The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #44227

Project-based learning via creation and testing of a silicone venous valve model

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Abstract

Project-based learning is an important tool in undergraduate engineering education, providing opportunities for students to deepen their understanding of engineering fundamentals, to enhance their capacity for problem solving and communication, and to develop specific engineering-related skills. Here, we describe the efforts of a team of undergraduate students in creating a silicone venous valve model and experimental flow control setup, and in demonstrating the basic capabilities of the overall experimental system. We describe the process of designing and building the venous valve models and test setup and lessons learned by the students through this experience. In addition to providing invaluable experience for the students involved, this project has provided a visual demonstration of the function of venous valves, and provides a platform for fundamental research on the effect of venous valve shape, size and mechanical properties on the development of disease such as deep vein thrombosis (DVT) and pulmonary embolism (PE), which are a leading cause of death in the United States, especially among hospital patients. Findings from research using this test setup can move us toward a better understanding of patient risk levels for DVT and PE, so that physicians can make informed decisions regarding preventative measures.

Introduction

Active learning is a vital part of the undergraduate engineering education, as it puts the learner front and center in the learning process and allows them to take charge of their own learning through performing meaningful activities and thinking critically about what they are doing [1]. One could even argue that it is impossible to truly learn without the learner being active in some way [2]. Active learning helps students to ascend above the initial cognition levels of remember and understand from the revised Bloom's taxonomy [3], requiring learners at the least to apply and analyze. Project-based learning is an important active learning technique, which allows students to build upon what they already know from previous courses [1] and further deepen their knowledge as they evaluate and create. In addition to deepening their knowledge of specific technical competencies from the engineering curriculum, project-based learning allows students to acquire skills that will be vital to them throughout their careers, including problem solving, communication, teamwork as well as specific skills and experiences that can inspire them and open doors to various career paths. In engineering programs, research is an excellent way of providing project-based learning opportunities to students while working toward meaningful goals that have the potential to change society for the better.

In this paper, we describe the efforts of a team of undergraduate mechanical engineering students in creating and demonstrating an experimental silicone venous valve model and flow control system for use in future scientific research aimed at ultimately reducing the impact of a widespread but often unseen disease. We describe the experimental test systems and reflect on student learning from this project. In order to understand on a basic level the need for this project and the technical challenges that the students experienced on this multi-year collaborative project, we turn now to a description of the problem underlying this project.

Venous valves are vital in the proper function of the circulatory system. These bileaflet valves, which in humans are most often located in the lower extremities, act as a series of miniature hearts. They open and close with oscillating pressure gradients from the contraction and relaxation of skeletal muscles to help provide a net pumping effect to return blood to the heart against the pull of gravity. However, venous valves are a frequent location of origination of deep vein thrombosis (DVT), where blood cells build up in the deep veins of the legs, blocking valves and preventing them from working properly. Additionally, parts of these thrombi (blood clots inside a blood vessel) can break loose to form an embolus, which then can travel through the blood stream to block blood supply to the lungs. This condition, known as pulmonary embolism (PE), often is first manifest through sudden death. PE is a leading cause of death in the United States, causing an estimated 200,000 deaths annually, a number which is likely a conservative figure since PE can be difficult to detect and is suspected to often go unrecognized [4]. Together, DVT and PE are known as venous thromboembolism (VTE).

Since thrombus formation is known to be linked to fluid flow conditions such as low shear stress, fluid stasis and high fluid residence time, we have set out to study the effect of venous valve morphology on flow conditions conducive to the development of VTE. We do this using both numerical simulations and experiments with silicone venous valve models. Findings regarding the effect of morphology on flow conditions conducive to VTE can be used to help medical professionals in determining patient risk levels and enabling them to make educated decisions regarding preventative measures that should be applied. The purpose of this paper is to describe how Mechanical Engineering students at Utah Valley University have created and tested silicone venous valve models in support of fundamental research on venous valves, and how this project-based learning experience has enhanced their engineering education.

In this paper, we first introduce our research team and venous valve model. We then describe in detail the methods that the students use for creation of silicone venous valve models. Next, we show initial basic testing of the silicone venous valve models in our flow control system. Finally, we discuss the effect of this project on active learning of students in the Mechanical Engineering program at Utah Valley University.

Research team

The overall research team for the “venous valves” project consists of a faculty mentor and multiple undergraduate students working on both numerical simulations and silicone model experiments to study the effect of venous valve morphology on flow conditions that are conducive to the development of VTE. In total, 12 different students have worked on the project, typically with 2-3 students at a time actively participating in undergraduate venous valves research, each for a time span ranging from a single semester to over a year. While the short duration of undergraduate student research availability poses serious challenges to research efficiency, it bears the benefit of increasing the number of students that can be given the chance to participate in the project. Further, undergraduate research can be fruitful if done with effective communication, documentation and training. The project began as being purely computational due to the faculty mentor's background in computational fluid dynamics (CFD) [5], [6], [7], but since 2021 it has expanded to include a significant experimental component [8]. Of the 12 total undergraduate students who have worked on the project, all but two have done a considerable portion of their research efforts on the experimental side of the project. In exchange for their work on the project, students typically either received credit toward graduation in the form of fulfilling the requirements of a technical elective course or received pay, funded by one of the two research grants that have funded the project. Providing either pay or credit toward graduation helps to make research accessible to a variety of students, whether their primary needs are financial or time related. Note, however, that for a student to be successful in research they must develop a burning desire to create new knowledge and gain important experience and their primary motivation cannot simply remain that of money or credit. Thus, the faculty mentor finds it to be extremely important to match students to projects that are likely to lead to such a burning desire, and to give students experiences that will help the desire to continue to grow.

