

CHARACTERIZATION OF ARTERIAL FLOW FOR JUNCTIONAL BLEEDING  
CONTROL

A Thesis

presented to

the Faculty of California Polytechnic State University,  
San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree  
Master of Science in Biomedical Engineering

by

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May 2018

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## ABSTRACT

### Characterization of Arterial Flow for Junctional Bleeding Control

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This study investigated reducing volumetric flowrate under steady flow conditions by varying lengths of compression with constant cross-sectional area and varying cross-sectional area reduction with constant length in order to better understand how to control junctional hemorrhaging. The hypotheses of this study were that length reduction will have little effect on volumetric flowrate and that cross-sectional area reduction would need to be approximately 80 percent in order to obtain bleeding control. The study found that length reduction has little effect on changing the flowrate. However, in order to obtain at least 80 percent reduction in flow, the area needs to be occluded by at least 95 percent. These results may help inform better tourniquet designs by using collapsible tube science.

## ACKNOWLEDGEMENTS

I would like to thank Dr. Griffin being a mentor and guiding me through my thesis. I would also like to thank Dr. Stankus, Dr. Rogers, and Dr. Whitt, on advising me on writing my thesis.

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## **Chapter 1 Introduction**

### **1.1 Establishing the Need to Study Bleeding Control**

Hemorrhage caused from trauma is the second leading cause of death in a military setting [2]. Traumatic injuries frequently occur in the battlefield. Many of these injuries are from improvised explosive devices (IED), which often cause victims to lose a limb. During the seconds after limb lost, it is crucial for medics to control blood loss from the injured patient. In some instances, there is no practical way to attach a tourniquet to control bleeding which can lead to limb loss. Further, an artery may be exposed to the outside making it more difficult to apply a normal tourniquet. Normal tourniquets are designed to be attached to injuries proximal to the site of injury. This allows for the tourniquet to be applied directly to the point of injury.

### **1.2 History of Tourniquet Use**

Tourniquets have been used since the Middle Ages during the battle of Flanders in 1674. It was used as a tight band around the upper and lower site of an amputation to reduce hemorrhaging and pain. There were many variations to the tourniquets including screw compressor, three tight bands, and others.

Modern tourniquets are accepted for use in combat situations. The Joint Theater Trauma System (JTTS) database includes data from Afghanistan and Iraq in 2004 and 2005, and demonstrates a need to improve solutions for controlling extremity hemorrhages [5]. Because of this, tourniquets have been developed and improved in 2005 and 2006 with included training on how to properly operate these devices [5]. Guidelines were developed on proper tourniquet techniques, and the effectiveness depends on the type of injury, the injury location, length of tourniquet use, etc. [5]. Military personnel are now encouraged to use tourniquets in wars in Iraq and Afghanistan [5].

### **1.3 Modern Tourniquet Studies**

Prior to analyzing studies on modern tourniquets, the functionality of a tourniquet will be defined. A tourniquet functions by applying pressure to a desired location circumferentially around a limb. The pressure is transferred to the blood vessel wall to occlude the artery or vein [6]. Modern tourniquets have been essential in assisting with bleeding control and there have been extensive studies for using tourniquets to control hemorrhages at the extremities including combat and civilian situations.

#### **1.3.1 Hemorrhage Control in Combat**

Tourniquets have been proven to be effective in saving lives by preventing hemorrhagic shock while also lowering the chance of morbidity. An observational study by *The Journal of Emergency Medicine* examined data from a military hospital in Iraq to analyze the morbidity and mortality connected to tourniquet use [7]. There were 499 patients in the study group using 862 tourniquets total on 651 limbs [7]. The study averaged 1.4 patients with 2.4 tourniquets per day and 1.3 tourniquets per limb [7]. 635 out of 651 limbs had an indicated medical use of a tourniquet; which is specifically defined as a vessel lesion hemorrhage not helped by pressure dressing or used tactically in battlefield [7]. All patients except one had arterial tourniquets placed. The one exception used a venous tourniquet in the emergency department [7]. Forty percent of this one patient's body was covered in burns. Ten patients, who were undergoing separate treatment from the main group, did not use tourniquets. They died from exsanguination from limb injuries because there was no effective blood control [7]. The 499 patients who used tourniquets had a 87% survival rate [7]. Further analyses indicated patients with tourniquet application prior to shock had a survival rate of 90% (429/476) while patients with applied tourniquet application after the onset of shock had a 18% (4/22) survival rate [7]. Effective tourniquet use has been shown to improve patient outcomes if applied

before the onset of shock [7]; however, these outcomes only apply to tourniquets that are applied distally to the limb [7]. There were limitations in the Kragh and Littrel study that may need to be addressed in further studies. The study contained no details on morbidity and was limited to war casualties [7].

Table 1.1: Classes of Hemorrhagic Shock [1]

| Parameter                                | Class I             | Class II       | Class III            | Class IV               |
|--|---------------------|----------------|----------------------|------------------------|
| blood loss in mL                         | <= 750 mL           | 750 – 1,500 mL | 1,500 – 2,000 mL     | >= 2,000 mL            |
| blood loss as percent total blood volume | <= 15%              | 15 – 30%       | 30 – 40%             | >= 40%                 |
| pulse                                    | > 100               | > 100          | > 120                | >= 140                 |
| blood pressure                           | normal              | normal         | decreased            | decreased              |
| pulse pressure                           | normal or increased | decreased      | decreased            | decreased              |
| capillary refill                         | normal              | delayed        | delayed              | delayed                |
| respirations                             | 14 – 20             | 20 – 30        | 30 – 40              | > 35                   |
| urine output                             | >= 30 mL/h          | 20 – 30 mL/h   | 5 – 10 mL/h          | minimal                |
| mental status                            | slightly anxious    | mildly anxious | anxious and confused | confused and lethargic |

The severity of hemorrhagic shock is defined in four classes with Class I being the least severe to Class IV being the worst [1]. War casualties focus on class 3 and 4 hemorrhagic shock (table 1.1) which constrained the study to a practical, prehospital interpretation “of shock with manual vital signs” [7]. These types of injuries are rare in the civilian community [7]. The study did not account for “injury severity” or head or

torso injuries [7]. In the war setting, people with limited training usually made the decision to use a tourniquet [7].

### **1.3.2 Hemorrhage Control in the Civilian Setting**

According to the Passos and Dingley study, the main cause of death in trauma patients is hemorrhaging [8]. Traditional civilian trauma training has had a negative view on tourniquet use [8]. The preferred treatment is a tight bandage over the wound which is recommended by the Advanced Trauma Life Support; a training program developed by the American College of Surgeons to help clinicians manage acute trauma cases [9]. Sometimes a tight bandage is ineffective in controlling bleeding and is actually more time-consuming to apply; therefore, tourniquets are better. The primary outcome of the study was in-hospital mortality rates. The secondary outcomes included Intensive Care Unit stay, length of stay, units of blood transfusion, amputation, and compartment syndrome (a condition where pressure within muscles builds up to an extreme level) [8]. Data was taken from the hospitals' trauma registry in the span of 10 years with 19,977 patients [8]. 360 of these patients suffered arterial injuries that led to amputation of the limb or revascularization [8]. The experiment "...excluded 101 patients who had thermal injuries, electrical burns, transfer from another province or country, and military patients. We also excluded 69 patients with Abbreviated Injury Score for head and neck, chest, abdomen and pelvis equal or greater than 3" [8]. 186 patients arrived at the emergency room with no tourniquet while four had a prehospital tourniquet applied [8]. The four patients with the prehospital tourniquet survived [8]. This was a very limited sample [8]. There were no significance in transfusion rates in patients with prehospital tourniquets vs without [8].

### **1.4 Tourniquet Limitations**

Both of the Kragh and Passos studies were mutually exclusive and were constrained

to variable definitions with different study limitations. As mentioned earlier in the Kragh wartime study, there was a limited definition class 3 and 4 hemorrhage control defined in table 1.1, which does not translate to the civilian study with no standardized procedure for tourniquet use. The prehospital definition of hemorrhagic shock in the wartime study significantly limited relating it to the civilian study. The civilian study didn't define proper tourniquet use when collecting data which created many variables and removed a lot of assumptions. The combat-related hemorrhaging studies that showed beneficial tourniquet use needs to be applied to civilian prehospital care.

A study by Paul C. Lewis translated the tourniquet procedures used in military settings to benefit civilian prehospital care [10]. During the Iraq and Afghanistan wars, the military redefined the common prehospital care in performing prehospital interventions [10]. This type of care is checking the patient's airway, breathing, and circulation (ABCs) [10]. This type of care is now known as the C-ABC, with the (C-) representing checking for catastrophic hemorrhaging in order to maintain circulating volume [10]. Also, the military adopted a mantra when in doubt, apply tourniquet along with extracting the patient rapidly to an emergency healthcare facility [10]. Evacuation times were typically less than 1 hour [10]. The current view in civilian care is that first responders already have sufficient resources to aid at the site of trauma, and most trauma cases only require one responder per patient [10]. However, this is not true now with the increase in casualties from mass shootings and terrorism. Paramedics need more training and resources at their disposal to handle these situations, which is similar to combat environments [10].

