**SOFTWARE DERIVED BRACHIAL ARTERY FUNCTION**

by

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ABSTRACT OF THE THESIS

**SOFTWARE DERIVED BRACHIAL ARTERY FUNCTION**

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Endothelial dysfunction has been proven to be an early indication of cardiovascular disease (CVD), a leading cause of death worldwide (Sorsen 1995; WHO 2017). There are three diagnostic methods for endothelial functions discussed: ultrasound Flow-Mediated Dilation (uFMD) that uses ultrasound to determine brachial artery size, Peripheral Arterial Tonometry (PAT) that uses finger pulse plethysmographs, and Cuff Flow-Mediated Dilation (cFMD) that uses pressure oscillations in a blood pressure cuff. Each of the three methods first collect a control or "resting" measurement before obtaining a vasodilation measurement of the blood vessels by occluding blood flow for 5-minutes with a blood pressure cuff. Output for uFMD and PAT testing results in a singular number, percent dilation (FMD%) and reactive hyperemia index (RHI) respectively, based on the blood vessel's percent dilation (Sorsen 1995; Allan 2013; Whitt 2010). Each method has multiple factors that influence results such as body mass index, coronary artery disease, peripheral artery disease and a patient's height (Van der Heijden 2017; Allan 2013; Schroeder 2000). It is proposed that a mathematical model used with cFMD

can generate a smooth continuous output for analysis and help understand the effect that transmural pressure has on vessel dilation.

In this thesis, a biomechanical model of the human brachial artery was programmed to represent both the resting and vasodilated conditions of the brachial artery. Data for the resting and vasodilated states of six subjects were collected using cFMD. First, the patient's blood pressure and heart rate were observed. Next, the resting curve was obtained before a 5-minute occlusion. Lastly, the vasodilated measurements were taken. For each of the 6 subjects, the model was found to accurately represent the data collected for the resting and vasodilated states.

Using the model, transmural pressure was found to influence the vessel's percent dilation curve. Combining the model with cFMD allows for FMD to be performed without ultrasound, generates a larger SNR, and allows for analysis of percent dilation at multiple values of transmural pressure. The accuracy of the automated model has potential to generate other graphs to understand the artery's compliance and the effects of physiological functions such as the pulse. Further research should be done to determine what transmural pressure value would be optimal in minimizing the factors that influence test results.

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# Chapter 1: Introduction

Cardiovascular disease encompasses many issues that can arise with the heart or the blood vessels. Most issues are related to a process called atherosclerosis, when plaque builds up in the walls of the arteries therefore restricting and potentially stopping blood flow (Fig. 1.1). Atherosclerosis starts when the endothelium cells that line the arteries become damaged by smoking, high blood pressure, high cholesterol, etc. Bad cholesterol, or low-density lipoprotein (LDL) cholesterol, starts to accumulate once the endothelium is damaged leading to plaque buildup (Heart Research Institute). If the plaque from an atherosclerosis lesion ruptures, it can form a thrombosis, or blood clot, that can further limit blood flow. Heart attacks occur when blood flow to part of the heart is blocked by thrombosis and the section of heart tissue starts to die. If the thrombosis blocks blood flow to the brain, it is an ischemic stroke which is significantly more serious than heart attacks since the brain cells have less regenerative potential (Heart Research Institute). There are a few other types of cardiovascular disease such as heart failure caused by the heart not pumping blood efficiently, arrhythmia when the heart beats irregularly, and lastly problems with heart valves such that the valves don't open or close properly therefore affecting blood flow in the heart (CAD 2017).

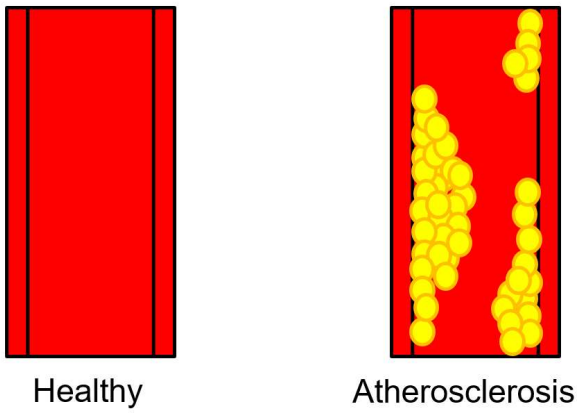


**Fig. 1.1:** Atherosclerosis

On the left, a healthy artery is shown with little to no plaque. On the right, there is an artery with atherosclerosis, or plaque build-up.