On this project, the faculty mentor and more experienced students trained new students on the basics of the research project and on research methods. The entire research team met with the faculty mentor weekly to discuss progress, challenges and solutions. This weekly meeting served several purposes. First, it gave students the opportunity to regularly discuss the project with the faculty mentor and with peers both on the experimental and computational sides of the project. While the faculty mentor had an open-door policy for students working on the project, a majority of discussion occurred in the weekly meetings. This was an opportunity for students to show what they had done, to describe what they had learned (both what worked and what did not work), and to discuss how to proceed to overcome challenges and move toward achieving research goals. Students were encouraged to share their thoughts on how their peers should overcome challenges that they brought to the group, which helped them to feel a sense of camaraderie and to learn how to work on cross-functional teams. Second, the weekly meeting provided an impetus for frequent documentation. In addition to keeping lab notebooks, students were required to compile slides demonstrating their findings for the week. They were taught that the slides were not meant to prove that they had done work, but rather to document what had been tried (with specific conditions, parameters and pictures), what came as a result (with data, plots and pictures, as appropriate), and what was done to overcome challenges. This not only aided discussion at weekly meetings, but since the weekly slides were saved in a repository it also provided detailed documentation of past results and served as a helpful aid in creating documentation of processes and best practices for various parts of the project. Finally, the weekly meeting provided the students with frequent accountability checks to help students to stay focused and determined to achieve results on the project.

With the training, guidance and support provided, students were expected to figure out how to design various systems such as the silicone venous valve model and flow control system, and to overcome the plentiful obstacles that arose throughout the project. They were to take initiative in identifying obstacles and potential solutions, and in developing the skills that they needed to be successful on the project. Students were reminded often that their education and development was as much of a goal of the project as was the accomplishment of research goals, and that it was advantageous to take time to acquire and hone skills that would make them more effective at performing the research at hand. Further, students were tasked with creating documentation of the methods that they developed and with training students who were new to the project or otherwise were shifting focus within the project. As will be seen later in this paper, working on this project provided students with an invaluable learning experience through solidifying engineering concepts, developing various skills, and increasing vision based on their experience working together in creating meaningful solutions beyond the level required in coursework.

Venous valve model description and purpose

Both the computational and silicone models in this project consist of a single venous valve sinus region consisting of a sinusoidal vessel filled with a viscous fluid and containing a bileaflet valve, as shown in Figure 1a. For simplicity, the numerical model uses a rigid vessel wall and flexible valve. To enable comparison to the numerical model, for this study the silicone model also uses a rigid vessel wall and a flexible valve. However, the model can readily be created with a flexible vessel wall, which makes it more physiologically representative. The sinus region of the vessel wall is created by sinusoidally varying the diameter of the vessel wall from minimum diameter D at the base of the leaflets to a maximum diameter of $1.5D$ at the center of the sinus region. Each valve leaflet is formed by the intersection of a plane with the vessel wall, as shown in Figure 1a. Additionally, the tip of each leaflet has a sinusoidal crescent tip of depth δ cut from it, as shown in Figure 1b. The leaflet tip shape is characterized by the dimensionless depth of cut, $D_c = \delta/D$. The shape of the valve leaflet is further characterized by the aspect ratio $A = L/D$, where L is the length of the valve leaflet. The symmetric bileaflet valve is composed of two identical leaflets, which are angled such that the leaflet tips meet at the center of the vessel wall. The crescent tip shape is seen physiologically in lymphatic [5] and venous valves [9], and among other advantages this tip shape allows the leaflet to readily open to allow forward flow. Deformation of the valve is characterized by the dimensionless bending stiffness, $K = 4k_b/\pi D^3 \Delta P$ [5], where ΔP is the pressure drop across the valve sinus and the bending stiffness for our geometry and Poisson's ratio of 0.5 is given by $k_b = 4Et^3/27\sqrt{3}$. Here, E is the Young's modulus and t is the valve thickness. We have developed silicone models with both $D = 1\ cm$ and $D = 5\ mm$, and vary D_c and A, with "default" values of $D_c = 0.4$ and $A = 1.25$. K is regularly varied by changing ΔP, D, E and t, and typical values are in the range of $0.25 \leq K \leq 1$. For simplicity, at this first stage in the project, flow is driven through the rigid-walled valve sinus by an oscillating pressure gradient applied to the two ends of the test section. In later stages of the project, flow will instead be driven by contraction of flexible vessel walls, more closely representing physiologically-relevant conditions.