It is important to note that though tourniquets have been extensively studied for extremity hemorrhages, there has not been too much analysis in the control of junctional hemorrhage. Junctional hemorrhaging is defined as blood loss at a location where an extremity and torso meet. Many of the studies had very little data on junctional

hemorrhage control.

### **1.5 Limits of Junctional Bleeding Control**

Many of the studies mentioned prior looked at tourniquets that were not designed to help with catastrophic head, chest, and abdominal injuries which do not have a location for direct pressure [7]. One patient in the [7] study died from a traumatic hemipelvectomy because the injury location was too difficult to compress [7]. The Oostedorp study; which analyzes treatment options for truncal and junctional hemorrhaging, mentions that 90% of potentially preventable deaths were due to hemorrhaging and in a prehospital setting, controlling bloodflow in anatomical sites where the application of a tourniquet is not feasible is still the biggest challenge [2]. Therefore, more research is needed to better understand junctional bleeding control.

### **1.6 Solutions to Junctional Hemorrhaging**

The study looked at 5 anatomically junctional areas which are: 1) axilla, 2) groin and truncal, 3) chest, 4) abdomen, and 5) pelvis [2]. Table 1 summarizes the types of prehospital care options with the pros and cons for each treatment [2]. This study looked at established, innovative, and future prehospital treatment for junctional hemorrhage control to care for trauma patients. The use of junctional tourniquets has increased due to changes in injuries [2]. There are more blast injuries from IEDs [2]. There is an increase in civilian trauma from increased mass shootings, stabbings, and bombings. The need for proper placement of junctional tourniquets and need to improve junctional tourniquet devices has increased [2]. This has been shown during the 2013 Boston Marathon bombing when there was not an effective way to control junctional hemorrhaging [2]. Junctional hemorrhage combat injuries are more common in the military than in civilian

situations, but soldiers are more fit to survive injuries compared to civilians, even though timelines for military rescues are longer than civilian extractions [2]. Emergency services may be similar to a military situation when the patient is located in a rural setting [2]. Early hemorrhage control on scene may prove to be more beneficial than quickly moving and transporting the patient to the nearest facility; even though applying direct pressure may not be feasible [2].

Table 1.2: Classes of tourniquets analyzed in the Oostendorp Study [2]

| Class                               | Adjunct       | Name  | Manufacturer                              | Pro's   | Con's  |
|-------------------------------------|---------------|---|---|---|--|
| Junctional tourniquets              | CRoC™         | Combat Ready Clamp™                         | Combat medical systems. Fayetteville, NC  | Easy. 4 h max   | Dislodgement, heavy, limb ischemia, longer application time than other JT's  |
|                                     | JETT™         | Junctional Emergency Tourniquet Tool™       | North American Rescue Products. Greer, SC | Easy. 4 h max. Stabilizes pelvis  | No reports of clinical use   |
|                                     | SAM-JT™       | SAM Junctional Tourniquet™                  | SAM Medical Products. Wilsonville, OR     | Easy. 4 h max. Stabilizes pelvis  | Little experience  |
|                                     | AAJT™         | Abdominal Aortic and Junctional Tourniquet™ | Compression Works. Hoover, AL             | Axillary, inguinal and truncal application. External compression of the abdominal aorta | Easily broken. Uncomfortable in truncal application. Truncal max 1 h. In penetrating trauma CI for truncal placement |
| Wound clamp                         | iTC™          | iTClamp™                                    | Innovative Trauma Care. San Antonio, TX   | Very easy, any location   | Only superficial seal, hematoma  |
| Haemostatic agent                   | XStat-30™     | XStat-30™                                   | RevMedx. Wilsonville, OR                  | Easy, tailored for deep penetrating wounds  | Only junctional, removal of sponges  |
| REBOA                               | 9-14 Fr       | Coda™ Balloon Catheter                      | Cook Medical, Indianapolis, IN            | Proximal control, raises central aortic pressure  | Invasive, requires physician, risk at (spinal) ischemia, challenging, time consuming                                 |
|                                     | 7 Fr          | ER-REBOA™                                   | Pryor Medical. Arvada, CO                 |   |  |
| Intra-abdominal gas insufflation    | -             | -   | -   | Minor invasive. Less risk at pressure necrosis than foam.                               | Abdominal compartment syndrome, risk of air embolisms, experimental  |
| Intra-abdominal self-expanding foam | ResQFoam™     | ResQFoam™                                   | Arsenal Medical. Waterland, MA            | Tamponade of abdominal compartment, less invasive than RT/REBOA, no physician required  | Pressure necrosis, abdominal compartment syndrome, needs surgical removal, experimental                              |
| Pelvic stabilizer                   | T-POD™        | Trauma Pelvic Orthotic Device™              | Pyng Medical. Richmond, Canada            | Easy applicable, wide experience, enables REBOA/AAJT                                    | Insufficient if origin of haemorrhage is arterial  |
|                                     | SAM-sling™    | SAM-sling™                                  | SAM Medical Products. Wilsonville, OR     |   |  |
|                                     | PelvicBinder™ | PelvicBinder™                               | PelvicBinder Inc. Dallas, TX              |   |  |
| Pelvic Sheet                        | -             | -   | -   | Low cost, widely available  | Inadequate application, dislodgement   |
| Resuscitative Thoracotomy           | -             | -   | -   | Very proximal control, raises central aortic pressure.                                  | Invasive, risk at infection, requires physician  |



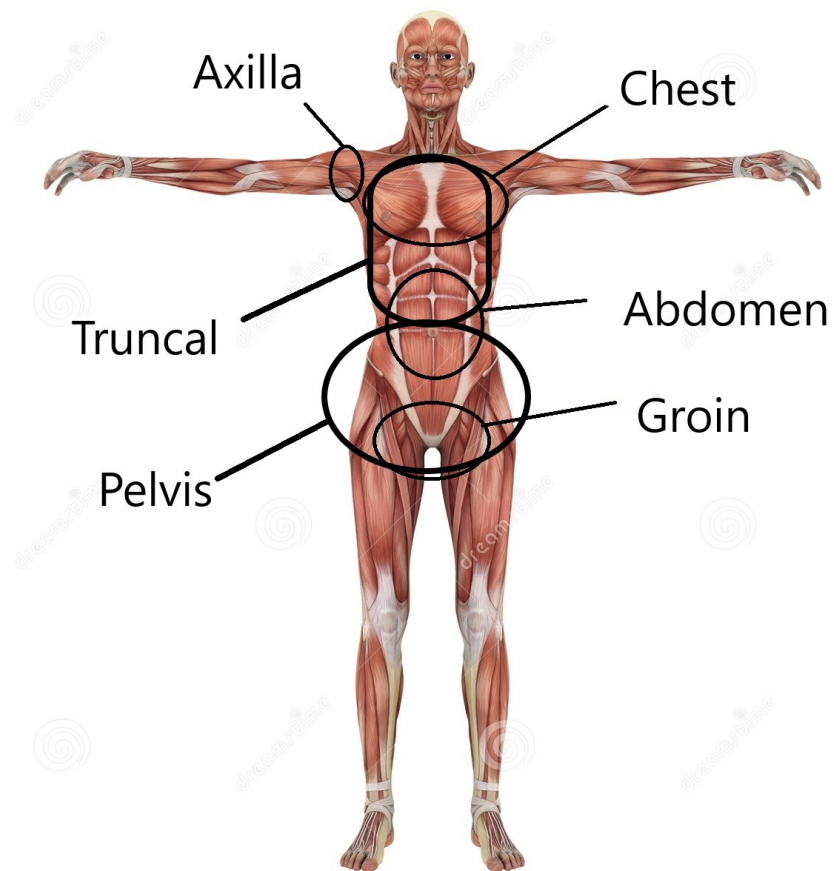


Figure 1.1: Junctional Areas [3]

Correctly applying early hemorrhage control has been proven to be effective in bleeding control [2]. On average when 44 clinicians had to provide bimanual compression (compressing artery inside and outside of body), the mean pressure applied was 39 kg

while the amount to occlude flow in the iliac and abdominal aortic artery required pressures of 54 kg and 63 kg respectively [2]. Effective military intervention was also shown to be beneficial in a civilian setting [2].

### 1.6.1 SAM-Junctional Tourniquet

It would be highly effective in saving lives if the majority of military and civilians used the SAM-Junctional Tourniquet [11]. The SAM Junctional Tourniquet(SAMJT) has been the preferred junctional tourniquet for US armed forces medics [2]. It is a device that can be inflated by a hand pump to apply pressure to inguinal or axilla areas to control hemorrhaging [11].



Figure 1.2: SAM Junctional Tourniquet



Figure 1.3: Combat Ready Clamp

The SAMJT is put on like a belt [11] and allows for 4 hours of hemorrhage control [11]. A Kragh study compared the SAM Junctional Tourniquet (SJT) with other models [12]. The tourniquets were placed on 10 subjects for 60 seconds [12]. Distal lower extremity pulse, heart rate, and systolic and diastolic blood pressure were checked during the experiment [12]. Pulse absence for SJT was shown to be effective 93% during first 15 seconds as compared to 77% at the last 15 seconds of 60 second experiment [12]. The absence of pulse was the factor for hemorrhage control [12].

A common method to assess SAM-JT bleeding control success is through Doppler flow studies [13]. Researchers use measure sound waves through ultrasound to determine blood pressure through vessels [13]. Bleeding control validation is determined at the time when the ultrasound cannot read blood pressure in the vessel [13]. This is not a quantitative method to measure the success for bleeding control. Therefore, there can be improvements to the design and testing of tourniquets, leading to better hemorrhage

control.

