5-1-2019

# EVALUATION OF FLOW RATE-DIAMETER RELATIONSHIPS FOR SMALL-DIAMETER VASCULAR GRAFTS, USING A COMPUTER-MODULATED BIOMECHANICAL TESTING SYSTEM

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by

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Presented to the Faculty of the Honors College of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

HONORS BACHELOR OF SCIENCE IN BIOMEDICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2019

ACKNOWLEDGMENTS

I would like to thank our mentor, Dr. Jun Liao, for guiding and motivating me for the past two semesters. He always emphasized the importance of realizing how every engineer learns from trial and error. I truly learnt a lot working under him this past year. His Teaching Assistant, Sara Mcmahan, was very helpful this semester. She provided as many samples as was needed for the testing processes.

I would also like to thank Dr. Xinglong Wang for his help in developing the MATLAB program that allowed my Senior Design team and me to automatically analyze multiple images at once. Dr. Khosrow Behbehani deserves special acknowledgment for all of the feedback and advice he shared since the start of Senior Design.

Finally, I would like to give special thanks to my Senior Design teammates – Vy Dang and Zakia Mizan – who worked on this project with me for the past two semesters. Without them, this project would not have been as successful as it turned out to be.

May 3, 2019

# ABSTRACT

## EVALUATION OF FLOW RATE-DIAMETER RELATIONSHIPS FOR SMALL-DIAMETER VASCULAR GRAFTS, USING A COMPUTER-MODULATED BIOMECHANICAL TESTING SYSTEM

Fariha Murshid, B.S. Biomedical Engineering

The University of Texas at Arlington, 2019

Faculty Mentor: Jun Liao

The need to prevent autotransplantation in patients with cardiovascular diseases has led to the increase in interest in the use of artificial vascular grafts (e.g. tissue engineered or synthetic grafts) as potential replacements for diseased blood vessels. Testing for the flow rate-diameter relationships of artificial small-diameter vascular grafts, using the biomechanical testing system, can help to determine their suitability of being potential replacements based on their biomechanical characteristics. Phosphate buffered saline (PBS) is pumped through each sample over a range of flow rates (gradually increasing from 1 mL/s), with the intention of mimicking extreme cases of increased blood flow through the blood vessels in the body under abnormal or diseased states. A high-resolution camera captures changes in the grafts' outer diameters. Using data from these

studies can help to determine the appropriate type of graft to implant into patients. Generally, longer and/or wider grafts were observed to have experienced less significant changes in their diameters, as opposed to their counterparts. However, the degree of deformation has shown to be more directly related to their elastic properties.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Significance of the Project

The proposed computer-modulated biomechanical system will be used to test, observe, and analyze the mechanical behaviors of small-diameter vascular grafts for ex-vivo and in-vivo use. It is desired to obtain suitable grafts that can be implanted into patients in order to maintain vascular mechanical homeostasis. This would require the vascular grafts to be able to withstand the body's internal environment, while simultaneously being able to maintain and perform their physiological functions. Therefore, this biomechanical testing system for small-diameter vascular graft is projected to test for several mechanical properties that are essential for the grafts to withstand before they can be implanted; this includes testing for factors such as the pressure and flow rate of the fluid passing through the grafts. The proposed computer-modulated biomechanical testing system will assist biomedical engineers, scientists, and medical manufacturers to determine the appropriate type of tissue or material to use to prepare the grafts, depending on the needs of the patient.

## 1.2 Existing Similar Systems

There are currently a few biomechanical systems that are similar in design and function to the system design in this Senior Project; they have similar components and are testing for similar outputs. In Figure 1.1, the biomechanical system shown tests for the

pressure-diameter responses of a stent graft that is intended to be used to treat abdominal aortic aneurysms (AAA) [1]. This system uses a manual syringe to pump solution through tubing and deliver the fluid pressure to the stented graft inside a chamber, then records the diameter change with an optical micrometer, and measures the pressure with a pressure transducer.

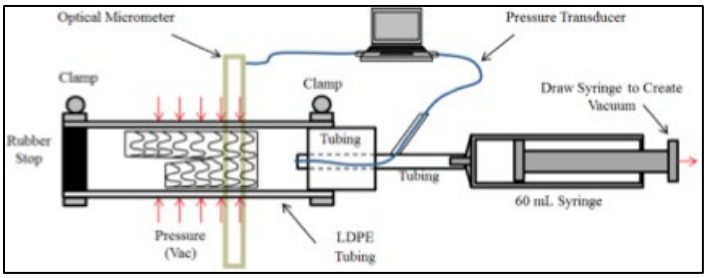


Figure 1.1: System for Testing Pressure-Diameter Responses

The system shown in Figure 1.2 tests vascular grafts in a bioreactor pulsatile conditions. This bioreactor mechanical system is able to adjust the pulse pressures, take compliance measurements, and perform conditioning/durability testing.

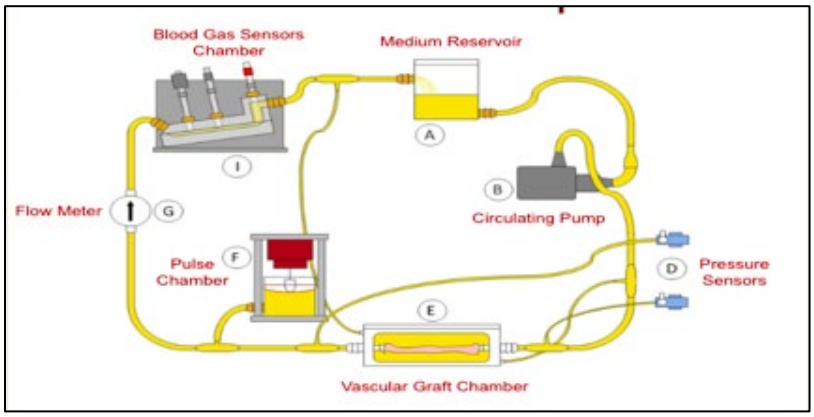


Figure 1.2: Pulsatile Bioreactor System for Durability Testing and Compliance Estimation of Vascular Grafts

Overall, both of these systems have several similar design aspects that can be comparable to the biomechanical testing system designed for this Honors Senior Project. However, the proposed system in this project is novel as it is able to accomplish

biomechanical testing via computer modulations – thus, allowing for a variation of tests to be carried out and for data to be collected and analyzed in a more efficient manner [1].

## 1.3 Objectives of the Project

The purpose of this system is to be able to test tissue-engineered and/or synthetic grafts in order to determine whether their mechanical characteristics enable them to act as suitable graft replacements. Grafts of varying types, materials, and dimensions can be tested to determine the appropriate replacement vessel, based on the needs of the patient. If such grafts are found suitable, this will eliminate the need for autotransplantation in patients, i.e. this will eliminate the need for patients to use a healthy vessel from another part of their own body as a replacement for a diseased vessel.