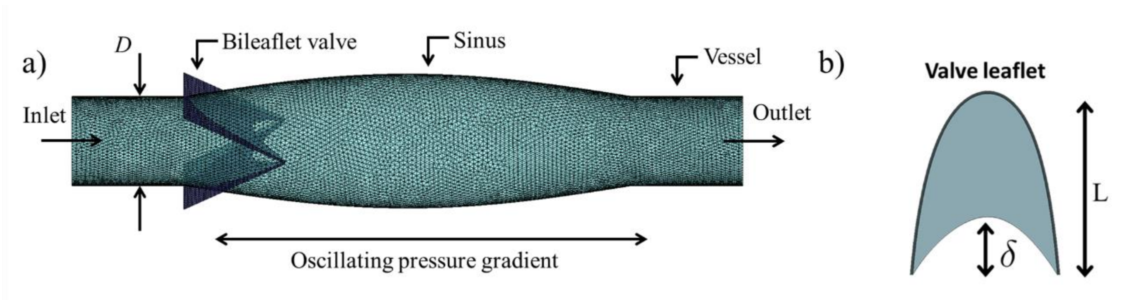

Figure 1. Representations of venous valve model. a) Diagram of venous valve model as used for numerical simulations and silicone model experiments. b) Valve leaflet crescent-tipped shape

The numerical and experimental models will be used in tandem to explore the effect of venous valve morphology on flow conditions conducive to disease. While numerical simulations are valuable in simulating a wide range of parameter sets and in obtaining data that can be difficult to accurately measure using experiments (such as shear stress), the silicone model can be used as further validation of the numerical model and can also readily be used to study fluid stasis and residence time. Further, in the future this silicone model can be used for thrombosis testing with whole blood, a step that will allow us to predict the effect of venous valve morphology on development of VTE more accurately than can be known purely based on numerical modeling. This is a vital step toward developing guidelines regarding patient risk management.

Creation of a silicone venous valve model

Silicone venous valve models are created by curing liquid silicone in 3-D printed molds. Here, we walk through the process of silicone model creation in detail to assist the reader in effectively creating high-quality silicone physiological models using relatively inexpensive techniques that can readily be done by undergraduate students.

The desired geometry for the venous valve silicone model is first created using a parametric computer-aided design (CAD) model, and a solid model of the four-piece molds needed to cast the model is created as a negative of the desired geometry with additional features in the mold to allow for ready alignment of the mold pieces and a funnel on the top end of the mold to allow for ready pouring of liquid silicone and for air to escape from the silicone during curing (Figure 2a). The geometry for the molds is then converted to .stl files and printed on a stereolithography (SLA) 3-D printer (Elegoo Saturn 3 Ultra). Siraya Tech Clear Sculpt resin is used for printing due to its heat resistance and optical clarity, which allow for curing at elevated temperatures and detection of bubbles in the silicone, respectively. Note that while it would be easier to use a fused deposition modeling (FDM) printer, the resolution and smooth finish of the molds required to capture the features of the model and enable optical clarity make SLA printing the better option.

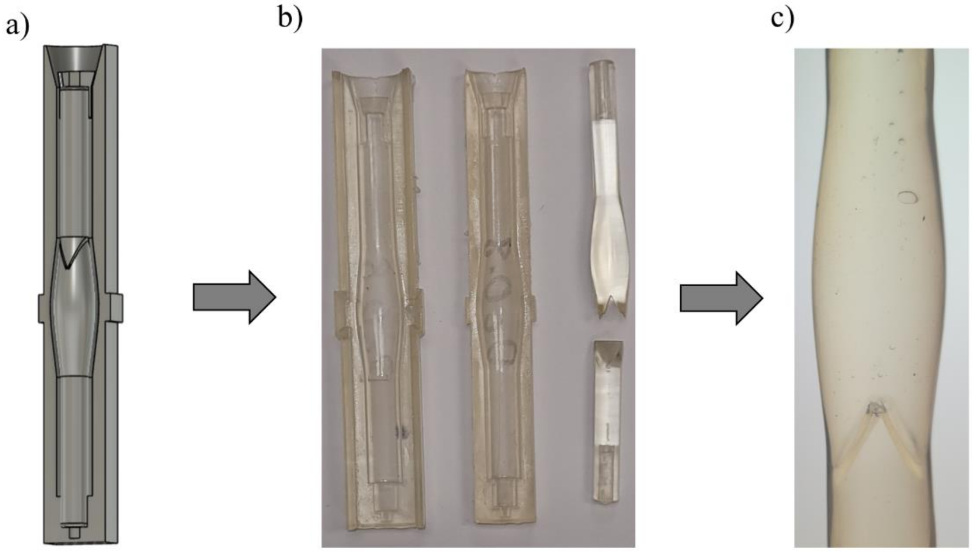

Figure 2. Overview of the silicone venous valve model creation process. a) CAD is used to create the desired geometry and corresponding negative molds. b) Four-piece molds are 3-D printed and treated in preparation for the silicone molding process. c) Silicone venous valve models are cured in the molds and optionally stiffened with an outer plastic layer.

The 3-D printed molds are designed to be pressed together to create a removable mold set, with the outer molds determining the shape of the outer vessel wall and the inner molds determining the shape of the inner vessel wall and the bileaflet valve (Figure 2b). This ultimately results in a sinusoidal vessel with a crescent-tipped bileaflet valve (Figure 2c).