### **1.6.2 Comparison of SAM-JT to Combat Ready Clamp**

A study compared two popular tourniquets; SAM-Junctional Tourniquet and Combat Ready Clamp (CRoC), for controlling junctional bleeding for trauma care outside the hospital [14] and in military combat. The CRoC is the first junctional hemorrhaging control tourniquet device recommended by the Committee on Tactical Combat Casualty Care [15]. It is a lightweight, collapsible device that can stop junctional hemorrhaging in under a minute [15]. It is used to clamp on a patient lying down while the SAM-JT can be placed as a belt.

The outcomes for the study were the full disruption of popliteal (back of the knee) arterial flow, time to effectiveness, and data collected from a subjective questionnaire [14]. In healthy volunteers, both tourniquets were around 90% effective in controlling arterial flow [14]. Results from this experiment show that current tourniquets are effective at junctional bleeding control [14]. There is also need for improvements. The SAM Junctional Tourniquet is only 1.356 lbs while the CRoC is 1.45 lbs [15, 16]. Based on personal observation, the SAM-JT is easier to use with a bulb as shown in figure 1.2 instead of a screw used in a CRoC as shown in figure 1.3.

### **1.7 Science of Flow Through Collapsible Tubes**

The current study will further analyze bloodflow to improve bleeding control through tourniquet use. When looking at flow through blood vessels, vessels are collapsible tubes under pressure. This collapsible tube phenomenon is seen in many biomedical applications including in cardiac aortic and venous valves, pulsatile flow through an artery, and “wheezing from forced expiration” [17]. All vessels inside the body have a higher internal pressure than outer pressure, also known as positive transmural pressure [17].

$$P_{Transmural} = P_{Inner} - P_{Outer} \quad (1.1)$$

When the internal pressure is below external, the tube buckles and changes shape, also known as collapsing [17]. As transmural pressure reaches zero, the tube becomes extremely compliant and the cross-sectional tube area changes [17]. This phenomenon can happen in the body [17]. In the cardiovascular system, arteries are usually sufficiently pressured and do not collapse [17]. Vessels collapse when they are actively squeezed [17]. Many studies on transmural pressure analyzed the pressure of a vessel with respect to the area reduction [17]. The relationship is shown in figure 1.4.

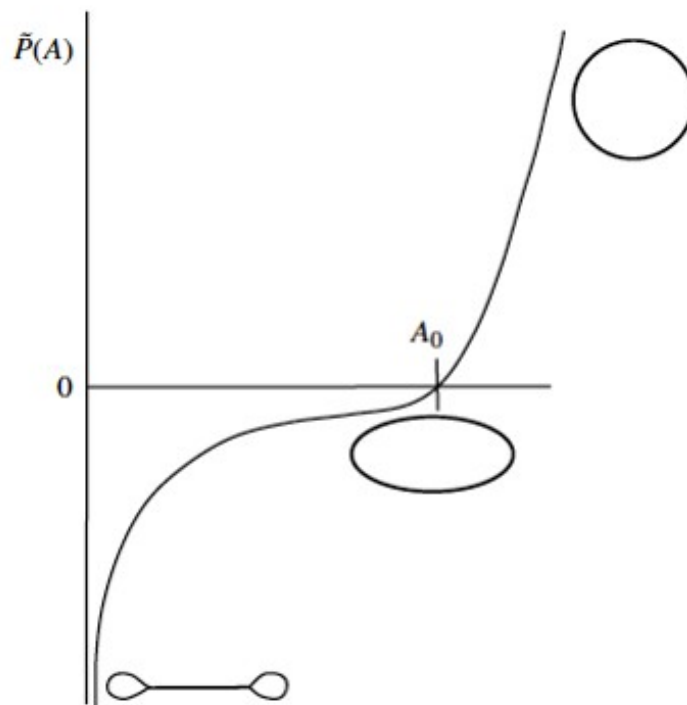


Figure 1.4: Pressure of a vessel as a function of area reduction [4]

The current experiment will analyze volumetric flowrate as a function of area reduction. In conclusion, transmural pressure is defined to help understand collapsible tubing phenomenon, which is a large portion of the current experiment.

## **1.8 Computational Methods**

Computer simulations using finite element analysis commonly use fluid-structure interactions (FSI) to combine the theory of elasticity with Navier-Stokes [18]. This provides the architectural frame work to combine the interaction between a dynamic fluid and a solid structure [18]. There are two common approaches to creating a fluid-structure interaction for thin-walled vessels; monolithic and partitioned [18]. A configured FSI solver, e.g. COM- SOL, uses a system of equations for the solid and fluid domains [18]. This is known as the partitioned approach [18]. There are limitations to this approach including a demanding computer power for large systems of equations and a “need for further development of preconditioning [18].” The advantages for the partitioned approach is that there are modules for selecting the “appropriate solver among the well-established solvers for each of the domains [18].”

A negative aspect to the portioned approach is that it has an “added-mass instability”, which includes “problems involving large deformation and lightweight structure” [18]. This may cause the solution to divergence and lead to a failed computation model [18]. A solution to this problem includes” coupling relaxation factors of interface loads” to maintain stability, although this solution will increase computational time [18]. To reduce computational time, COMSOL uses adaptive relaxation techniques to take information from earlier iterations to get stability [18].

## Chapter 2 Objectives

The goal of this thesis is to characterize steady fluid flow in collapsible tubes with a view towards understanding how to control bleeding. While the science of flow in collapsible tubes has been extensively studied, the application to controlling bleeding through the use of tourniquets represents a knowledge gap. For example, it is not well-known how much the artery needs to be compressed to control bleeding or whether a longer length of compression is better than a shorter length. While tourniquets work very well if there is a limb extremity available proximal to the wound, if the extremity has been traumatically amputated or the wound is in a junctional area, there is no convenient attachment point for a tourniquet. The information gained from this thesis may be useful to improve the design of devices that can be used to control bleeding in areas where a conventional tourniquet cannot be applied.

*Hypothesis 1. Compressing the tube over a longer length will provide greater reduction in flow for the same cross-sectional area reduction.*

*Hypothesis 2. A collapsible tube will need to be compressed at least 80% of its original cross-sectional area to gain bleeding control.*

Experiments will be conducted under steady-flow conditions. The first set of experiments will be conducted using a constant area reduction and varying the length of the obstruction. The second set of experiments will be conducted by controlling the reduction in cross-sectional area for a constant length. A computational fluid structure interaction model will be developed and the results of the experiments will be used as a validation.

## **Chapter 3 Materials & Methods**

The experiment will analyze flowrate of collapsible tubes under pressure. It will start with the initial setup which includes the material for the collapsible tubing and the materials used in the experimental setup and the collapsible tubing setup, along with data collection, and statistical analysis.

### **3.1 Experimental Setup**

A 1 cm specialized silicone tubing with material properties similar to an artery was used to represent the collapsible tube. The experimental setup used 1) a reservoir, 2) tubing, 3) a shutoff valve, 4) connections (Hose Barbs, 5) the collapsible tube (1 cm ID x 15.3 cm), 6) a collection beaker, and 7) a scale as shown in figure 3.1 and figure 3.2. A bucket is used as a reservoir for the fluid source. Tubing was used to allow the height to create static pressure at the outlet, the shutoff valve stopped the flow of fluid between experiments, and the collapsible tube represented the artery.