## 1.4 Distinguishing Features of Proposed System

### *1.4.1 Computer Modulations*

Other similar systems mainly either use manual controllers or LabVIEW to operate the system. LabVIEW is a visual programming language from National Instruments. This program requires certain levels of advanced knowledge about coding, circuitry, and computational data acquisition in order to be able to create a single program controller that can manipulate the entire system. LabVIEW is practical when the system requires multiple components to be modulated simultaneously. However, it is only practical when operated by experienced users.

This proposed biomechanical system unique as its components are controlled using software that are user-friendly and easy to operate. The motor controlling the syringe pump is programmed using the software COSMOS, and the imaging system is controlled by

MATLAB and ImageJ. These software can easily be operated by any engineer, physician, scientist, or technician.

*1.4.2 Mounting Mechanism*

Based on the advantages and disadvantages of the graft mounting mechanisms from the previously discussed biomechanical systems [Figure 1.1 and Figure 1.2], the proposed biomechanical system incorporates a simplistic, modified mounting mechanism. The aforementioned systems applied sutures or clamps to stabilize the vascular grafts, which potentially damaged the grafts at their ends. To minimize this tissue damage and to further increase the stability of the vascular grafts within the mounting chamber, it was decided to use tissue adhesive to mount the grafts to the tubing system.

*1.4.3 Environmental Conditions*

Since those biomechanical systems involves some other components such as bioreactor, pulsatile pump, etc. that requires certain environmental conditions to ensure the functional requirements, such as air-tight or sterile surroundings, these biomechanical systems have to be performed inside a fume hood. Proposed biomechanical system, however, can be used to test under normal laboratory conditions with basic safety practices.

*1.4.4 Cost*

Those similar biomechanical systems use optical micrometers as primary imaging system. Due to budget constraint, proposed system uses a standard-resolution camera to collect data. The option is cost-effective, and affordable compare to optical micrometers. However, optical micrometers would obtain high-definition images compare to standard laboratory camera.

# CHAPTER 2

# PROJECT SPECIFICATIONS

## 2.1 Detailed Functional Specifications

The system consists of a mounting chamber that acts as the testing site for the samples. This chamber was designed to accommodate small-diameter vascular grafts of varying lengths and diameters. The fabricated chamber was able to accommodate grafts less than 14 cm in length, as this was the amount of space that was available inside the chamber. Silicone tubing inserted at the two ends of the chamber were not fixed in place; hence, they could be easily moved inwards and outwards to accommodate the varying lengths of the samples. Plastic connectors of varying diameters (~ 4.7 mm to 11 mm) were used to mount the samples to the tubing system. Two connectors closely matching the inner diameter of the graft being tested would be glued to the two ends of the sample using tissue adhesive. After waiting an appropriate amount of time to allow the adhesive to completely dry, the samples would be connected to the tubing system. This allowed grafts of varying diameters to be mounted within the chamber.

A camera with a resolution of 1024x768 pixels was used to observe and record the changes occurring in the graft during each test run as the flow rate of fluid passing through them was varied. The variation in flow rates was made possible due to the motor that was programmed using the software COSMOS. The program allows the user to input a desired flow rate to be tested, which it then converts into the number of step rotations at a set velocity of 6000 revolutions per second. This causes the motorized stage, acting as the

syringe pump, to pump the fluid from the syringe at the respective flow rate. The images that were collected from the camera were analyzed using ImageJ to determine the initial lengths and outer diameters of the grafts, as well as their average outer diameters that resulted due to the pressure experienced from within the grafts at the given flow rate.

Finally, it was important to ensure the graft remained moist throughout the testing process. Although it was initially desired to keep the graft submerged in PBS throughout the trial runs, it was noticed that the fluid was affecting the quality of the images being captured. Aside from that, it was also observed that the grafts were not drying out as fast as was originally expected. Because of this, the grafts were simply spritzed with PBS periodically during testing; in the meantime, the samples that were not in use were submerged in a vial filled with PBS

The functional specifications for the system are summarized in Table 2.1[refer to Appendix A].

## 2.2 Detailed Physical Specifications

The overall system is a non-sterile, benchtop setup, not intended to be portable. Hence, the overall weight of the system depends on the exact components, models, and materials used. The total weight, however, is not expected to exceed 10 pounds, excluding the laptop that is used to control the individual electrical components.

Ideally, the system would be tested at temperatures that would mimic the physiological conditions of the body, i.e. 37˚C. However, the temperature would have been difficult to maintain throughout the testing process. More importantly, in past studies the temperature at which the graft is under has shown to not have a significant impact on the variables being tested (e.g. compliance, burst pressure, and pressure-diameter relations)

[2]. Thus, the testing process were simply carried out under normal room temperature and conditions, i.e. at approximately 25˚C and at an atmospheric pressure of around 1 atm.

Since image/video capturing is a key function for this system, sufficient lighting is crucial in order to allow the camera to swiftly capture any deformations of the vascular graft without needing to adjust focal points.

The physical specifications for this system are summarized in Table 2.2 [refer to Appendix A]

## 2.3 Safety Standards

This system encompasses four major areas of safety as regulated by institutions, chemical safety data sheets, and The United States Department of Labor Occupational Safety and Health Administration (OSHA).

### *2.3.1 Biological Safety Standards*

The most important safety concern in the system is biological safety. This system requires the use of porcine tissue, which is a biohazard and possesses risks of spreading bloodborne pathogens. In order to handle the porcine tissue and gain lab access, several preliminary training and vaccination had to be completed. These include: Hazard Communication and Waste Management training, Biosafety Level 2 (BSL-2), Bloodborne Pathogen for Research Laboratory Personnel, and receiving the Hepatitis B vaccine. Along with the safety measures specific to each training, general lab safety had to be observed as well. These included [3]:

- wearing gloves, safety goggles, and aprons during the handling of porcine tissue;
- disinfecting and properly cleaning surfaces, equipment, containers, and other objects that came into contact with the tissue;

- properly disposing of biological waste in the designated biohazard waste containers.

*2.3.2 Chemical Safety Standards*

Chemical safety also must be followed while handling this system because of the use of phosphate buffered saline (PBS) and cyanoacrylate adhesive. PBS is hazardous when in contact with the skin, eyes, and respiratory system. It is a skin and eye irritant, which can also cause respiratory irritation if inhaled. Cyanoacrylate adhesive is a combustible liquid that can bond to skin in seconds. It can cause eye and respiratory irritation when in contact or inhaled. General lab safety protocol should be practiced when handling these two chemicals, such as by wearing gloves and safety goggles [3].