To ensure the smooth surface finish that is required for optical clarity of the silicone model and to prevent cure inhibition of the silicone which is typical for platinum silicones in resin molds, the molds undergo a multi-step post-processing treatment prior to casting. First, the molds and attached 3-D printing build plate go through a preliminary wash in 91% isopropyl alcohol for 5 minutes in a 3-D print wash station (Elegoo Mercury X Bundle) to clean uncured resin from the molds. After the initial rinse, the build plate is removed and the molds are detached from the build plate. The molds then undergo a second rinse of 91% isopropyl alcohol in a separate (clean) wash station (Elegoo Mercury X Bundle) for an additional 5 minutes to remove residual resin prior to post-curing. After rinsing is complete, the molds are removed from the alcohol bath and are allowed to air dry. Once dry, the molds are cured in a 3-D printing UV cure station (Elegoo Mercury X Bundle) for 30 minutes, with the molds laid horizontally on the rotating platform and flipped over after 15 minutes to ensure even and complete curing. As the last step of the curing process, the molds are placed in an oven at $150\ °F$ for 30 minutes. Note that incomplete curing of the molds will typically prevent effective curing of silicone in the molds.

After the mold has been allowed to fully cool, it is removed from the oven and undergoes surface treatment processes to prevent cure inhibition and further improve the surface finish of the molds. The surfaces which will come into contact with the silicone, including the entirety of the two inner pieces and the inner section of the outer pieces, are sanded. This is done by hand using dry sand paper, starting at 600 grit, then 1000 grit, and finally 2000 grit sand paper. The molds are then wiped clean using a clean wetted cloth and allowed to dry. The molds must then be kept clean and free of dust for the rest of the preparation and molding process. A clear coat of Krylon Gloss Crystal Clear acrylic spray paint is then applied. To apply the clear coat with a consistent and clear finish, the Krylon is first sprayed into a small cup and then is brushed onto the molds using a foam brush. Excess Krylon should be removed to avoid alteration of the mold geometry, but care should be taken to ensure that the entire surface that will contact silicone is covered with Krylon.

Once the clear coat has been allowed to dry for a minimum of 30 minutes, the molds are ready for use. The molds are assembled with the V-shape of the joint of the inner two sections facing toward the funnel end of the mold and clamped together with the funnel facing upward in preparation for pouring the silicone.

The silicone used for the venous valve models is Smooth-On EcoFlex 00-31 Near Clear. This silicone was selected due to its combination of optical clarity, relatively low Young's modulus, and exceptional tear resistance which allows for ready removal of silicone models from the molds. To prepare the silicone for pouring, equal parts by mass of parts A and B are poured into a cup and mixed thoroughly. The cup is then placed into a vacuum chamber at approximately 700 mbar vacuum pressure and $70\ °F$ for approximately 5 minutes (until the silicone appears to be bubble free) to remove air bubbles from the liquid silicone. It is poured into the funnel end of the mold, taking care to pour it slowly to allow remaining bubbles to escape from the silicone prior to entering the mold. The silicone-filled molds are then pressurized to $60\ psi$ inside a pressure pot to ensure that the silicone reaches the entirety of the inside of the molds and that remaining air bubbles are purged from the silicone, and is cured at this pressure for 24 hours at approximately $70\ °F$.

After curing has finished, the silicone models are removed from the molds, taking care to keep the surfaces of the silicone models clean as dust or fingerprints significantly decrease the optical clarity of the model. The outer molds are removed from the silicone model without touching the surface, excess silicone at mold lines is trimmed from the exterior of the model, and the exposed silicone is immediately covered in plastic wrap to avoid dust exposure. To remove the inner mold sections, the silicone model is gently rolled up on itself and the inner molds are slowly pulled out. This is done first for the smaller inner mold and then is repeated for the larger inner mold. Note that while the sinus sections of the inner molds are larger than the openings of the ends of the silicone models, the silicone used can readily be rolled and stretched to allow removal of the molds. For this reason, the silicone models were made of EcoFlex 00-31 rather than Sylgard 184 (Dow Chemical) polydimethylsiloxane (PDMS), which has superior optical clarity and well-documented mechanical properties but is easily torn and did not lend itself to this molding process. Note that special attention must be given to not damage the thin valve leaflets during the demolding process.

Since our initial experiments are used to replicate conditions from numerical simulations with rigid vessel walls, we additionally add stiffness to the outer vessel walls through the use of clear plastic heat shrink on the outside of the silicone model vessel walls. To reliably apply heat shrink without deforming the vessel shape, the heat shrink is pre-formed using a solid silicone vessel section which is molded using the same outer molds as the silicone model, but without use of the inner mold sections. The heat shrink is formed to the shape of the solid model by slowly rotating the solid section while applying heat to the heat shrink using a heat gun set to $500\ °F$. After forming the heat shrink and allowing it to cool, the solid model is removed from the heat shrink by pulling it out of the end and allowing it to stretch out. The inner surface of the formed heat shrink and the outer surface of the silicone vein model are then painted with a small amount of uncured EcoFlex 00-31 silicone, and the vein model is carefully inserted into the heat shrink and is cured in the pressure pot at $60\ psi$ for an additional 24 hours. If the silicone vein model is placed well within the formed heat shrink, bubbles will typically come out of the silicone-heat shrink interface while curing at elevated pressure. Once it is cured, the vein model is removed from the pressure pot and wrapped in plastic wrap to keep it clean until it is needed for use in experiments. Note that if a flexible silicone vein wall is desired, the heat shrink process can be skipped. Additionally, the wall could be stiffened by increasing the vessel wall thickness and foregoing the heat shrink process, but the additional wall thickness greatly decreases the optical clarity of the model.

