007/s13239-023-00660-8

[6] F. Adams *et al.*, "Soft 3D-printed phantom of the human kidney with collecting system," *Annals of Biomedical Engineering*, vol. 45, no. 4, pp. 963–972, Nov. 2016. doi:10.1007/s10439-016-1757-5

[7] C. Özcan, Ö. Kocatürk, C. Işlak, and C. Öztürk, "Integrated particle image velocimetry and fluid–structure interaction analysis for patient-specific abdominal aortic aneurysm studies," *BioMedical Engineering OnLine*, vol. 22, no. 1, Dec. 2023. doi:10.1186/s12938-023-01179-8

[8] M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light, Seventh (Expanded) Edition*. Beijing: 世界图书出版公司, 2022.

[9] "Refractiveindex.info," Refractive index of Pharmacoat 606 (Hydroxypropyl methylcellulose, HPMC) - Juntunen, https://refractiveindex.info/?shelf=other&book=Pharmacoat606&page=Juntunen

[10] R. J. Adrian and J. Westerweel, *Particle Image Velocimetry*. Cambridge: Cambridge University Press, 2011.

[12] M. N. Antonuccio *et al.*, "Fabrication of deformable patient-specific AAA models by material casting techniques," *Frontiers in Cardiovascular Medicine*, vol. 10, Sep. 2023. doi:10.3389/fcvm.2023.1141623

[13] W. H. Ho, I. J. Tshimanga, M. N. Ngoepe, M. C. Jermy, and P. H. Geoghegan, "Evaluation of a desktop 3D printed rigid refractive-indexed-matched Flow Phantom for PIV measurements on cerebral aneurysms," *Cardiovascular Engineering and Technology*, vol. 11, no. 1, pp. 14–23, Dec. 2019. doi:10.1007/s13239-019-00444-z

[14] Scharnowski, S., & Kähler, C. J. (2020). Particle image velocimetry - Classical operating rules from today's perspective. *Optics and Lasers in Engineering*, *135*, 106428. https://doi.org/10.1016/s0143-8166(20)31843-1

[15] Tokgoz, S., et al. "Spatial resolution and dissipation rate estimation in Taylor--Couette flow for tomographic PIV." *Experiments in Fluids*, vol. 53, no. 3, 2012, pp. 561–583, https://doi.org/10.1007/s00348-012-1311-7.

[16] G. Cavazzini, *The Particle Image Velocimetry : Characteristics, Limits and Possible Applications*.

London, England: IntechOpen, 2012

[17] B. J. Schürmann, P. Creutz, T. Schmitz-Rode, U. Steinseifer, and J. C. Clauser, "Ghost Cells as a Two-Phase Blood Analog Fluid—Optical Thrombus Growth Detection Using Particle Image Velocimetry," *Artificial organs*, vol. 49, no. 10, pp. 1532–1539, 2025, doi: 10.1111/aor.15042.

[18] A. Paar, "Viscosity of whole blood – viscosity table and viscosity chart: Anton Paar Wiki," Viscosity of Whole Blood, https://wiki.anton-paar.com/en/whole-blood/ (accessed Feb. 1, 2026).

[19] Dan Puperi, "Modeling pipes / blood vessels in SOLIDWORKS," YouTube, Feb. 14,2019. https://www.youtube.com/watch?v=NGUhYcr7plA (accessed Feb. 20, 2026).

[20] Dan Puperi, "Modeling blood vessel blockage in SOLIDWORKS," YouTube, Sep. 23, 2019. https://www.youtube.com/watch?v=jtq-5qVgrJ0 (accessed Feb. 20, 2026).

[21] *Cardiovascular Hemodynamics*. Edited by Adrian W. Messerli and Arman T Askari, Second ed., Springer International Publishing, 2019, pp. 95–130, ia903408.us.archive.org/2/items/emergency_medicine_books/Cardiology%20%26%20CCU/Cardiovascular%20Hemdynamics%20-%20An%20Introductry%20Guide%20-%20Second%20Edition%20-%202019.pdf

[22] Dabiri, Dana. *Cross-Correlation Digital Particle Image Velocimetry – a Review*. 2007

[23] LLC, Cospheric . "Density Marker Beads - 1.010g/Cc - Precision Microspheres, Beads, Microparticles for Creating Percoll Density Gradients." *Cospheric.com*, 2020, www.cospheric.com/density_marker_beads_1010.htm.

[24] Luisi, C A, et al. "Investigation of Cerebral Hemodynamics during Endovascular Aspiration: Development of an Experimental and Numerical Setup." *Cardiovascular Engineering and Technology*, vol. 14, no. 3, 22 Feb. 2023, pp. 393–403, https://doi.org/10.1007/s13239-023-00660-8. Accessed 10 Apr. 2025.

[25] Mao, Qinghao, Brady Wu, Bryan VanSaders, and Heinrich M. Jaeger. "Structural Reconfiguration of Interacting Multi-Particle Systems through Parametric Pumping." *Nature Communications*, vol. 16, no. 4637, 19 May 2025, doi:10.1038/s41467-025-59631-3.