*2.3.3 Electrical Safety Standards*

Electrical safety is the next major component since the system requires power for the motor, camera, and laptop. Electrical hazards can cause burns, shocks, electrocution, and death. General precautions must be followed such as: using caution when handling the motorized stage, the camera, laptop, and its associated wires, especially damaged or broken cords, and keeping wires/equipment away from open liquids. OSHA outlines specific electrical safety guidelines that applies to this system [4]:

- Never assume that a wire is safe to touch even if it is down or appears to be insulated.
- Never operate electrical equipment while you are standing in water.
- Never repair electrical cords or equipment unless qualified and authorized.
- Have a qualified electrician inspect electrical equipment that has gotten wet before energizing it, if working in damp locations.

- Inspect electric cords and equipment to ensure that they are in good condition and free of defects.
- Use a ground-fault circuit interrupter (GFCI).
- Always use caution when working near electricity.

*2.3.4 Mechanical Safety Standards*

Lastly, mechanical safety must be followed because this system incorporates a motorized pump and syringe. Mechanical safeguarding as listed by OSHA, relevant to this system, include [5]:

- prevent contact.
- secure objects.
- having protection from falling objects.
- create no new hazards.
- create no interference.
- prevent contact: hands, arms, and any other part of a handler's body must be kept away from moving parts such as the motorized stage and syringe.
- secure objects/equipment and protect them from falling objects; all equipment must be secure so that they do not fall into the moving parts, the motorized stage/syringe, or onto people handling the system.
- prevent the creation of new hazards such as from sharp or jagged corners and edges that can cause cuts, scrapes, or lacerations.
- keep the workspace clean and free of clutter that can impede a person from quickly and comfortably handling the system.

# CHAPTER 3

# SYSTEM DESIGN

## 3.1 Rationale for Design Selection

The selected design and components for this biomechanical system were evaluated and chosen based on the size of the system, its power requirements, the resolution of the camera, the overall cost of the whole system, and the overall efficiency of the system.

Instead of using sutures that damage the graft samples and cause leakage during the testing process, tissue adhesive is used to mount them to the tubing system. This greatly minimizes potential destruction of the testing samples, while simultaneously stabilizing the vascular grafts in place.

Other important elements of the system design include the power requirements and the imaging component. The power requirements mainly include a 120 V AC wall outlet. For the imaging module, a standard resolution camera is used in order to capture the deformation of the graft, with stutter speeds of 30 frames per second. The camera is positioned strategically so that no additional holes have to be drilled into the chamber in order to accommodate the camera.

The cost and efficiency of the system was also evaluated before finalizing this design. The total cost is reasonable for a system of this caliber (less than $1000). This design results in quite an efficient system as most of its components have long life expectancies.

## 3.2 Connections Between System Components

The main system components and the envisioned setup for the final design are shown in Figure 3.1. Similar to the proposed optimum design, the mounting chamber is connected to the tubing that will be carrying fluid through it and the graft. The chosen fluid for the system is Phosphate Buffer Saline (PBS). In this design, the PBS is pumped from a syringe, connected to a computer-controlled motor pump, directly into the tubing. The flowrate of PBS passing through the system is controlled by the motor pump, which is programmed and modified using COSMOS software. The testing sample graft is glued, rather than sutured, directly to the tubing using tissue adhesive. This method of mounting the vascular graft in the chamber eliminates the need to learn proper suturing techniques. In addition to that, gluing the vascular graft to the tube will make testing process more efficient – time wise and cost wise.

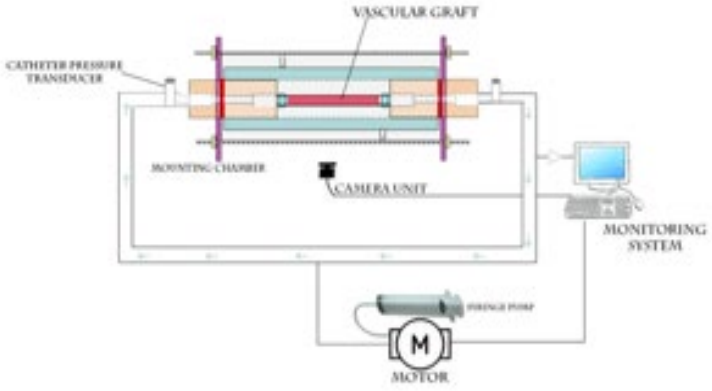


Figure 3.1: Schematic of System Design

Figure 3.2: Actual System Setup

## 3.3 The Mounting Chamber

For this system, the main fabricated component was the mounting chamber. The remaining components were either provided by the supervising mentor or were purchased [Tables 3.1 and 3.2, Appendix B]. This acts as the testing site for the graft samples. It is essentially a hollow box made of Plexiglass, with walls of 1-inch thickness. It has two holes of approximately 10 mm drilled into its two ends. The overall dimension for the chamber is 16 cm in length, 10 cm in width, and 4.5 cm in height [Figure 3.3].

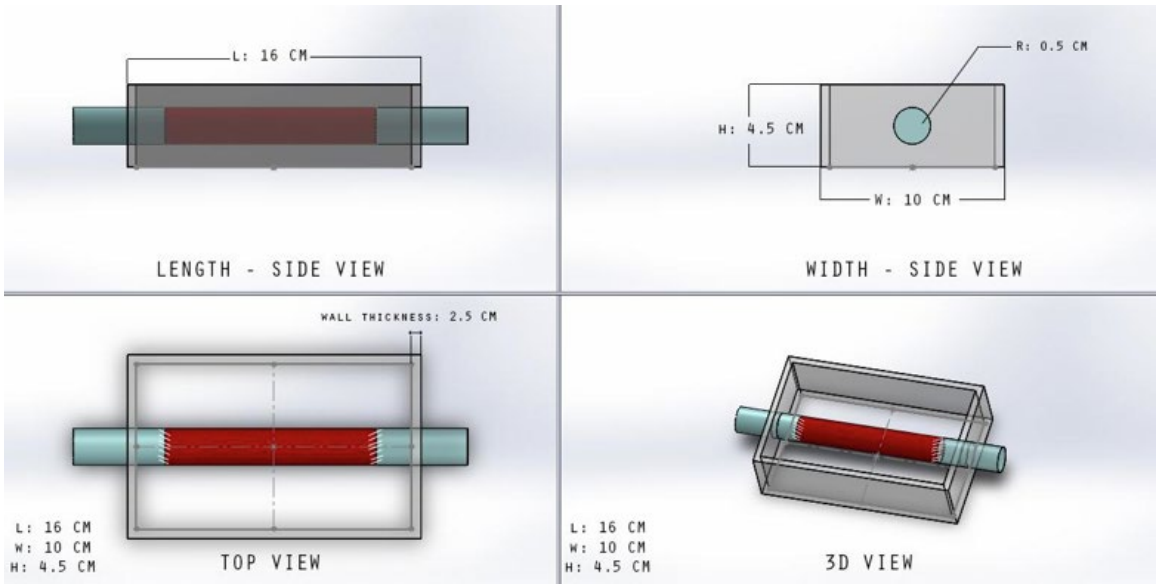


Figure 3.3: Schematic Representing Dimensions for the Mounting Chamber

## 3.4 Weight of System

The overall weight of the system is expected to be approximately 10 pounds - not including the laptop to be used to control the electrical components. Since the system is not meant to be portable, the weight is not an issue when it came down to the system design. The overall weight mentioned was estimated from the addition of the weights for each individual component, listed in Tables 3.1 and 3.2 [Appendix B].