Cardiovascular disease is the number one cause of death globally and three quarters of the deaths occur in low to middle income countries. To decrease the death rate caused by cardiovascular disease, early detection methods are crucial as well as addressing behavioral risk factors (WHO 2017).

Endothelial dysfunction has been proven to be an early step in atherosclerosis formation and an early indication of cardiovascular disease (Sorsen 1995; Allan 2013). The endothelium cell layer (Fig. 1.2) plays an important role in the "regulation of vascular tone" by relaxing or tensing the smooth muscles in the artery. The endothelial cell layer relaxes smooth muscles by releasing nitric oxide or NO (Heitzer 2001). When the smooth muscles relax, vessel stiffness decreases due to the reduced tension in the artery but there also is a slight stiffening due the increased tension in collagen and elastin fibers (Bank1999). Endothelium function is impaired in the presence of cardiovascular

risk factors, such as diabetes or smoking, and is thought to be caused by oxidative stress (Schroeder 2000; Cai 2000). Oxidative stress, which is the increase in oxygen radical concentration, impairs endothelial function by inactivating NO in endothelial cells (Cai 2000). In treatments with antioxidants, there is reduced risk of coronary events and endothelial function is shown to improve in the coronary and peripheral circulation (Heitzer 2001). Due to its significance in cardiovascular disease and atherosclerosis, endothelial dysfunction is used in diagnosis methods.

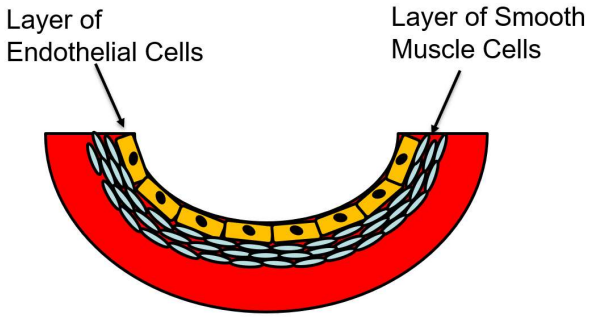


**Fig. 1.2:** Arterial Wall

This figure shows a cross section of an artery. The innermost layer is composed of endothelial cells while the middle layer consists of smooth muscle cells. The endothelial cells cause vasodilation or vasoconstriction by sending signals to the smooth muscles.

Through atherosclerosis, cardiovascular disease damages the blood vessels of the vascular system. Two of the most important organs of the body are the heart and brain, therefore, blood vessels in those organs are the primary blood vessels of concern. However, the same processes occur in arteries outside of those organs. The brachial

artery is easily accessible to determine the state of vascular disease and is therefore utilized in the noninvasive detection methods.

### 1.1 Detection Methods

The noninvasive gold standard for determining endothelial function is to use ultrasound flow mediated dilation or uFMD. This method uses high resolution ultrasound on the brachial artery to measure the arterial diameter from the 2D visual images (Fig. 1.3). First, a "resting", or control measurement is taken first after 10 minutes of rest. Second, endothelial dependent vasodilation is induced using cuff occlusion where a blood pressure cuff placed on the subject's forearm and held at a pressure higher than the systolic blood pressure for 5 minutes. This high pressure restricts blood flow to tissue downstream from the cuff limiting oxygen supply. When the pressure is released, the tissue has used its oxygen supply and vasodilation occurs to rush oxygen to the starving tissue. Lastly, 45-60 seconds after cuff deflation, a second measurement is taken to observe the vessels dilation (Sorsen 1995). The percent difference in arterial diameter between the resting and vasodilated states determines the patient's percent dilation as a singular number, FMD% (Mitchell 2004). Results for FMD% depend on the blood vessel's resting diameter but for vessels 6.00 mm and less,10% vasodilation is expected (Celermajer 1992). When FMD% is small, it indicates improper vasodilation and endothelial dysfunction (Pyke 2005). This non-invasive technique is accurate and reproducible (Sorsen 1995).