The morphology of the silicone venous valve model can be readily modulated to vary the characteristic dimensionless parameters A, D_c and K. Geometric feature dimensions such as, D, δ, L and t are adjusted through the CAD model, which was designed to allow for ready parameterization of these and other dimensions. Additionally, the stiffness of the EcoFlex 00-31 can be modulated by mixing the liquid silicone with silicone thinner (Smooth-On) [10] prior to de-gassing and pouring it into the molds.

Testing of the silicone venous valve model

To allow for testing of the silicone venous valve model, a source of viscous fluid (in this case, de-ionized water) must be connected to either end of the test section. As shown in Figure 3, holding tanks are filled with water, and the water level in both tanks is kept constant through use of a pump gently and constantly pumping fluid from a lower section of the holding tank to an upper pan in the holding tank, which allows excess water to overflow into the lower region. In this stage of the project, flow is driven through the test section by means of a pressure drop applied across the test section. To provide a controllable pressure drop, either favorable or adverse, a piezoelectric pressure controller (ElveFlow OB1 Pressure Controller) is used to provide air pressure to the air-tight water holding tank. The pressure controller allows the pressure to be rapidly increased up to a maximum pressure of 2,000 mbar using compressed shop air, and rapidly vented down to atmospheric pressure. Limitations on the reaction time are primarily determined by the air source, and thus it is not recommended that a small portable compressor be used as the air source if dealing with this large of a holding tank. Tubing is connected through the top of each pressurized water holding tank and submerged in the water of the top pan to allow water to be sucked from or added to the pan, depending on the direction of the applied pressure gradient. The tubing from each water tank is then connected to an end of the silicone venous valve model to allow for a pressure drop to be applied across the test section, and the interface between the tubing and the test section is mounted in place to ensure that the silicone model is maintained in a straight and unstretched position. To make the system easier to use, ball wye valves are placed between the holding tank and test section on either side of the test section. During experiments, these valves allow flow to readily flow between the holding tanks via the test section. However, the valve can be turned between experiments to allow for flow to be diverted around the test section to allow fluid to be returned to the inlet-side holding tank via an adverse pressure gradient. This is an important feature, since silicone venous valves largely prevent backward flow, and an amount of water that would take one minute to flow in the positive direction can take as much as a half hour to flow in the backward direction if forced to go backward through the silicone valve model.

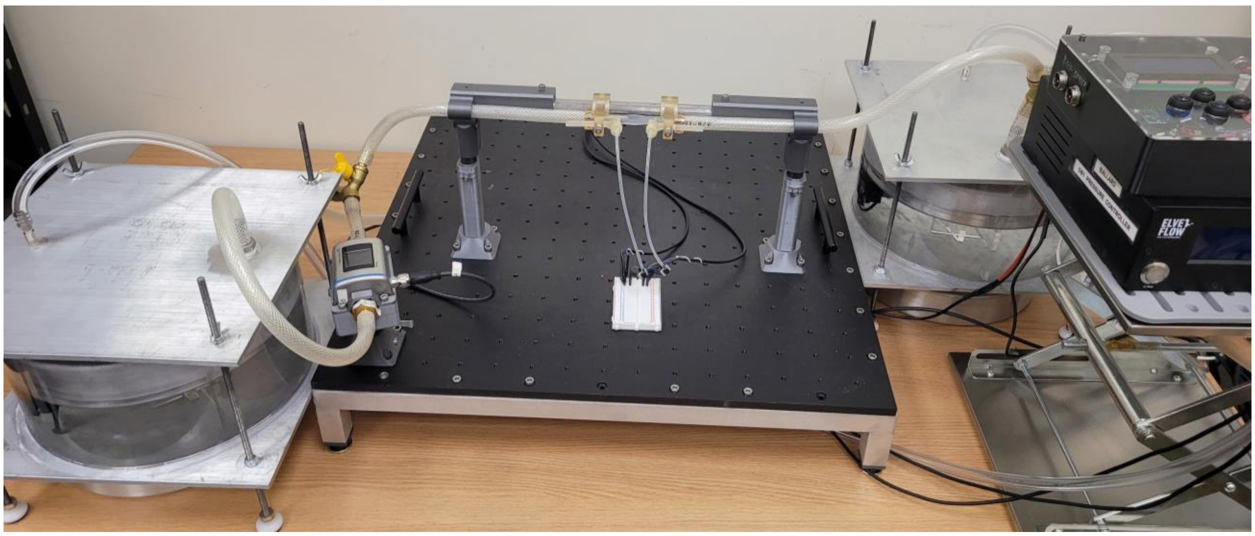

Figure 3. Flow control setup. Venous valve silicone test section (center) is mounted with pressure sensors on either side of the test section. The pressure on each side of the test section is controlled by a piezoelectric air pressure controller connected to water tanks, with the water level maintained at a constant level to transduce air pressure to the sides of the test section. An inline flow meter measures the flow rate of water that is passed through the test section.

To aid in collecting data, pressure sensors (Honeywell ABP series) are connected to needles which are mounted to measure the pressure at the centerline of the vessel directly on either side of the venous valve test section and thus give the pressure drop across the venous valve sinus region (Figure 4). Additionally, an inline flow rate sensor (Endress+Hauser Picomag) is installed in the tubing between the test section and one of the water holding tanks, giving the flow rate through the test section. These data allow us to calculate relevant dimensionless numbers and to determine their effect on the resulting flow rate. Note that in this flow control setup, it is important to manage head loss such that it is both low and consistent, to aid in effective pressure control not only in the water tanks but also at the ends of the test section.