## 3.5 Power Requirements

The individual power requirements of the electrical components of our system can be found listed in Table 4 [Appendix B]. Overall, the system is mainly powered using the 120 V power outlet, since the motor pump and laptop (via its charger) are powered by the wall outlet. Only the camera is USB powered.

# CHAPTER 4

# ANTICIPATED SYSTEM PERFORMANCE

## 4.1 Input Function: Flow Rate

The input for this biomechanical system is the flow rate of PBS being pumped through the system. The flow rate of PBS is meant to represent the flow rate of blood through the vascular graft. Because of this, the flow rate was originally expected to be calculated using the equation that is normally used to determine the blood flow:

$$Flow\ Rate = \frac{\pi \Delta P r^4}{8\eta\lambda}$$

Where,

ΔP: difference in pressure across the graft,
r: radius of the graft,
η: viscosity of fluid through the graft, and
λ: length of the graft.

The radius and length of the graft would have been measured prior to the mounting of the graft. Since PBS is composed of 97% water, the viscosity of the PBS would have been approximated to be equal to the dynamic viscosity of water: 8.90 x 10^-4 Pa. s. The pressure difference of PBS passing through the two ends of the graft would have been determined by using the readings obtained from a pressure sensor. However, due to budgeting and time constraints, it was not possible to incorporate a pressure sensor into the system. Hence, the following calculations were used to determine the steps needed to produce the respective flow rate that was desired to be tested:

$$Steps = \frac{Desired\ Flow\ Rate\ \left(\frac{m^3}{s}\right) \times Velocity\ (steps\ per\ second) \times 1000}{\pi\ \times\ d^2/4}$$

Where,

Velocity = 6000 steps per second (maximum velocity of motorized stage)
d = diameter of the syringe (m)

Based on literature studies, it was found that the blood flow in the body is generally less than 1 mL/s on average (~ 0.26 - 0.83 m/s) [6]. In extreme cases, it was found that the blood flow *may* rise up to 3 mL/s, although this is extremely rare. Regardless, it was decided that the samples should be tested at flow rates *starting* at 1 mL/s, and then gradually increasing the rates up to the point of rupturing. This would allow the samples to be tested under the most extreme cases, ensuring they would be safe to function in patients even under diseased conditions.

### 4.2 Output Function: Change in Outer Diameter

The initial outer diameter of the grafts would be measured using vernier calipers prior to their mounting. The initial outer diameter and the length of the grafts can also be determined later using ImageJ analysis of images captured using the camera in the system, as shown in Figure 5.

When attempting to find the change in diameter due to particular pressurized flow of fluid, the new average outer diameter of the graft would need to be determined from the images captured by the high-resolution camera. The average change in the outer diameter can be found by simply subtracting the new outer diameter – obtainable from ImageJ analysis – from the initial diameter.

*4.2.1 MATLAB Imaging Code*

Although ImageJ can be used to analyzed the images [Figure 4.1], it would only allow one image to be analyzed at a time. Each trial run produces at least 30 images – one image is captured per second for a time period of 30 seconds. Hence, analyzing each image for a single trial run alone can become a tedious task. Because of this, a major addition to the Honors Senior Project was a MATLAB program that would be able to extract and analyze multiple images at once. Its output would be the average change in the graft's outer diameter over time. The MATLAB program that was prepared is shown in Appendix C.

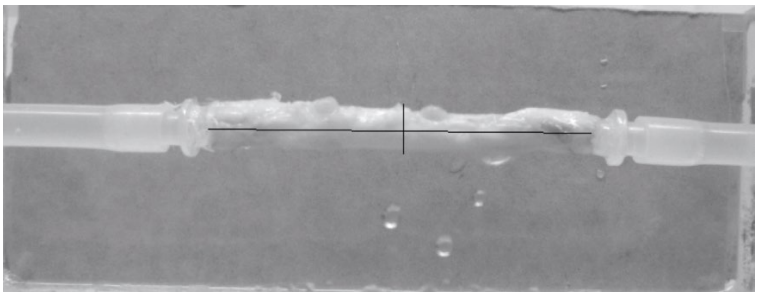

Figure 4.1: ImageJ Analysis: Horizontal Mark Indicating Length of Graft; Vertical Mark Indicating Initial Outer Diameter

The code first imports all the images from the respective test run folder that needs to be analyzed. A *for loop* is used to read them into the MATLAB workspace. All the images are sharpened using a Sobel Kernel filter. This helps to enhance the image contrast to allow for better edge detection. The program then identifies a region of interest by establishing a vertical column/region on the images. This region contains the exact point on the upper and lower boundaries on the graft, which will be used to calculate the average outer diameter. The program forms a histogram of all the points within this region of interest; an example of this is shown in Figure 4.2. The histogram presents two significant peaks: the highest peak represents the upper boundary point, while the relatively shorter peak represents the lower boundary point. The program finally determines the average

change in the grafts outer diameter by calculating the difference between the upper and lower boundary values.

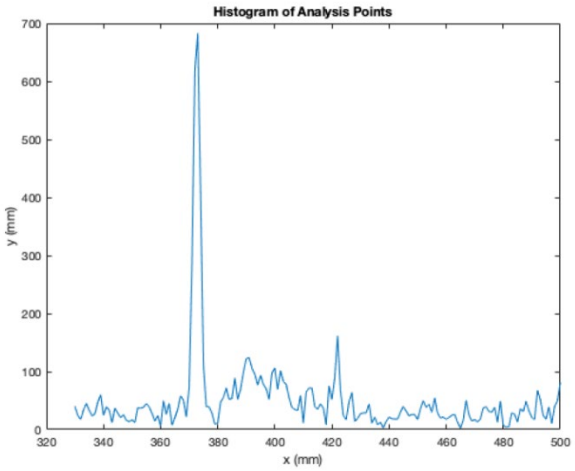


Figure 4.2: Histogram Representation of Analysis Points

## 4.3 Resolution and Repeatability

The camera being used in the system – *The Imaging Source [DMK 31BU03]* – has a resolution of 1024 x 768 pixels. The smallest pixel size it can detect, both horizontally and vertically, is 4.65 µm in size. This means the imaging system will allow us to detect changes in the diameter of the graft at the microscopic level, given that the changes are no smaller than 4.65 µm.