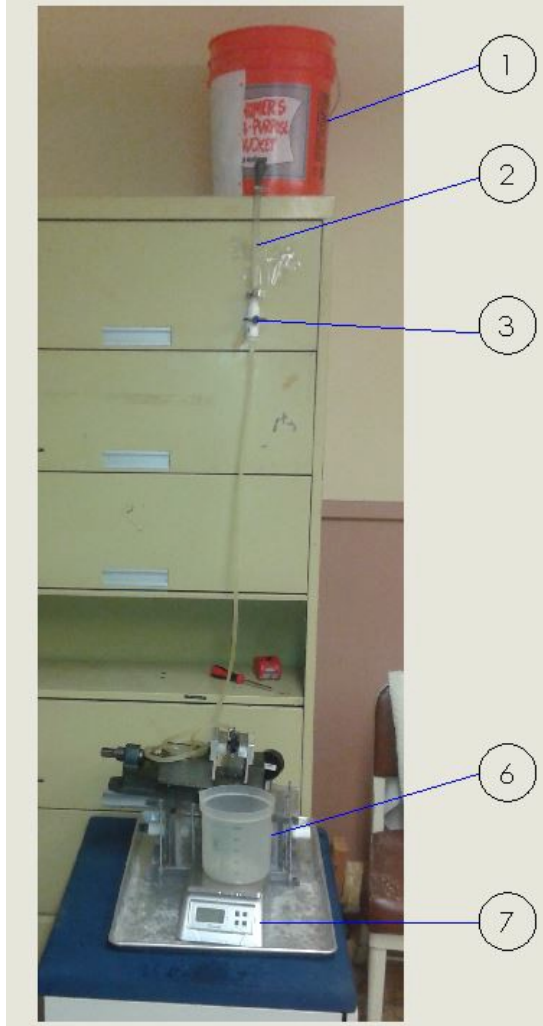


Figure 3.1: Experimental Setup

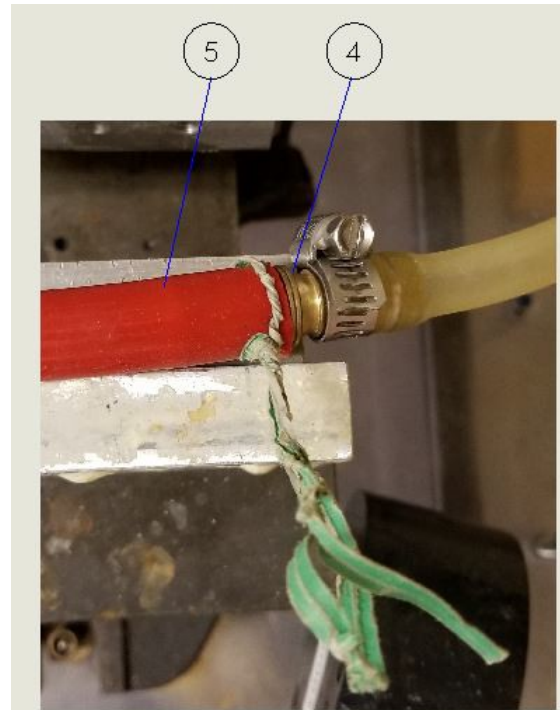


Figure 3.2: Connection for Collapsible Tubing

### 3.2 Bernoulli's Equation

In order to mimic arterial flow through a collapsible tube, the fluid pressure had to have the same outflow pressure as average arterial pressure, which is around 110 mmHg. A method to utilize the effect of fluid height on outflow pressure is Bernoulli's Principal. This hydrodynamic principal dictates that for fluids in an ideal state, the density of a fluid is inversely proportional to the pressure [19]. Therefore the fluid velocity decreases as the height increases. Bernoulli equation, a derivation of the continuity equation in fluid mechanics, represents the energy balance between pressure, height, and velocity [19]. The Bernoulli equation is:

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^2 + \rho g h_2 \quad (3.1)$$

The variables P,  $\rho$ , V, g, and h represent pressure, fluid density, fluid velocity, gravity, and height as respectively. In equation 3.1, state 1 was considered the reservoir and state 2 the inlet to the vessel. The assumptions for this experiment are that the bucket is considered to be a large reservoir and open to the atmosphere which removes the initial dynamic energy and pressure respectively. The height  $h_2$  is considered the datum, and the outflow was assumed to be a laminar, steady, and fully developed flow to simplify measurements. The equation can be simplified for the current experiment by assuming initial fluid velocity and pressure are negligible. Based on the assumptions, the simplified Bernoulli equation shows the total pressure as a function of static and dynamic pressure assuming no energy losses:

$$P_2 = \frac{1}{2}\rho V_2^2 - \rho g h_1 \quad (3.2)$$

Using a final pressure, density, and gravity at 110 mmHg,  $1000\text{kg}/\text{m}^3$ , and  $9.81\text{m}/\text{s}^2$  respectively, the initial height,  $h_1$  is determined to be approximately 4.888 ft. This value was used to determine sufficient height for the fluid reservoir to provide enough

fluid pressure of 120 mmHg out of the inlet as shown in figure 3.3.

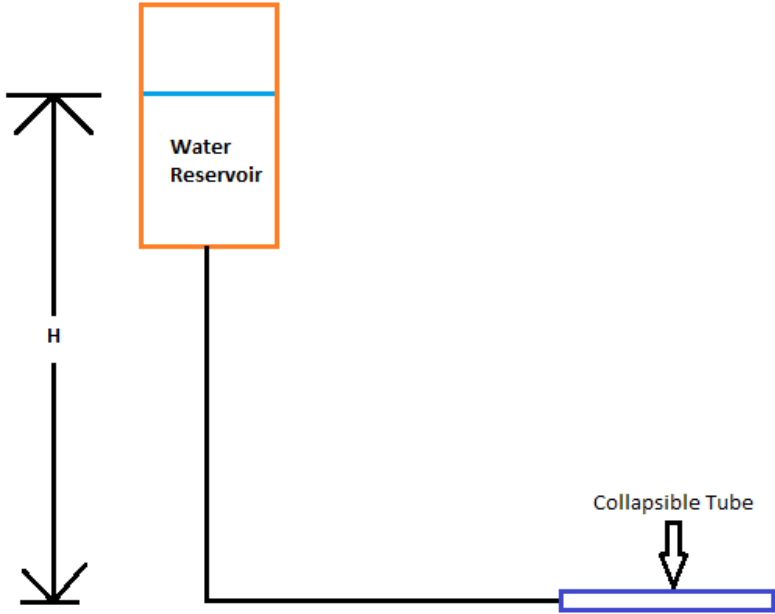


Figure 3.3: Height determination of fluid reservoir

### 3.3 Collapsible Tubing Setup

#### 3.3.1 3D Printed Compression Boxes

Compression boxes (CB) were created using the computer-aided design software Solidworks and a 3D printer. In experiment 1, these CB's had varying lengths at 5, 10, 15, 20 and 30 mm with a constant height and width of 5 mm. In the second experiment, the boxes had a constant length and height of 10 mm with a changing width of 5, 6, 7, 8, and 10 mm. Figure 3.4 represents the box design.

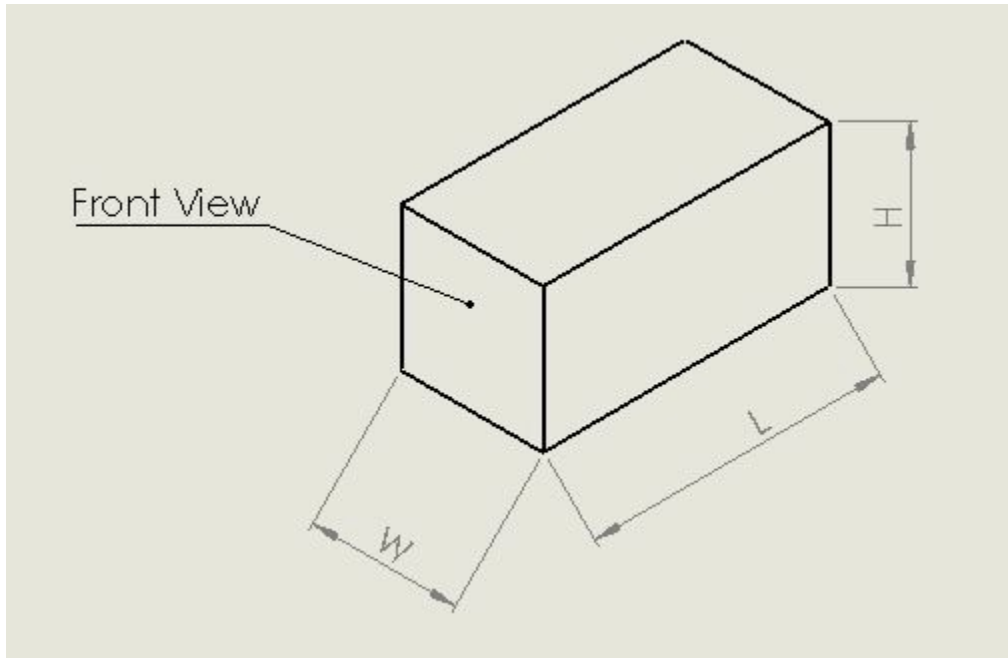


Figure 3.4: Sample Compression Box Design

Both experiments required 2 copies of each box. Edges on the boxes were filed down to prevent puncturing the tubing. The boxes were glued to a plastic piece to allow for an easier application during the experiment. The boxes were also taped together for easier application during testing. The final design is shown in figure 3.5.

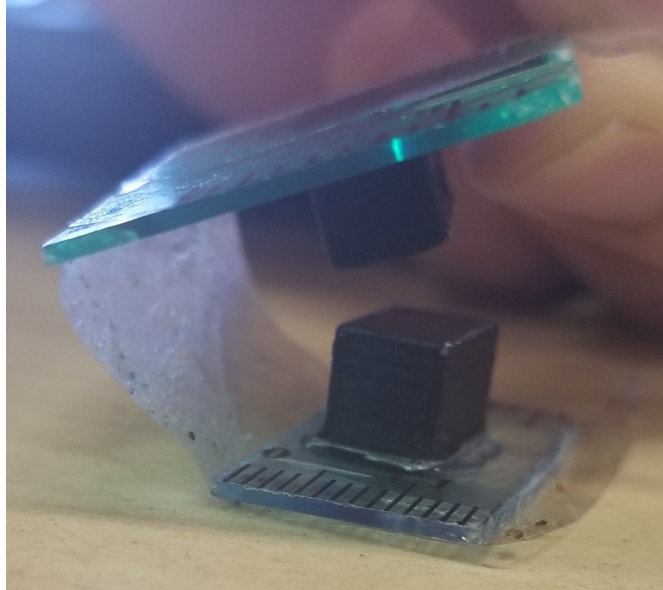


Figure 3.5: Final design for compression boxes

### 3.4 Experimental Procedures and Data Collection

#### 3.4.1 Experiment 1 - Length Effect

Experiment 1 analyzed the effects on length reduction volumetric flow rate on a collapsible tube. The factor in this experiment was compression box length. The 5, 10, 15, 20, and 30mm length samples were placed in a vice and the tubing was clamped onto the boxes as shown in figure 3.6. The experiment was repeated at least 10 times.