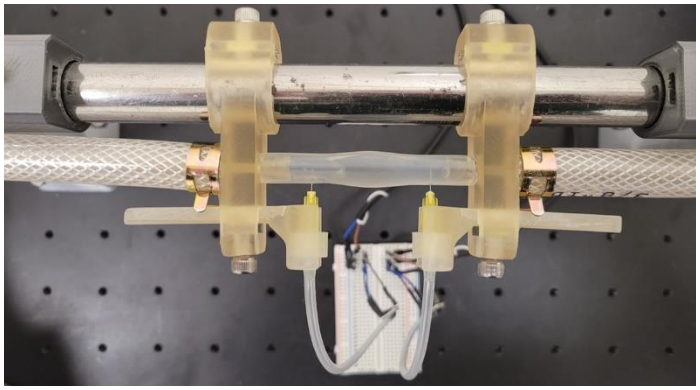

Figure 4. Test section mounted in the flow control setup. Pressure sensors are attached to needles which are mounted on either side of the test section to measure the pressure drop across the venous valve sinus region

With the silicone venous valve model mounted in the flow control system, a pressure gradient is applied across the test section. As shown in Figure 5a, application of a favorable pressure gradient across the valve results in the valve opening to readily allow forward flow of the fluid through the valve sinus. However, application of an adverse pressure gradient causes the valve to close (Figure 5b), largely preventing backflow of fluid through the valve.

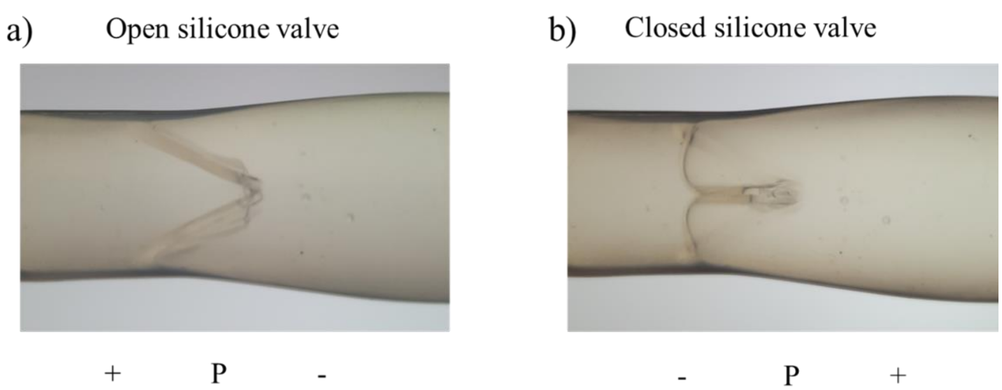

Figure 5. Zoomed-in view of a silicone venous valve test section. a) Open configuration under favorable pressure gradient. a) Closed configuration under adverse pressure gradient

With a functional silicone venous valve model and flow control system that can provide pressure drop and flow rate data, the system can now be used alongside numerical simulations to explore the effect of valve morphology on pumping performance. Further, we plan on introducing dye and tracer particles to the flow to visualize regions of fluid stasis, and to approximate the residence time of fluid in the venous valve region to further determine the effect of valve morphology on flow conditions conducive to VTE.

Reflections on student learning

Note that creation of the silicone venous valve model and flow control systems in their current forms was very much an iterative process, and that many obstacles were faced along the way. Going through these struggles, however, was a catalyst for learning. While there is not space here to discuss all of the challenges that were faced throughout the development process, here we highlight some key challenges and the learning lessons that they afforded.

The initial stages of the development of the silicone model and flow control system were especially challenging. At that point, while simulations had provided a fairly clear picture of the geometry and functionality to be developed and of the system parameters that should be explored, the research lab was new to experimental fluid dynamics and thus the team could not build on personal experience in many of the areas of development.

To design the flow control system, the team applied basic principles which were understood from the mechanical engineering curriculum, including fluid mechanics and system dynamics and controls, to perform analysis in support of determining specific design requirements that needed to be set to achieve the desired functionality. With design requirements set, the team turned to concept generation and research of alternative design options. They researched a variety of options for flow control, including syringe pumps, hydrostatic pressure tanks, and air pressure control, as well as options for sensors and feedback loops to obtain and measure the desired pressure gradients and flow rates. The team opted to avoid the use of syringe pumps, since in this project the independent variable was the pressure drop, and the resulting flow rate was to be measured and not prescribed as would be done with use of syringe pumps. While options for feedback loops that would modulate the flow rate to obtain the desired pressure drop were identified, these options were likely to lead to unwanted oscillations and were also cost prohibitive, as at that time our equipment and materials budget for the entire project was only $4,000. Since air pressure controllers that could give the desired pressure gradient waveforms were also too expensive, the team opted to develop a control system that applied both constant pressure drops and pressure drop waveforms based on hydrostatic pressure variation across the test section. Regarding this process of considering design alternatives, one of the students responsible for this process later said the following: *"While researching these topics, it was enlightening to see how engineering principles could be directly applied to an application while using a variety of different mechanisms."*