The motor pump can be directly programmed to produce a range of flow rate values. However, it is the motorized stage [Figure 4.3] that will be physically implementing the commands by pumping the syringe. The plunging shaft of the motorized stage can move between 2 and 30 inches, as long as the maximum load is no greater than 35 pounds. The accuracy of its linear movements in any one direction is 0.025 mm. The minimum motor torque that will be required by this motorized stage is 0.18 N. m. The motorized stage has a repeatability of ~ 0.0001 inches over the short term. However, this may vary depending on the degree of wear in the long run.

Figure 4.3: Motorized Stage

## 4.4 Dynamic Range

The flow rate to be tested should be varied from 1 mL/s to at least 10 mL/s. This means the motor would need to make the motorized stage pump the syringe at its max velocity of 6000 steps per seconds, varying its steps from 8067 to at least 80677. However, the true movement of the motorized stage is actually dependent on the torque of the motor. The *Velmex 2 VXM Motor* displays 185% torque at 0.2 rev/s, 200% at 5 rev/s, and 340% at 10 rev/s.

For the camera, the smallest change it will be able to detect is 4.65 μm. Its dynamic range is 8-bit.

## 4.5 Durability

The durability of the system is dependent on the conditions and life cycles of the individual components. Each component is expected to last a minimum of 10 years. However, they may need to be replaced before then in order to maintain a desired degree of accuracy and repeatability.

Any power outages may result in the temporary shutdown of the system, since the wall outlet powers almost all of the main components. Aside from that, any problems

associated with the software that will be controlling the individual components may result in the temporary malfunctioning or shut down of the system as well.

## 4.6 Simulation Results

For the flow rate-diameter tests, the diameters of the grafts were expected to increase as the pressure of PBS – caused by its respective flow rate – flowing through it increased. The diameters of the grafts are expected to increase up until it reaches its bursting point. The graph shown in Figure 4.4 was obtained from a study similar in experimental design and setup as this Honors Senior Project. The main difference in this study's experiment was the fact that the researchers varied the diameters of the graft rather than the flow rate of the fluid through it. In addition to that, they studied the effect the variation in diameters had on the resulting pressure experienced within the graft – a variable that could not be incorporated into the Honors Senior Project due to the lack of a pressure sensor.

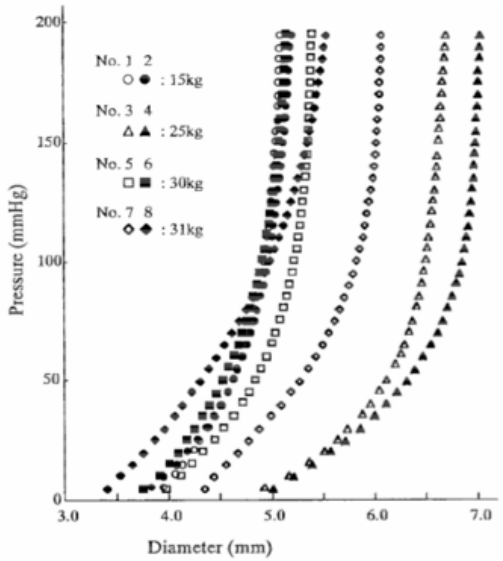


Figure 4.4: Pressure-Diameter Relation Test in Canines

Regardless, the general trend they obtained was similar to what was expected from the results that were to be obtained from the system designed in this project, an increase in

pressure (due to increased flow rate) would lead to an increase in the outer diameter of the graft. It is also expected for the grafts with smaller initial outer diameters to display a more significant change since they have smaller volumes to be filled with fluid. Thus, based on the experimental data to be collected from the biomechanical system, it is likely to obtain a graph that may resemble the inverse of the one shown in Figure 4.4.

## 4.7 Assessment of Chances of Success

Considering the original functional requirements of the system design, the success of the system was estimated in terms of a 'success ratio', where the percentage of success based on the percentage of functional requirements that were successfully achieved through the fabricated system was determined. The original function requirements are listed below:

1. accommodating small-diameter grafts of varying sizes (length: 4-12 cm; diameter: 4-8 mm)
2. varying flow rate of PBS through the system, up to at least 10 mL/s
3. observing and recording changes in the grafts during each test run
4. measuring pressure of fluid passing into the graft
5. determining the flow rate at which the grafts burst, as well as the respective burst pressure
6. keeping the graft moist throughout the testing process

Out of all of these requirements, the only features that were not achieved were the ones related to the pressure. As mentioned previously, the pressure sensor was not incorporated into the system due to budgeting and time constraints, hence, it was not possible to measure the pressure values causing the changes in the grafts at each respective flow rate.

Considering this, it can be estimated that the ratio of *achieved requirements*: *desired requirements* is approximately 4.5:6. This gives the system a success rate of approximately 75%.

# CHAPTER 5

# FABRICATION

## 5.1 Mounting Chamber

The Plexiglass sheets used to fabricate the chamber were purchased from Tap Plastics with exact dimensions proposed in Figure 3.3.

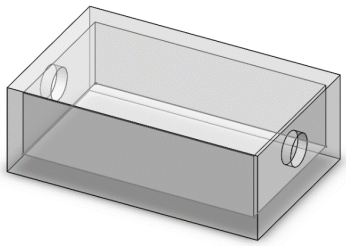

Figure 5.1: SOLIDWORKS Model of Mounting Chamber

One 16 x 10 cm sheet served as the chamber bottom, two 16 x 4.5 cm sheets served as the front and back walls, and two 10 x 4.5 cm sheets with 10 mm diameter holes drilled into the centers served as the side walls. The sheets were glued in place using industrial-level acrylic glue.

Figure 5.2: Fabricated Mounting Chamber

## 5.2 Locking Mechanism for Motorized Stage

The provided motorized stage was missing a few components that would normally help to stabilize the syringe in place as it was being pumped. Using Solidworks and Kisslicer, two clamps were designed and three-dimensionally printed to serve as locking mechanism for the syringe barrel by deadlocking the barrel flanges in place [Figure 5.3].