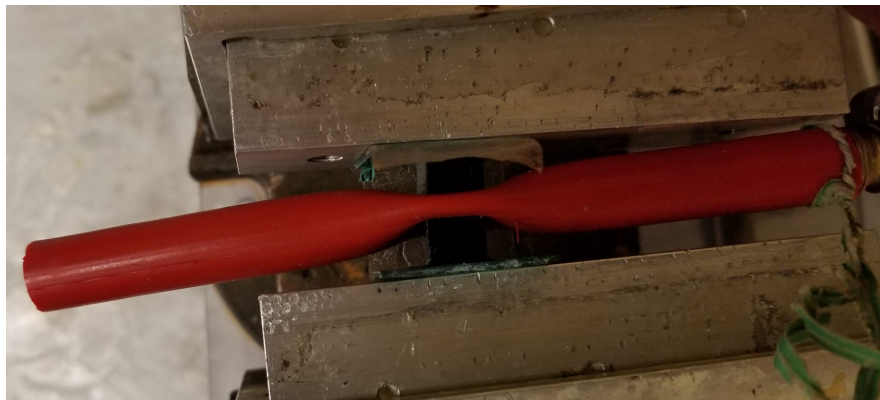


Figure 3.6: Top of Tubing including the applied pressure of the compression boxes

The nominal time to collect to 1 liter of fluid was measured. Both collected mass and time

were recorded and the experiment was reset for each trial. The final mass and fill time were recorded, and the volumetric flow rate was calculated using mass of liquid collected/time.

### **3.4.2 Experiment 2 - Area Reduction**

Experiment 2 was performed similarly to the first, except with the CB having varying widths of 5, 6, 7, 8, and 10mm and constant length and height of 10mm. The final mass and fill time were recorded, and the volumetric flow rate was calculated as described in experiment 1.

## **3.5 Area Reduction Measurement**

The cross-sectional area reduction was digitally measured using photos of the reduced area and an image program, ImageJ. ImageJ is a Java program developed by the National Institutes of Health to process and analyze image using user-defined length statistics[20]. The user can define a known length and the program will match that length to the amount of pixels giving a measured length per pixel.

### **3.5.1 ImageJ Calibration**

In figure 3.7, a picture was taken of the collapsed cross-sectional area tubing and a ruler to provide a reference length. A known distance was measured using the straight line draw setting on ImageJ and the ruler in the picture. It gives a reference measurement based on pixels/unit length. The scale is shown in the picture below at 221.34 pixels/cm.

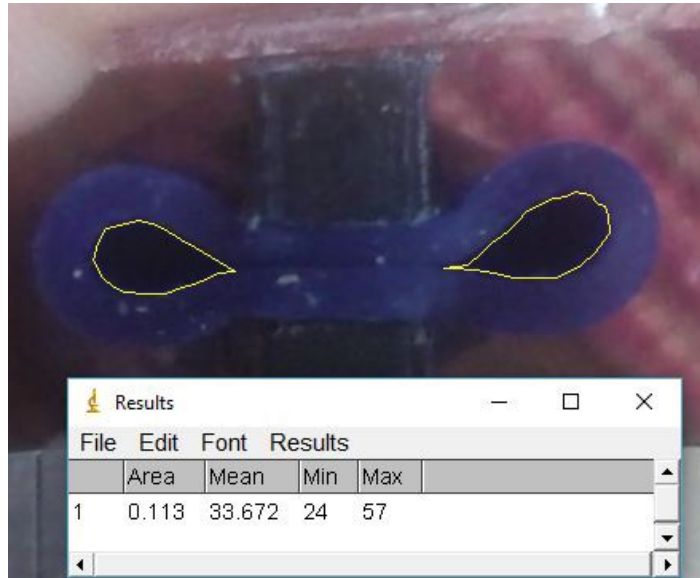
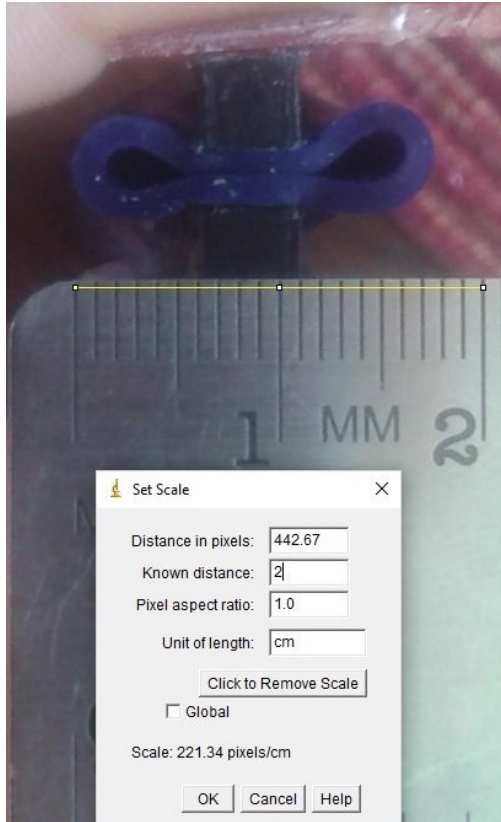


Figure 3.7: ImageJ Calibration      Figure 3.8: Area Measurement

### 3.5.2 Cross-Sectional Area Measurement

Since ImageJ is calibrated to the image, an outline of the open enclosures was taken using the polygon option in ImageJ and the measurement tool was used to calculate the diameter. This is in Figure 3.8 showing the measurement for both enclosures. The second hole is also measured and the two areas are combined to get the final occluded area. The resultant area was compared to the calculated area of 1 cm diameter tube to determine the amount opening and then subtracted from 100 to determine the percentage of area reduction.

## 3.6 Computational Model

A fluid-structure interaction model in COMSOL was used to get volumetric flowrate data for comparing to the experiment data. As shown in figure 3.9, the CB are represented as a cylinder in the computation model. The cylinder length is changed at

5mm, 10mm, 15mm, 20mm, and 30mm and the cylinder radius is changed at 5mm, 6mm, 7mm, 8mm, and 10mm for experiment 1 and experiment 2 respectively.

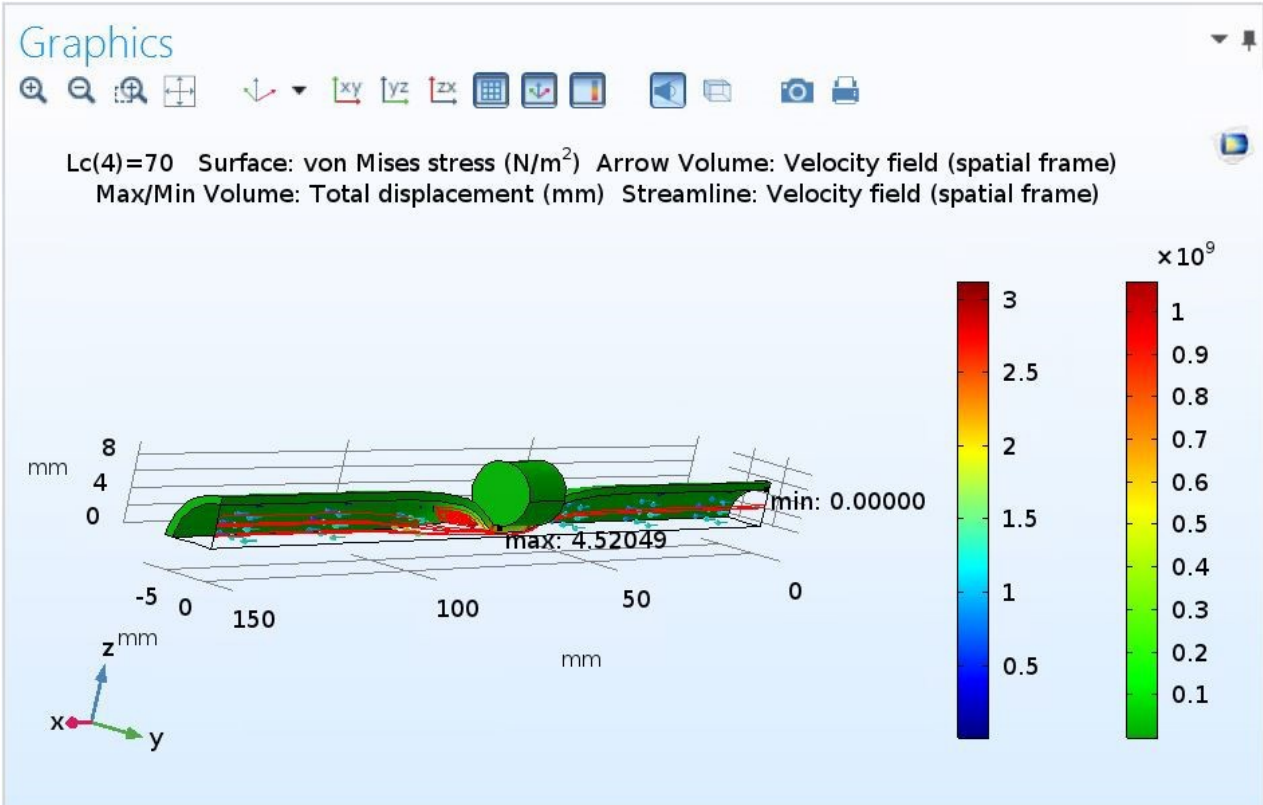


Figure 3.9: COMSOL Model

### 3.7 Statistical Analysis

A one-way ANOVA with an assumption of unequal variances was used to determine significant differences between the varying obstructions and a control for both experiments. Games-Howell Pairwise Comparisons were used to find associations between different samples for a small sample size in both experiments.