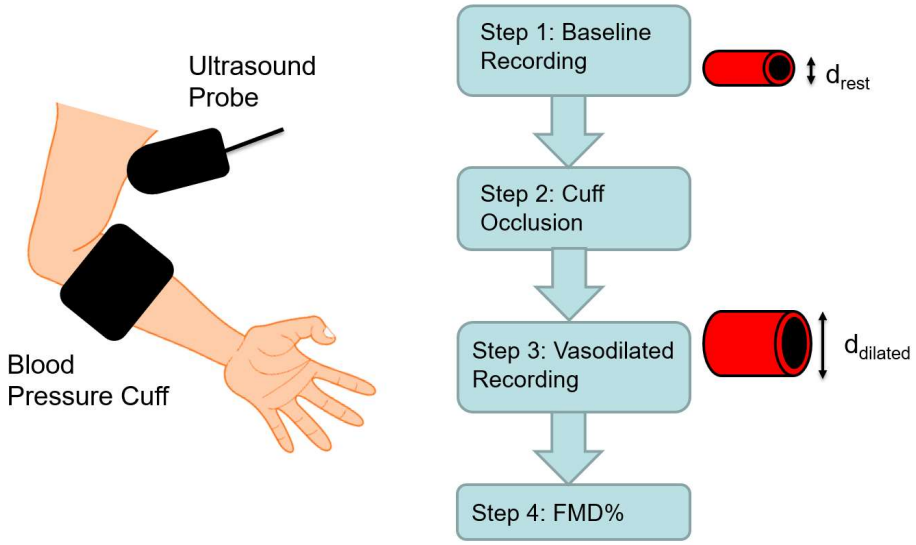


**Fig. 1.3:** Ultrasound Flow Mediated Dilation (uFMD)

This figure shows the outline for the uFMD diagnostic method. The blood vessel's baseline and vasodilated recordings are measured from the ultrasound images of the brachial artery. Cuff occlusion induces vasodilation caused by signals from the endothelial cells. Results are shown as a percent dilation called FMD%.

Another noninvasive method is called Peripheral Artery Tonometry, or PAT, and is typically performed by a device called EndoPAT created by Itamar Medical Ltd in Israel. A blood pressure cuff is placed above the elbow of one arm and a plethysmography probe is placed on the index finger of each hand and measures volume changes in the arteries. There is a 5-minute base period where the pulse is recorded to obtain a control dataset. Then the blood pressure cuff on one arm is inflated to 250 mmHg for total occlusion of the brachial artery before a final 5-minute reactive time where the vasodilation is observed. The results are presented as the reactive hyperemia index or RHI by studying

the pressure differences in the pulse between the resting and vasodilated arm (Allan 2013). The pulse with time during a PAT diagnosis test are shown in Fig. 1.4 for a normal vasodilation response in (A) and a non-normal, insufficient vasodilation response in (B) (Hamburg 2008).

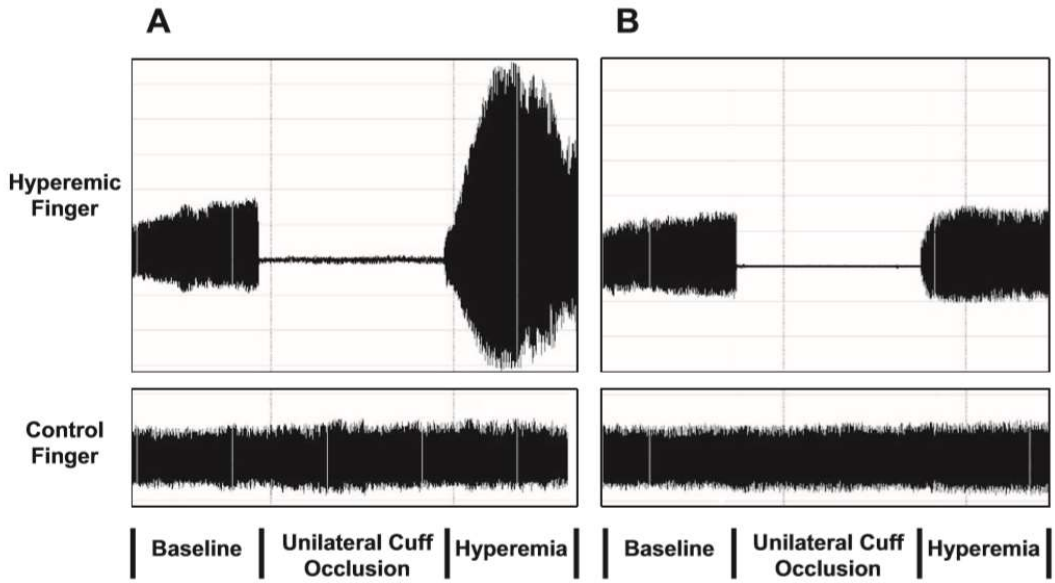


**Fig. 1.4:** PAT pulse amplitudes (Hamburg 2008)

(A) Normal response from a healthy patient which contains the vasodilation response after cuff occlusion ends. (B) Non-normal response from a diseased patient contains a smaller, almost zero vasodilation response after cuff occlusion.