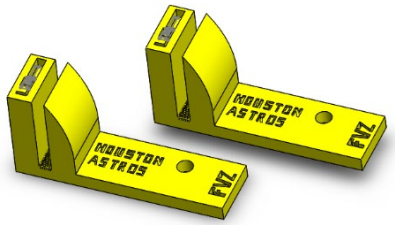


Figure 5.3: SOLIDWORKS Model of Locking Mechanism

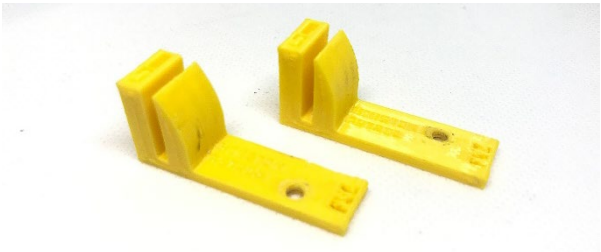

Figure 5.4: 3D Printed Prototype of Locking Mechanism

## 5.3 Platforms for Mounting Chamber and Camera

The tubing system connecting the syringe to the inside of the mounting chamber were initially unleveled due to height difference between the syringe and the mounting chamber on the benchtop. Consequently, the mounted testing samples attached to the tubing could not remain straight; instead, it would bend or fold during testing. Thus two platforms were designed, scaled up, and three-dimensionally printed to level out both the mounting chamber and camera with respect to the motorized stage.

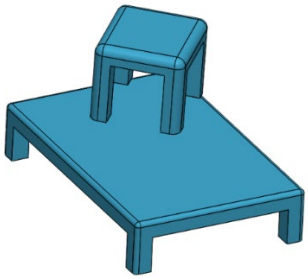

Figure 5.5: SOLIDWORKS Model of Platforms

Figure 5.6: 3D Printed Prototype of Platforms

# CHAPTER 6

# SYSTEM PERFORMANCE

## 6.1 Testing Procedure

The general setup of the system consisted of simple USB connections of the motor and the camera to the laptop controlling them. The motor was also plugged into the wall outlet. The system components were all switched on to allow the respective software controlling them to identify the port allowing the connection between the device and the laptop. A syringe is filled with a fixed volume of PBS for every test run. The syringe is then mounted onto the motorized stage that is connected to and controlled by the programmable motor. The body of the syringe is secured in place with the help of two clamps [Figure 5.4]. The syringe is then connected to the silicone tubing with the help of sealing wires to eliminate any risk of leaks. The flexible silicone tubing is inserted at the two ends of the mounting chamber in the form of a loop to allow the fluid to be recycled and continuously pumped through the system during the trial run.

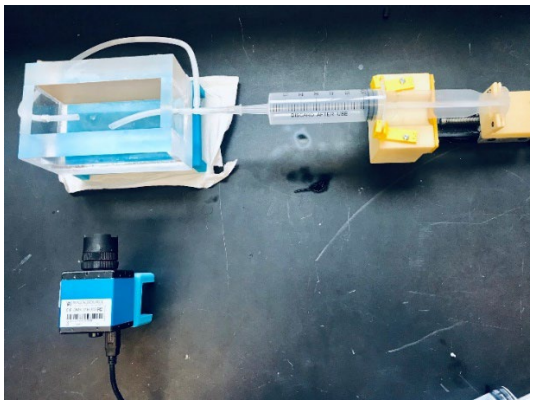

Figure 6.1: System Setup Showing Tubing Loop

Prior to their mounting, the graft samples - porcine neonatal abdominal aortas - were adhered to connectors closely matching their initial diameters using a few layers of tissue adhesive. Generally, the samples were given a day to completely dry to ensure the connection was strong and would not be affected by the PBS. The samples that were not in use were submerged in a vial containing PBS to prevent them from drying out. The sample to be used would be spritzed with PBS for rehydration prior to its mounting; it would simply be secured in place by sliding the open ends of the connectors into the tubing.

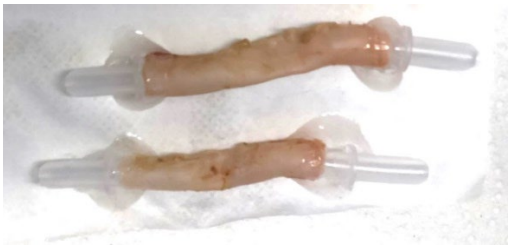

Figure 6.2: Preparation of Graft Samples

The camera would be positioned in front of the chamber, focusing solely on the graft being tested. The desired flow rate would be converted into the respective steps for the motorized stage to move to achieve the inputted rate. This was calculated using the equation discussed in Section 4.1. The camera would then be started as the motor is switched on. The syringe would be pumped at the respective flow rate, pumping PBS into the graft sample. The camera would then collect a series of images for the duration of the test run, which would later be analyzed to obtain the results. Generally, the test run was allowed to run for 30 seconds, unless the graft ruptured before then.

When changing samples, the graft and its connectors would be removed from the tubing system. A new sample would be mounted as described earlier. The syringe would be refilled prior to its mounting, and the entire test procedure would be carried out again.

Figure 6.3: Camera Placement in System

## 6.2 Analysis of Test Results

Based on the data collected from the trial runs, it was possible to determine how the outer diameter varied over the course of the test run. In Figure 6.4, the average change in the outer diameter over a period of 11 seconds has been displayed for a graft that was 6 cm in length, with an initial outer diameter of 6.2 mm. From this, the rhythmic behavior of the graft with each pump from the syringe can be observed; this closely resembles the rhythmic expansion and contraction that would be expected from a healthy blood vessel with each pulse in the body. This behavior was also visually observed, as shown in in Figure 6.5. The maximum diameter reached at the points of expansion was around 12 mm, while the minimum diameter reached at the points of contraction was around the initial value – 6.2 mm.