Over the course of almost a year, students designed and built a flow control system that made use of four air-vented water holding tanks, valves, pumps, water level sensors, pressure sensors and a flow sensor. The system used feedback loops to vary the water level of the various tanks to achieve the desired pressure drop (both constant values and waveforms) in either direction across the silicone venous valve model test section, and made use of a system of valves to provide rapid changes in applied water pressure to switch the direction of flow through the test section. This provided a student with the opportunity to deepen their understanding of control systems and electronics through creation of an entire control system. Of this experience, the student said the following: *"One skill that I specifically focused on throughout the project was control systems. To maintain a consistent pressure differential, we decided that a control system would best* *provide the constant conditions required for our testing. This allowed me to fully research and develop a control system that would allow conditions to be constant with very little steady-state error. This vastly improved my understanding of PID control systems and how they are tuned in real-world situations."*

Ultimately, the hydrostatic pressure flow control system was functional but had drawbacks including unwanted pressure oscillations, somewhat slow response and a large required fluid volume. The arrival of funding from a research grant from the National Science Foundation (NSF) allowed for the procurement of an air pressure controller (Elveflow OB1) that removes many of these drawbacks, so the project turned away from the hydrostatic system to the development of the system described previously in this paper. While at first glance it seems like the efforts and resources spent on the original flow control system were wasted, lessons learned from that design process greatly influenced the design of the new flow control and measurement system and some system components were recycled in the new system. Further, it was a meaningful part of the education of the student who developed the original flow control system, who said the following about their experience: *"Working on the venous valves project was one of the pinnacles of my undergraduate studies. It provided me with specific, applicable experience during my college education to directly apply engineering principles, work with my colleagues, and jump-start my engineering career."*

Once the new air pressure-based flow control system was designed and built, the challenge of designing tests and preparing to gather data remained. In the preliminary tests with the new system, one major issue that was identified was that the pressure drop data were noisy and inconsistent and did not match what we expected to see based both on intuition and on previous numerical simulations. This issue gave the student working to solve this issue the opportunity to put the principles learned in their undergraduate fluid mechanics course into practice. They calculated the major and minor head loss through the tubing and other components in the system and after some struggles and help from the faculty mentor found that the head loss (pressure drop) through the flow control system was much greater than the pressure drop across the silicone venous valve model. Additionally, since the pressure drop across the test section was much less than was initially thought, the pressure sensors did not have sufficient resolution and were too far from the test section to get accurate pressure drop data. This rendered the resulting data useless and made it difficult to determine the pressure drop which the pressure controller must provide. After analyzing the data and evaluating possible solutions based on calculations for each system component, the student reduced the overall length of tubing in the system and replaced two connectors that were severely constricting flow. These changes greatly reduced the overall head loss in the flow control system. Further, new pressure sensors with a pressure range appropriate for taking accurate pressure measurements across the test section were procured and were installed via needles placed directly at the locations where pressure values were needed. Of this experience, the student said that the *"project helped me see the applied physical applications of fluid dynamics."*

To create the silicone venous valve models themselves, the students went through multiple iterations of designs. They initially brainstormed various design alternatives. Multi-piece models were considered, since the vessel wall was required to be rigid and transparent but the valve leaflets needed to be highly flexible. However, based on calculations and prototypes it was determined that using thin leaflets and thick vessel walls could yield non-deforming walls and highly deformable leaflets. PDMS would be optically transparent, could be tuned to get the needed material properties [11], and is commonly used in a variety of engineering research applications. This made single-piece models a viable option, which is much simpler than trying to reliably mount individual leaflets inside of a rigid vessel, and a single-piece model design was ultimately selected. To get the desired geometry and remove the inner molds afterward, we tried 3-D printing the inner molds out of dissolvable filament using an FDM printer. However, dissolving the inner molds each time a silicone model was created was time-consuming and FDM printing left layer lines which did not result in a surface finish that afforded adequate optical clarity. We tried removing the PDMS from solid inner molds, but PDMS tears too easily for that, and we could not get an intact model from PDMS molded with solid inner molds. Finally, we turned to alternative silicone materials, and after testing several we found that Smooth-On EcoFlex 00-31 Near Clear silicone gave a good combination of reasonable optical clarity, relatively low Young's modulus, and outstanding toughness. It could be readily removed from solid inner molds without tearing. As is the case with other platinum silicones when used with SLA printed molds, it requires full curing of the molds and additional surface treatment of molds to prevent cure inhibition, but with significant effort we successfully created silicone venous valve models in a single piece out of this excellent silicone material.

With this new selection of silicone, the optical clarity needed to be improved to allow for visualization of the interior of the vessel. First, bubbles were removed by degassing in a vacuum chamber prior to pouring the liquid silicone into the molds. Some bubbles remained, and sometimes the silicone did not fully enter the valve leaflet region of the mold, giving deformed leaflets. To solve this problem, the silicone was pressurize in a pressure pot to force the silicone into even tiny spaces inside the mold and to force bubbles out of the silicone. This greatly improved the result but letting the silicone cure for 24 hours in the pressure pot was even better, leading to reliable formation of full valves (as long as the molds are prepared well enough to prevent cure inhibition) and removal of bubbles. Even without bubbles, the optical clarity of the model was not good enough. In testing materials by casting them in a cup, we found that the optical clarity of the same material was much better if cast in a cup than in our molds. Upon examination of our molds under a microscope, we found that there were layer lines in our molds, but that they were extremely fine and close together. We developed a process for sanding the molds prior to casting, which greatly improved the optical clarity of the resulting silicone models. We then found that optical clarity was excellent right after molding but then significantly degraded over time due to dust accumulation, so procedures were developed for keeping the silicone models clean.