### 3.8 Minimizing Errors

In order to prevent repeatable errors by getting similar flow rates, the experiment was adjusted each time to prevent repeatable errors. The boxes were taken out of the



placement location and put back into the vice to collect another sample. Careful consideration was taken to make sure the obstruction was placed in the middle of the tubing to get equal openings on both ends of the tubing. If the placement of the boxes was off, it would change the flow from laminar to turbulent flow affecting the outlet flow rate.

## Chapter 4 Results

### 4.1 Effects of Obstruction Length on Volumetric Flowrate

As shown in figure 2a, the general pattern for length reduction showed a significant drop in the open case compared to the occluded group. In appendix B, there were no significant differences between the 5mm length compared to any other obstruction length ( $p < 0.05$ ). Note that the computational model made in COMSOL shows a similar trend to the data in figure 2a. There were no statistically significant flowrate reductions between any length and the 5 mm control. However, there was a statistically significant decrease in flowrate of 4.53 percent between 30mm and 10mm ( $p=0.007$ ). As shown in appendix C, the ANOVA results showed that the mean flowrate of the obstruction lengths are all significantly different compared to the open case.

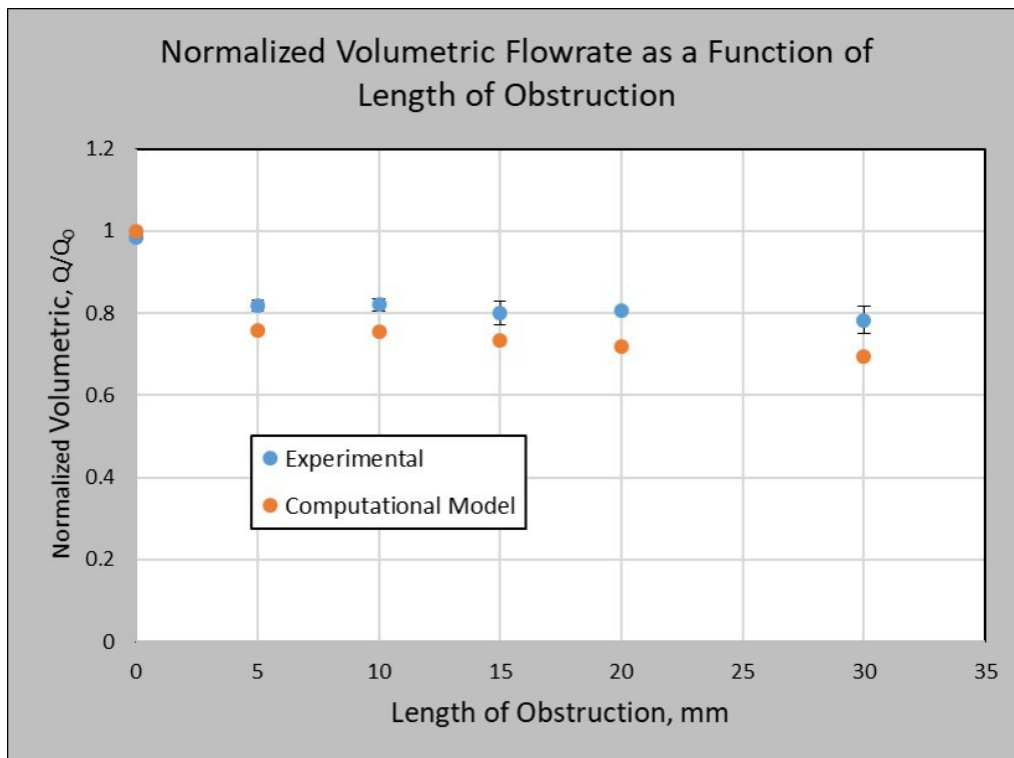


Figure 4.1: Experimental Pattern vs Computational Data

## 4.2 Effects of Area Reduction on Volumetric Flowrate

As shown in figure 4.2, the flowrate dropped significantly for the occluded groups as compared to the open case. The flowrate started to drop significantly around 95-98% area reduction. In appendix D, there was a significant difference ( $p=0.000$ ) in mean volumetric flowrate between the samples and control. The computational model in COMSOL showed a similar trend to the experimental data, but volumetric flowrate was significantly slower in the computer model as compared to the experiment.

Table 4.1: Area Reduction to box length

| Compression Box Width (mm) | % Area Reduction |
|----------------------------|------------------|
| 0                          | 0.0%             |
| 5                          | 84.2%            |
| 6                          | 85.9%            |
| 7                          | 90.7%            |
| 8                          | 93.1%            |
| 10                         | 93.3%            |

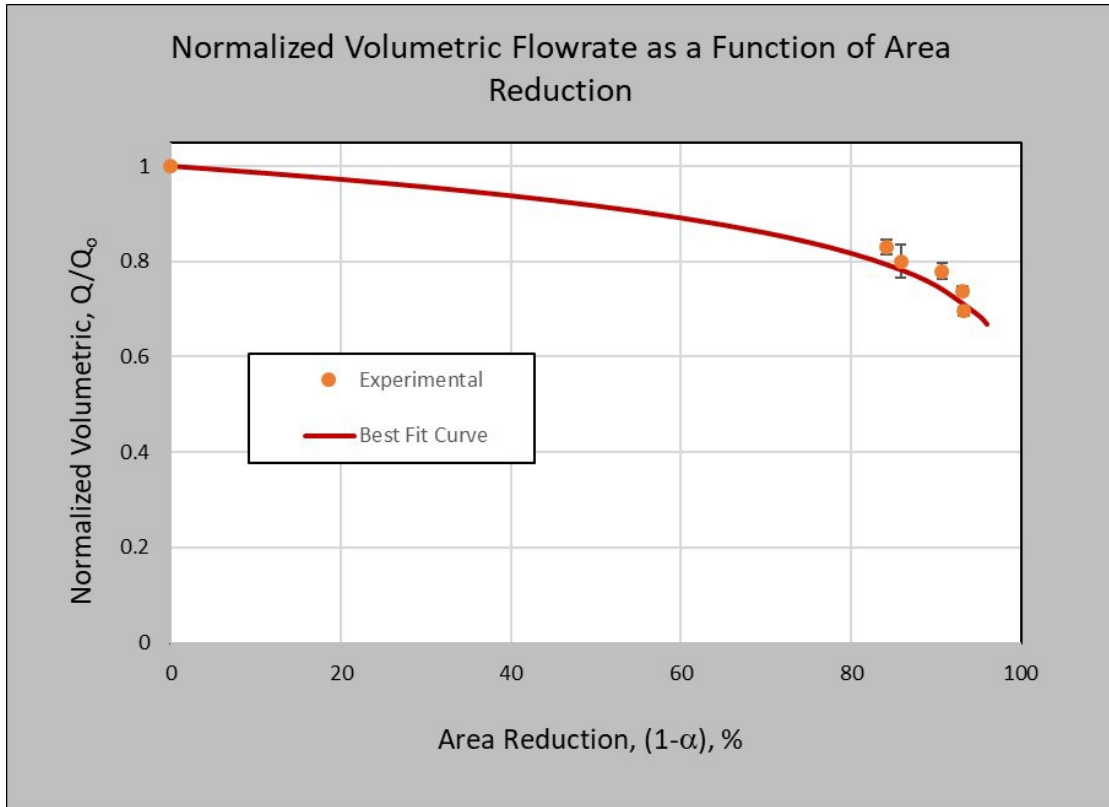


Figure 4.2: Area Reduction

## **Chapter 5 Discussion**

While hemorrhaging occurring from extremity injuries have been extensively studied, there is a lack of knowledge for junctional site hemorrhages or hemorrhaging at locations with an inconvenient attachment point for a tourniquet. Most tourniquets have been shown to be beneficial for injuries proximal to the wound at the extremities; however the benefit is not well known for junctional hemorrhaging. Flow through collapsible tubes has been extensively researched but the application to bleeding control has not. It is not well known how much the length of an artery needs to be compressed or the relationship between cross-sectional area and flow rate reduction. This study examined the effect of length reduction and area reduction on flowrate. It was hypothesized that an area reduction of 80% will cause the collapsible tube to slow for bleeding control and longer length reduction will improve reduction in flow.

### **5.1 Experiment 1 - Length Effect**

The hypothesis was that compressing the tube over a longer length will provide greater reduction in flow for the same cross-sectional area reduction. The experiment showed that increasing length does not have a statistically significant effect on volumetric flowrate. It was observed that the 10mm length was different from the 30mm. However, since the control was 5mm, the length effect was not significant. Error rate for comparison using  $p=0.05$  with a confidence interval of 95% removes any significance in the experiment. The variances in volumetric flowrate increased as the length as the length of obstruction increased due to experimental setup errors. It was difficult to repeat similar results because it was harder putting the boxes in the exact place for each sample test. The enclosure was not in the same spot along the tubing for each of the experiments. The difficulty of placing the boxes in the same spot effected results by switching between laminar and turbulent flow. The changing flow characteristics either

increased or decreased volumetric flowrate.