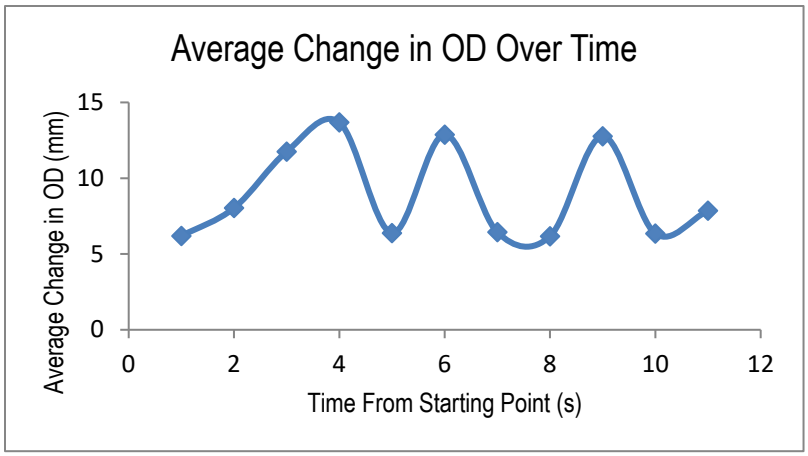


Figure 6.4: Average Change in Outer Diameter Over Time

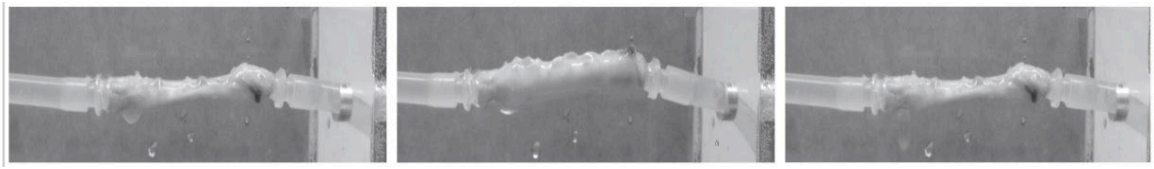

Figure 6.5: Rhythmic Deformation of Graft Sample

Another main observation that needed to be made was the relationship between the flow rates and the outer diameter. From Figure 6.6, the outer diameter increased as the flow rate was gradually increased. The increase in the degree of expansion can be accounted for by the increase of pressure experienced within the graft due to the buildup of PBS at the higher flow rates. It can be observed that the increasing trend was lost somewhere between 6 and 8 mL/s. This tells us that graft must have ruptured at some point due to these flow rates. Hence, it can be estimated that the maximum this particular graft can handle is approximately 6 mL/s. Results like these allow for the limit of grafts to be determined in cases where the rupturing of grafts is not visibly observable.

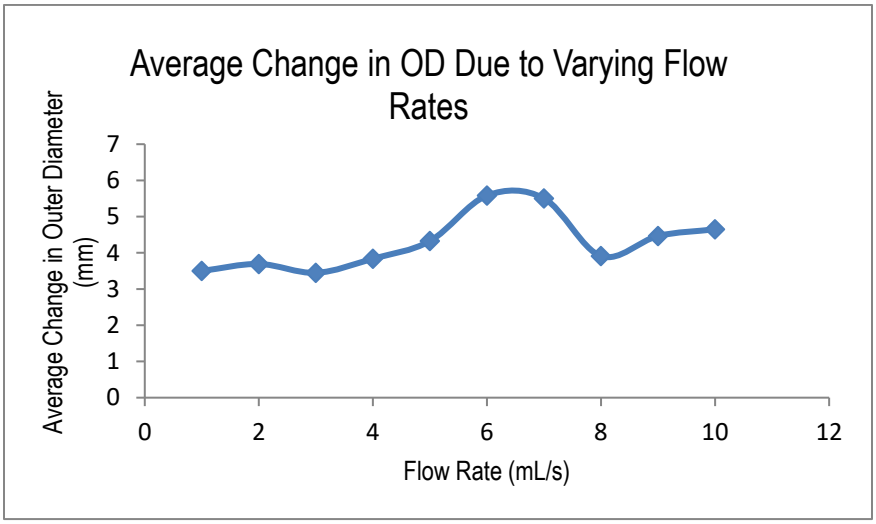


Figure 6.6: Average Change in Outer Diameter Due to Varying Flow Rates

In general, it was observed that the shorter grafts with smaller outer diameters experienced the most significant expansion, as there was a much smaller volume within the graft to be filled with fluid at a given point. The longer grafts had a comparatively

greater volume to fill at a given point; hence, less PBS was able to accumulate to cause a significant degree of expansion.

### 6.3 Performance Evaluation

Overall, the system was able to perform under all the physical specifications that were set out for it - room temperature/pressure and natural lighting [Appendix A]. All of the functional requirements were also met from the system, apart from being able to record pressure values since a pressure sensor could not be incorporated into the system [Appendix A].

The main focus of the Honors Senior Project was to ensure that a biomechanical testing system was fabricated to allow the mechanical properties of grafts of varying sizes to be studied; the motorized pump was programmed to allow a variation of flow rates to be tested. It was also important to incorporate an imaging program that could analyze multiple images at once; this was made possible using the MATLAB code shown in Appendix C. Since both of these features were achieved by the final system, the overall outcome was quite successful.

# CHAPTER 7

# RECOMMENDATION FOR FUTURE IMPROVEMENTS

## 7.1 Incorporation of a Microfluidic Pressure Sensor

The major component of the original proposed system that was not incorporated in the current system was the pressure sensor that was able to take fluid pressure readings during testing. The system's current design will allow for a pressure sensor to easily be incorporated in the future without the need of changing the system setup or design. A microfluidic pressure sensor can be connected to the tubing system to record the pressure of the fluid as it passes through it.

Two compatible pressure sensors were originally considered to be implemented into the current system: Elveflow Microfluidic Pressure Sensor [Figure 7.1] and Utah Medical Products Inc: Deltran I Disposable Pressure Transducer [Figure 7.2]. The Elveflow MPS can be directly connected to the system's tubing. It can measure up to 100 psi. This pressure sensor can be programmed using any one of the following software: C++, MATLAB, Python, and/or LabVIEW.


Figure 7.1: Elveflow Microfluidic Pressure Sensor

The Deltran I Disposable Pressure Transducer is biocompatible and easily sterilizable. It can measure pressures up to 300 mmHg and flow rates up to 30 cc/hour [7].

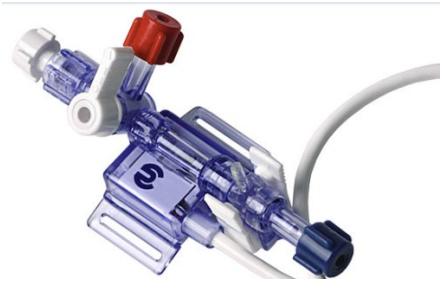

Figure 7.2: Deltran Blood Pressure Transducer

## 7.2 Substituting Current Testing Fluid

The current system utilizes phosphate buffered saline (PBS) as the test fluid that is pumped through the vascular graft. In order to obtain more accurate data, Doppler test fluids can be used instead. This specialized type of fluid is used in Doppler ultrasound tests that measure the amount of blood flowing through arteries and veins. CIRS Doppler Test Fluids are reliable, stable, and non-hazardous fluids; they more closely mimic the acoustic and physical properties of blood compared to PBS [8].

## 7.3 Switching To a Higher Resolution Camera

The data that was obtained from the MATLAB imaging program were not as accurate as the data that was obtained from manual analysis of the images via ImageJ. This was mainly due to the poor resolution quality of the images captured by the camera. In order for the MATLAB program to yield more accurate results, the current camera would need to be replaced with one of higher resolution. The Imaging Source: DFK 38UX267 USB 3.1 color industrial camera is one possible upgrade that can be made to the system for better quality images. This is a 12-bit camera with a resolution of 4,096×2,160 (8.8 MP) that can capture up to 35 frames per second (fps). It has a USB 3.1 interface and is compatible with both Windows and Linux software [9].