Similarly, a host of other issues came up and were solved in future iterations of the silicone venous valve models. The faculty mentor constantly emphasized the importance of thoroughly documenting your methods and findings and required that students develop and follow detailed procedures. Whenever a team member prepared to leave the team or a new team member joined the team, documentation checks and training were done to ensure that knowledge was passed on.

To help impress upon students the importance of documentation, students were taught to closely follow procedures and were given assignments early on that were not critical to the project but would invariably fail if procedures were not followed with exactness. This early failure helped students to understand the importance of creating effective documentation and of following procedures. Many students later commented about how important this lesson was to them. Regarding this, one student later said the following: *"Working on such a significant project emphasized to me the significance of effective communication. Every detail must be well documented to allow work to be picked up later by any team member as well as allowing work to be completed effectively. When I am currently working on a project, I now understand the importance of documenting my work."* Another student remarked the following:*"I also learned about "working with" team members who are not there in person, including people who had previously worked on the project and people who will work on it in the future, through effective documentation."*

Through the project, students learned and refined a variety of skills, such as computer aided design, 3-D printing, silicone molding, manufacturing processes, computer programming, data collection and analysis, attention to detail, and many others. Of special note is 3-D printing. Entering the project, very few of the students had any experience with 3-D printing. However, they left the project with significant 3-D printing expertise and many went on to use those skills in course and Capstone projects, personal projects, entrepreneurial endeavors and in future employment. This is a skill that our Mechanical Engineering program at Utah Valley University is now building up across the curriculum, and the students who learned this skill on this project have been impacted for the better by development of this skill.

Additionally, working on this project helped students to improve their teamwork and communication skills. They learned how to carry out their independent responsibilities through interdependent interactions, sharing their insights and talents freely with each other to help everyone to be better at their job. They learned effective communication skills. One student said the following: *"Each week we put together short presentations detailing our progress for the week and presented it to the other members of the lab. This process taught me how to choose relevant information and convey it in a clear, concise way rather than just listing everything I had done and leaving the other person to parse the information."* This communication through effective presentations to a small group and the subsequent discussions were important to learning to work effectively with others. Students also learned to communicate their findings through conference presentations. Said one student: *"While working on the project, I presented our work at two different conferences. This task demanded that I distill our work into a coherent narrative that other scientists and engineers would be able to grasp within a ten-minute presentation. This required creating figures that illustrated the points I would like to communicate, and practicing what I would say to properly convey the information. The conferences featured a question-and-answer period following each presentation, prompting me to consider the material from an audience's point of view and anticipate points of inquiry. The experience of presenting at the conferences forced a significant leap in my communication skills."*

Students also learned critical thinking skills for this project. As was explained already in detail, students were given much practice in critical thinking to solve problems that came up frequently during the model development process. One student said: *"Additionally, I learned how to ask interesting questions for research... Developing the skill of asking insightful questions was a key aspect of the valuable skills I learned during the venous valve project."*

This project helped students to bring together what they had learned in their coursework in a variety of courses in new and meaningful ways to solve problems. One student described it this way: *"Over the course of this degree I've had classes about analytical calculations and classes about manufacturing processes; in this project the analysis and manufacturing was combined and I learned how to integrate the two skillsets into a single engineering process."*

In addition to learning information, techniques and skills that will benefit them throughout their careers, many of the students were inspired to find their interests in mechanical engineering and to elevate their career goals. Said one student: *"The venous valve project gave me the opportunity to explore my interests and learn skills that have been instrumental in shaping my current path... I am grateful that I had the opportunity to work on the venous valve project. It provided an opportunity to apply the things I learned in class to a real problem with potential to make a positive impact on society."*

Conclusions

This project has led to the creation of a silicone venous valve model and flow control test system that will be instrumental in research on the effect of venous valve morphology on flow conditions that are conducive to disease, namely venous thromboembolism. These physical products will be used to gain understanding that can guide medical professionals in determining guidelines in assessment of patient risk factors and determining appropriate preventative measures. These products can also be used for the effective design of medical devices and other products.

In addition to the physical products of this project, working on the project has allowed the students involved to grow beyond merely understanding concepts taught in the mechanical engineering curriculum. Through applying concepts and tools from previous courses, analyzing data and other results, evaluating alternative problem-solving methods and ultimately creating a test system that can be used for meaningful research, students have prepared themselves to be effective engineers and have become more engaged in their own learning than they ever could be in traditional classroom coursework. Additionally, this project and its resulting physical products have become an effective tool for STEM outreach and for helping students in mechanical engineering courses to see valuable applications of the material that they are learning. All of these help to increase both the quantity and quality of students graduating in mechanical engineering and going on to create positive change in our world.

Acknowledgements

We gratefully acknowledge the National Science Foundation (NSF) CMMI 2138836 grant and a Utah Valley University (UVU) Undergraduate Research Summer Institute Grant (URSIG) for financial support.

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