[26] A. Mizutani and H. Shea, "Particle Imaging in electrohydrodynamic pumps operating at several KV," 78th Annual Meeting of the Division of Fluid Dynamics, https://meetings-archive.aps.org/dfd/2025/z38/4/

[27] Parker, Kevin. *Cardiovascular Hemodynamics*. Imperial College London, 2015. kparker.bg-research.cc.ic.ac.uk/homepage/BSc_lectures/Cardiovascular_Haemodynamics.pdf.

[28] R. W. Fox, A. T. Mcdonald, and P. J. Pritchard, *Introduction to fluid mechanics.* Hoboken, N.J.: Wiley & Sons, 2010

[29] *Particle image velocimetry : a practical guide*. Berlin: Springer, Cop, 2007.

[30] Y. Huang, J. He, and R. Yang, "Mechanical and adhesive properties of RTV silicone rubber blended with silicone polyurethane modified epoxy resin," *Journal of Macromolecular Science, Part A*, vol. 61, no. 8, pp. 565–578, Jun. 2024, doi: https://doi.org/10.1080/10601325.2024.2365271.

[31] F. Adams *et al.*, "Soft 3D-Printed Phantom of the Human Kidney with Collecting System," *Annals of Biomedical Engineering*, vol. 45, no. 4, pp. 963–972, Nov. 2016, doi: https://doi.org/10.1007/s10439-016-1757-5.

[32] M. Katan and A. Luft, “Global Burden of Stroke,” *Seminars in Neurology*, vol. 38, no. 02, pp. 208–211, Apr. 2018, doi: https://doi.org/10.1055/s-0038-1649503.

[33] “Castaldo LiquaSil Clear RTV Rubber – Castaldo,” *Castaldo.com*, 2021. https://www.castaldo.com/castaldo-liquasil-clear-rtv-rubber-2/ (accessed Feb. 02, 2026).

[34] Art of the Part, “ SolidWorks: Core & Cavity Assemblies for Casting & Mold Making,” *Youtu.be*, 2026. https://youtu.be/Bsh7crTQgo8?si=2b9zCtsTrUYIa68Q (accessed Feb. 25, 2026).

[35] McKeen, L. W. (2016, March 23). *Hoop stress - an overview | sciencedirect topics*. Introduction to Fatigue of Plastics and Elastomers: 1.1.5 Hoop Stress. https://www.sciencedirect.com/topics/engineering/hoop-stress

[36] “Cospheric LLC,” Cospheric Microspheres - Precision Spherical Particles Globally, https://www.cospheric.com/microsphere-settling-time-calculation.aspx

[37] “Rhodamine B polyethylene microspheres 0.98g/CC - 10UM to 1000um (1mm),” Cospheric, https://www.cospheric.com/RHBPMS_solid_polymer_rhodamine_B_spheres.htm

[38] S. Schwartz and C. Rapoport “Imperative Care CDAT Checklist”

[39] “Getting Started with Ansys Fluent | Ansys Certifications,” *Ansys Certifications | Ansys Innovation Space*, Feb. 28, 2023. https://innovationspace.ansys.com/certifications/courses/getting-started-with-ansys-fluent/

[40] “Understanding Particle Image Velocimetry Techniques | Ansys Innovation Courses,” *Innovation Space | Ansys Innovation Space*, Aug. 30, 2024. https://innovationspace.ansys.com/product/particle-image-velocimetry-techniques /

[41] “Vacuum Pumps | JB Industries, Inc.,” *JB Industries*, 2023. https://www.jbind.com/product-category/vacuum-pump/

[42] Snell’s law -- the law of refraction, https://personal.math.ubc.ca/~cass/courses/m309-01a/chu/Fundamentals/snell.htm (accessed Mar. 30, 2026).

[43] MIT OpenCourseWare. (n.d.). *Lecture 16: 2d and 3D Waves, Snell’s law: Physics III: Vibrations and waves: Physics*. MIT OpenCourseWare. https://ocw.mit.edu/courses/8-03sc-physics-iii-vibrations-and-waves-fall-2016/pages/part-ii-electromagnetic-waves/lecture-16/

[44] *Snell’s Law*. Snell’s Law - Physics Book. (n.d.). https://physicsbook.gatech.edu/Snell%27s_Law

[45] W. Weng, S. Jaw, J. Chen, and R. R. Hwang, “Optimization of particle image distortion for PIV measurements,” *Journal of Hydrodynamics*, vol. 22, no. S1, pp. 296–306, Oct. 2010, doi: https://doi.org/10.1016/s1001-6058(09)60210-9.

[46] R. D. Keane and R. J. Adrian, “Optimization of particle image velocimeters: II. multiple pulsed systems,” *Measurement Science and Technology*, vol. 2, no. 10, pp. 963–974, Oct. 1991. doi:10.1088/0957-0233/2/10/013

[47] Stanislav Solnař, J. Štípek, Fadi Alzarzouri, and R. Žitný, “A simple mechanical spring-driven rheometer for measurement of Newtonian and non-Newtonian fluids - design, validation, and input correction,” *Journal of Food Engineering*, pp. 112198–112198, Jun. 2024, doi: https://doi.org/10.1016/j.jfoodeng.2024.112198.

9 APPENDICES

N/A