# CHAPTER 8

## SUMMARY

The *Computer-modulated Biomechanical Testing System for Small-Diameter Vascular Grafts* described in this report was designed to test, record, and analyze tissue engineered or synthetic vascular grafts potentially suitable for in-vivo graft replacements. This system can test the biomechanical properties of vascular grafts varying in length (4-12 cm) and diameter (4-8 mm) as fluid flow rates starting from 1 mL/s is input into the system.

This system was able to implement almost all of its originally proposed functional specifications. The major component unable to be incorporated into the current version of the system, due to budget and time constraints, was the pressure sensor able to measure the fluid pressure flowing into the vascular graft during testing. Therefore, any pressure related calculations were not obtained for the vascular grafts tested in this system.

For future improvements or versions of this system, equipment such as a pressure sensor and a higher resolution imaging system may be incorporated. Furthermore, to more accurately mimic the properties of blood, the current testing fluid can be switched to a one with similar viscosity as blood.

This system design is simplistic enough to be replicated in industry, laboratories, and at other research settings.

# APPENDIX A

# FUNCTIONAL AND PHYSICAL SPECIFICATIONS OF FINAL SYSTEM

Table 2.1: Functional Specifications of Final System

| Functional Requirements | Functional Aspects |
|---|---|
| Accommodate Small Diameter Grafts (Length < 14cm & Diameters Between 4.7 and 11 mm) | Space within chamber is 14 cm long, hence samples smaller than this can be accommodated. Connectors used to attach the grafts to the tubing varied in size from 4.7 to 11 mm. Hence, grafts with inner diameters within this range could be mounted. |
| Be Able to Vary Flow Rates Up To At Least 10 mL/s | Motor was programmed using COSMOS to allow it to produce the desired flow rates by inputting the respective steps for the motorized stage to move to produce the given rate. |
| Observe/Test For Changes in Graft Due To Varying Flow Rates | Camera allows changes as small as 4.65 μm to be detected. The captured images are analyzed by ImageJ and MATLAB to determine the changes in the outer diameters due to the varying flow rates. |
| Determine Bursting Point of Grafts | Programmable motor allowed for the flow rate to be gradually increased up until the graft ruptured. Camera was able to determine the point of bursting. |
| Keep Graft Moist | Grafts being tested were periodically spritzed with PBS to keep them moist. Grafts not being tested were kept submerged in a vial filled with PBS. |

Table 2.2: Physical Specifications of Final System

| | Physical Requirements | Physical Aspects of Final Design |
|---|---|---|
| Size | Benchtop machine | Entire setup takes no more than 25 x 25 inches of space. |
| Optimal Operating Temperature | Normal room temperature of 25 degrees Celsius. | Slight variations in room temperature, may not be exactly 25 degrees Celsius. |
| External Pressure Exerted on Device | Atmospheric pressure (1 atm) acting externally on chamber | Setup will be under normal atmospheric pressure. |
| Ambient Light | Normal and sufficient lighting for the camera imaging system | Polycarbonate is transparent. Camera will be placed under proper lighting system. |
| Power Requirements | Not battery powered; powered by 120 V AC outlet. | All components are powered by the wall outlet, except for the camera which is USB powered. |

# APPENDIX B

# DEVICE SPECIFICATIONS

Table 3.1: Electrical Device Specifications

| ELECTRICAL DEVICES | | | |
|---|---|---|---|
| | Brand/Model | Price | Features |
| Camera | *The Imaging Source* [DMK 31BU03] | $400 | Weight: 265g [ approximately 0.6 pound]<br>Shutter speed: 1/10,000 to 30 frame per second<br>Sensitivity: 0.05 lx<br>Resolution: 1024x768 pixels<br>Dynamic range: 8-bit<br>Pixel size: 4.65 µm (horizontally and vertically)<br>Power: 4.5-5.5 V DC (USB powered)<br>Dimensions (H x W X L): [50.6 x 50.6 x 50] mm |
| Motor Pump | *Velmex* 2 Model VXM Stepping Motor Controller | $500 | Weight: 1.76 kg (3.9 pounds)<br>Flow rate/Speed range (min-max): 1-6000 pulses/second<br>Power: 100 – 240 V AC<br>Dimensions (H x W x L): [3.52 x 4.37 x 6.89] inches |

Table 3.2: Non-Electrical Device Specifications

| NON-ELECTRICAL COMPONENTS | | |
|---|---|---|
| Components | Price | Features |
| Mounting chamber | $20 per sheet of dimensions of 12x12 [length x width] | Material: Plexiglass, also known as poly (methyl methacrylate) [PMMA]<br>Weight: approximately 5 pounds |
| Tubing | $26 per 48 inches of tubing | Length to be used: approximately 30 inches<br>Inner diameter: 4-10 millimeters |
| Sealing wires | $16 for 5 pieces | Inner diameter: 1.7-6 millimeters |
| Tissue adhesive | $30 | Material: cyanoacrylate<br>Size: 0.7 mL (0.02 oz) |
| Syringe | $7 | Material: Polypropylene<br>Volume 150 mL |

# APPENDIX C

# MATLAB IMAGING PROGRAM

```
for i =1:1
    image_loaded=
 double(rgb2gray(imread(strcat('IM',num2str(i),'.jpg'))));

Ksx=[-1,0,1;   -2, 0, 2;  -1,0,1];
Ksy=[-3,-4,-3;  0, 0, 0;   3,4,3];
AAx=conv2(Ksx, image_loaded);
AAy=conv2(Ksy, image_loaded);
AA=sqrt(AAx.^2 + AAy.^2);
figure;colormap(gray(256));imagesc(AA);xlabel(' Filter
 (x)');ylabel('Filter (y)');title('Filtered Image');

loc = find(AA(330:500,659)>100);
figure
plot(330:500,AA(330:500,659));xlabel('x (mm)');ylabel('y
 (mm)');title('Histogram of Analysis Points');
temp = AA(330:500,659);
upper = find(temp == max(AA(330:500,659)));

lower = loc(length(loc));
distance_of_OD(i) = abs(upper - lower);

end
```

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## BIOGRAPHICAL INFORMATION

Fariha Murshid is graduating with an Honors Bachelor of Science in Biomedical Engineering in May 2019 from The University of Texas at Arlington, with minors in Chemistry and Mathematics.

She has previously worked with Dr. Liping Tang in designing an arm cuff intended to be used to test for vascularization of implanted tissue grafts. She also assisted Dr. Young-tae Kim in his research focusing on the effect of hypoxia on the motility of A549 lung cancer cells. She briefly assisted the Associate Director of Research for Texas A&M's College of Medicine with editing clinical research publications.

Fariha is currently pursuing a Master of Science in Biomedical Engineering from The University of Texas at Arlington. She dreams of one day being able to make a great contribution to the healthcare industry by working at a medical device company.