The computational model followed a similar trend to the experiment with a slow drop in flowrate as the obstruction length increased. The COMSOL model followed similar conditions as the experiment by assuming the inlet pressure of the collapsible tubing used Bernolli's Principal. The COMSOL model had different flow rates than the experiments due to differences in the model from the experiments. However, when normalized to the open flowrate, the trends were good.

Current tourniquets (eg. Abdominal Aortic & Junctional Tourniquet or AAJT) are designed with larger cuffs. The benefit is not necessarily due to a length effect on flowrate. Larger areas of applied pressure helps reduce the amount of pressure needed to compress the vessel using a hand bulb. This is based on the relationship that pressure is the force over area. As the cuff length gets shorter, more force is required to apply the same pressure to the vessel. On AAJT tourniquets, between 230-300 mmHg is the optimal pressure required to compress the vessel [21]. Therefore, designing the length of compression on a tourniquet is vital in applying the correct pressure.

## **5.2 Experiment 2 - Area Reduction**

The hypothesis was that the collapsible tube will need to be compressed at least 80% of its original cross-sectional area to gain bleeding control. This is a common view in the medical community that the flowrate can be controlled with an 80% reduction in area. This experiment shows that in order to obtain bleeding control; which is basically 80% reduction in flow rate, is accomplished by an area reduction of more than 90% which was higher than expected. Flowrate reduction was commonly viewed as a linear relationship, but it actually is more non-linear.

A reason for this may be because of the relationship between flow and resistance, known as Poisuelle's equation, which relates flowrate to change in pressure over resistance.

As shown in equation the flowrate is inversely proportional to the viscosity, therefore if the viscosity is higher, the flowrate decreases. The viscosity of blood is higher than water since it contains red blood cells, whiteblood cells, and platelets. Therefore, the flowrate may more closely match expected results with a fluid more similar to blood.

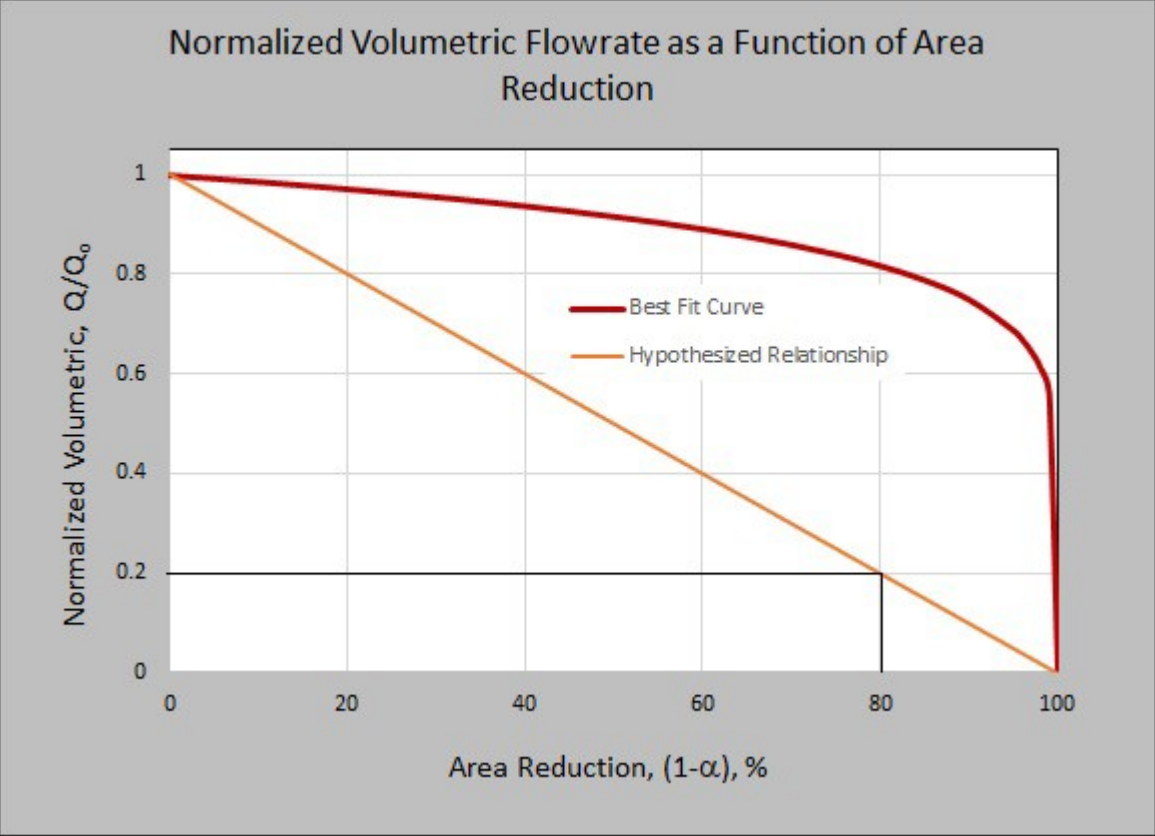


Figure 5.1: Flow Pressure Relationship

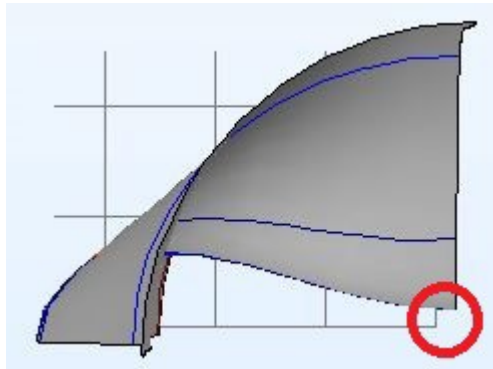


Figure 5.2: Gap Limitation in COMSOL Model

The computational model followed a similar pattern to the experiment, but the flowrate was higher in the computational model. There were limitations in the computational model that have led to higher flowrates than expected. The collapsed portion of tubing in the COMSOL model does not exactly follow the experiment where both sides of the tubing come into contact as pressure is applied. The collapsible tubing in COMSOL has a small gap as circled in figure 5.2. Two surfaces do not touch in COMSOL, leaving a gap for fluid to flow through the tubing. This leads to a discrepancy between the area flowrate relationship between the model and experiment.

The CAD model had different material properties than the artery while the experimental model was custom made to mimic structural properties of an artery. Structural properties closer to an artery in the CAD model may produce a similar compliance on the tubing under pressure as the experiment.



## Chapter 6 Further Research

Modeling arterial pressure using water is not the best method due to the fact that blood is a Non-Newtonian fluid. Non-Newtonian fluids do not follow the linear pattern for their shear stress/strain relationship that water does. Blood is an example of a shear thinning fluid where the viscosity of blood drops as the shear rate increases [22]. An improved experiment would match the shear-thinning characteristics of blood. The experiment and CAD model assumed the fluid flowing through the tube was water. Further experiments will more closely model arterial bleeding by using a fluid as similar to blood. Future experiments will add complexity to the current experiment by taking into account pulsatility. The heart muscle beats at a rhythm and contains a systolic and diastolic pressure. The systolic pressure is when the heart muscle contracts and diastolic pressure is when the heart relaxes. This affects changing outflow pressure at junctional bleeding sites and is not represented in the current model. Finally, a combination of pulsatility and viscosity can be in the experiment.

### 6.1 Collateral Flow

Arteries at junctions contain multiple conduits blood can flow through. Junctional hemorrhages may contain multiple exposed arteries/veins and would require mechanical pressure on each artery. The amount of mechanical pressure is unknown for control bleeding from multiple arteries. There may be too little pressure on the artery to control bleeding or too much pressure could cause a backpressure which will increase the amount of pressure required on the other artery. It is a balance of pressures between multiple arteries in collateral blood hemorrhaging. Future research can be performed to analyze the effect of collateral flow on an artery. Collateral flow is defined as the circulation of blood through smaller vessels when an adjacent major artery is obstructed [23].

## Chapter 7 Conclusion

In conclusion, a better understanding of junctional hemorrhaging is important for preventing patient mortality and morbidity in trauma situations. There is no quantitative analysis on performance metrics on successful bleeding control using junctional tourniquets. Junctional tourniquets could be improved, and there may be situations with inconvenient tourniquet placement, e.g. hemipelvectomy.

The current experiment analyzed the length effect and area reduction of different shaped boxes on collapsible tubes. Applying longer lengths of pressure with a constant cross-sectional area on a collapsible tube was found to not effect volumetric while applying longer cross-sectional lengths did effect volumetric flowrate. Future experiments can apply pulsatility and a viscosity closer to blood in the experiment. Also, there can be experiments analyzing collateral flow and junctional bleeding control. In final, a better understanding of bleeding control may be applied to other applications. This includes reducing flow, specifically the aortic artery during surgery, reducing or blocking flow to cancer cells, or controlling blood flow rate through an artificial pancreas in controlling insulin secretion.

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## Appendix A: Length Affect Experimental Values

Table 1: Length Effect on Volumetric Flowrate DOE

| Length Reduction<br>(mm) | Normalized Volumetric Flowrate |       |       |       |       |       |       |       |       |       |         |
|--------------------------|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
|                          | 1                              | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | Average |
| 0                        | 0.996                          | 0.978 | 1.000 | 0.980 | 0.979 | 0.990 | 0.974 | 0.989 | 0.980 | 0.982 | 0.985   |
| 5                        | 0.827                          | 0.813 | 0.837 | 0.819 | 0.804 | 0.807 | 0.804 | 0.838 | 0.806 | 0.825 | 0.818   |
| 15                       | 0.752                          | 0.767 | 0.818 | 0.802 | 0.854 | 0.810 | 0.810 | 0.806 | 0.783 | 0.792 | 0.799   |
| 20                       | 0.809                          | 0.799 | 0.807 | 0.805 | 0.810 | 0.801 | 0.809 | 0.801 | 0.806 | 0.810 | 0.806   |
| 30                       | 0.722                          | 0.755 | 0.749 | 0.816 | 0.794 | 0.779 | 0.778 | 0.806 | 0.808 | 0.824 | 0.783   |

## Appendix B: Length Affect Statistical Analysis

### One-way ANOVA: Normalized Volumetric Flowrate ... Reduction (mm)

#### Method

|                        |                         |
|------------------------|-------------------------|
| Null hypothesis        | All means are equal     |
| Alternative hypothesis | Not all means are equal |
| Significance level     | $\alpha = 0.05$         |

*Equal variances were not assumed for the analysis.*

#### Factor Information

| Factor                | Levels | Values            |
|-----------------------|--------|-------------------|
| Length Reduction (mm) | 5      | 5, 10, 15, 20, 30 |

#### Welch's Test

| Source                | DF  |         | F-Value | P-Value |
|-----------------------|-----|---------|---------|---------|
|                       | Num | DF Den  |         |         |
| Length Reduction (mm) | 4   | 19.8185 | 4.49    | 0.010   |

#### Model Summary

| R-sq   | R-sq(adj) | R-sq(pred) |
|--------|-----------|------------|
| 29.94% | 23.85%    | 13.76%     |

#### Means

| Length Reduction (mm) | N  | Mean    | StDev   | 95% CI             |
|-----------------------|----|---------|---------|--------------------|
| 5                     | 10 | 0.81806 | 0.01328 | (0.80856, 0.82756) |
| 10                    | 11 | 0.82019 | 0.01803 | (0.80808, 0.83230) |
| 15                    | 10 | 0.79938 | 0.02817 | (0.77923, 0.81953) |
| 20                    | 10 | 0.80576 | 0.00403 | (0.80288, 0.80865) |
| 30                    | 10 | 0.7830  | 0.0330  | (0.7595, 0.8066)   |

### Games-Howell Pairwise Comparisons

#### Grouping Information Using the Games-Howell Method and 95% Confidence

| Length Reduction (mm) | N  | Mean    | Grouping |
|-----------------------|----|---------|----------|
| 10                    | 11 | 0.82019 | A        |
| 5                     | 10 | 0.81806 | A B      |
| 20                    | 10 | 0.80576 | A B      |
| 15                    | 10 | 0.79938 | A B      |
| 30                    | 10 | 0.7830  | B        |

*Means that do not share a letter are significantly different.*

#### Interval Plot of Normalized Volumetric Flowrate vs Length Reduction (mm)

#### Residual Plots for Normalized Volumetric Flowrate

## Appendix C: Statistical Comparison 10&30 mm Length Effects

### One-way ANOVA: Normalized Volumetric Flowrate ... Reduction (mm)

#### Method

|                        |                         |
|------------------------|-------------------------|
| Null hypothesis        | All means are equal     |
| Alternative hypothesis | Not all means are equal |
| Significance level     | $\alpha = 0.05$         |

*Equal variances were not assumed for the analysis.*

#### Factor Information

| Factor                | Levels | Values |
|-----------------------|--------|--------|
| Length Reduction (mm) | 2      | 10, 30 |

#### Welch's Test

| Source                | DF  |         | F-Value | P-Value |
|-----------------------|-----|---------|---------|---------|
|                       | Num | DF Den  |         |         |
| Length Reduction (mm) | 1   | 13.6471 | 9.97    | 0.007   |

#### Model Summary

| R-sq   | R-sq(adj) | R-sq(pred) |
|--------|-----------|------------|
| 35.65% | 32.26%    | 20.95%     |

#### Means

| Length Reduction (mm) | N  | Mean    | StDev   | 95% CI             |
|-----------------------|----|---------|---------|--------------------|
| 10                    | 11 | 0.82019 | 0.01803 | (0.80808, 0.83230) |
| 30                    | 10 | 0.7830  | 0.0330  | (0.7595, 0.8066)   |

#### Games-Howell Pairwise Comparisons

##### Grouping Information Using the Games-Howell Method and 95% Confidence

| Length Reduction (mm) | N  | Mean    | Grouping |
|-----------------------|----|---------|----------|
| 10                    | 11 | 0.82019 | A        |
| 30                    | 10 | 0.7830  | B        |

*Means that do not share a letter are significantly different.*

##### Interval Plot of Normalized Volumetric Flowrate vs Length Reduction (mm)

##### Residual Plots for Normalized Volumetric Flowrate

## Appendix D: Area Effect Experimental Values

Table 2: Area Reduction DOE: For % Occlusion radius

| % Occlusion | Normalized Volumetric Flowrate |       |       |       |       |       |       |       |       |       | Average |       |
|-------------|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|-------|
|             | 1                              | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |         | 11    |
| 0           | 0.996                          | 0.978 | 1.000 | 0.980 | 0.979 | 0.990 | 0.974 | 0.989 | 0.980 | 0.982 | N/A     | 0.985 |
| 1           | 0.853                          | 0.807 | 0.798 | 0.795 | 0.835 | 0.838 | 0.815 | 0.815 | 0.831 | 0.824 | 0.810   | 0.820 |
| 2           | 0.796                          | 0.842 | 0.812 | 0.775 | 0.772 | 0.827 | 0.799 | 0.766 | 0.723 | 0.763 | N/A     | 0.788 |
| 3           | 0.781                          | 0.723 | 0.766 | 0.771 | 0.780 | 0.780 | 0.767 | 0.769 | 0.769 | 0.774 | N/A     | 0.768 |
| 4           | 0.728                          | 0.704 | 0.730 | 0.734 | 0.736 | 0.726 | 0.729 | 0.731 | 0.729 | 0.725 | N/A     | 0.727 |
| 5           | 0.687                          | 0.665 | 0.691 | 0.678 | 0.684 | 0.690 | 0.686 | 0.689 | 0.686 | 0.691 | N/A     | 0.685 |

0 = 0mm or 0%

1 = 5mm 84.2%

2 = 6mm or 85.9%

3 = 7mm or 90.7%

4 = 8mm or 93.1%

5 = 10mm or 93.3%



## Appendix E: Area Effect Statistical Analysis

### One-way ANOVA: Normalized Volumetric Flowrate versus % Occlusion

#### Method

|                        |                         |
|------------------------|-------------------------|
| Null hypothesis        | All means are equal     |
| Alternative hypothesis | Not all means are equal |
| Significance level     | $\alpha = 0.05$         |

*Equal variances were not assumed for the analysis.*

#### Factor Information

| Factor      | Levels | Values           |
|-------------|--------|------------------|
| % Occlusion | 6      | 0, 1, 2, 3, 4, 5 |

#### Welch's Test

| Source      | DF  |         | F-Value | P-Value |
|-------------|-----|---------|---------|---------|
|             | Num | DF Den  |         |         |
| % Occlusion | 5   | 25.2259 | 1352.22 | 0.000   |

#### Model Summary

| R-sq   | R-sq(adj) | R-sq(pred) |
|--------|-----------|------------|
| 96.67% | 96.37%    | 95.90%     |

#### Means

| % Occlusion | N  | Mean    | StDev   | 95% CI             |
|-------------|----|---------|---------|--------------------|
| 0           | 10 | 0.98466 | 0.00850 | (0.97858, 0.99074) |
| 1           | 11 | 0.82019 | 0.01803 | (0.80808, 0.83230) |
| 2           | 10 | 0.7875  | 0.0348  | (0.7626, 0.8124)   |
| 3           | 10 | 0.76788 | 0.01688 | (0.75581, 0.77996) |
| 4           | 10 | 0.72725 | 0.00893 | (0.72086, 0.73363) |
| 5           | 10 | 0.68475 | 0.00805 | (0.67899, 0.69051) |

### Games-Howell Pairwise Comparisons

#### Grouping Information Using the Games-Howell Method and 95% Confidence

| % Occlusion | N  | Mean    | Grouping |
|-------------|----|---------|----------|
| 0           | 10 | 0.98466 | A        |
| 1           | 11 | 0.82019 | B        |
| 2           | 10 | 0.7875  | B C      |
| 3           | 10 | 0.76788 | C        |
| 4           | 10 | 0.72725 | D        |
| 5           | 10 | 0.68475 | E        |

*Means that do not share a letter are significantly different.*

#### Interval Plot of Normalized Volumetric Flowrate vs % Occlusion

#### Residual Plots for Normalized Volumetric Flowrate