Both diagnostic methods have advantages and disadvantages. Although uFMD is reproducible and accurate, it requires the use of ultrasound and is expensive. Results are dependent on variables including the angle of the ultrasound probe and the operator (Allan 2013). Some researchers believe the blood pressure cuff's location also affects vasodilation and distal forearm occlusion generates a smaller dilation than proximal

occlusion, but it is specifically mediated by NO, or endothelial function (Allan 2013; Vogel 2008). Arteries with a diameter smaller than 2.5mm are harder to measure using ultrasound (Corretti 2002). PAT method is “easy to use, standardized, and validated cut-off thresholds” making it an increasingly popular choice (Allan 2013).

A new noninvasive method called cuff flow mediated dilation (cFMD) combines a blood pressure cuff with plethysmography to monitor oscillatory volume changes within the blood pressure cuff. Again, two measurements are taken for the resting, or control, and vasodilated states of the artery. To start the experiment, the patient sits still as possible and the arm is supported at the elbow. A blood pressure cuff is placed above the elbow and is inflated past systolic pressure, it is deflated slowly while the cuff’s volume oscillations are recorded. Then the blood pressure cuff is inflated 20 mmHg past the patient’s systolic pressure and held for 5 minutes before taking the second set of measurements during deflation (Drzewiecki 1998; Whitt 2010). This new method has been used in Idei et al. to study if the pressure oscillations within the blood pressure cuff could assess endothelial function. This oscillatory method called enclosed zone flow mediated dilation, or ezFMD, was found to have results significantly lower in patients with cardiovascular diseases (Idei 2013). In a different study, the pressure oscillations were converted into the brachial artery’s lumen area. Once the area was extracted, it was converted into the artery’s diameter and compared to diameter values extracted from ultrasound images. The calculated diameter values were 1.4x greater than the values from the ultrasound images but the difference was attributed to the measurements being taken at proximal versus distal brachial artery locations respectively (Drzewiecki 1998; Whitt 2010). The cFMD method was used in this study using a CuffSoft Data Acquisition Unit

version 3 created by APM, Applied Processor and Measurement, Inc. in New York. The CuffSoft Data Acquisition Unit takes the pressure changes in the blood pressure cuff and analyzes it to obtain the luminal area of the brachial artery. Device set up and patient collection is outlined in Fig. 1.5.

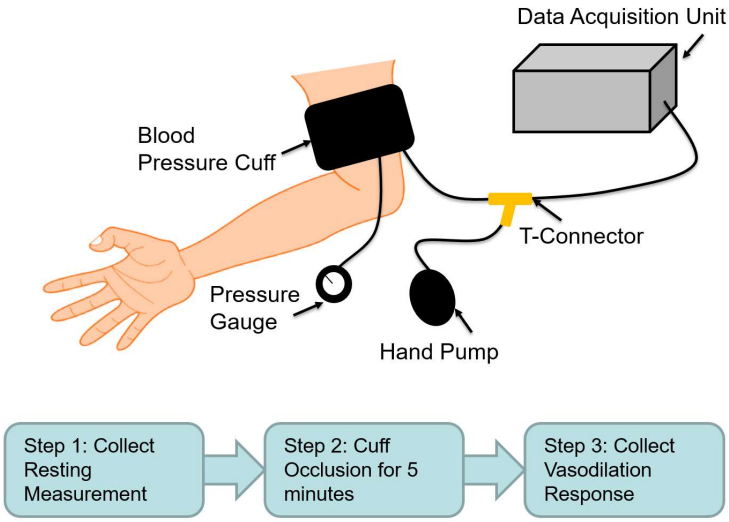


**Fig. 1.5:** Cuff Plethysmograph (cFMD)

This figure outlines the steps for cFMD diagnostic methods. The resting and vasodilation responses are recorded as the blood pressure cuff is deflating providing a discrete beat-to-beat dataset as an output.

## 1.2 Factors that Influence Test Results

With each diagnostic method, there are factors that influence test results. Since the diagnostic tests are used to determine a patient's health, factors such as a patient's height and gender influence test results but do not indicate patient health. First, a subject's height has been directly correlated to lumen area of the brachial artery and inversely related to FMD% results. This indicates that smaller arteries and shorter subjects have a

higher dilatational response in vasodilation. On the other hand, larger arteries and taller subjects have a lesser dilatational response in vasodilation. Due to females being on average shorter than males, females have a smaller brachial artery and therefore a greater dilation, or uFMD, response (Schroeder 2000). Since subject information that influence test results don't determine endothelial function, they need to be accounted for when performing diagnostic testing.

Despite the subject information, many diseases and risk factors have been proven to be detected when studying endothelial function. First, BMI is "closely related to the occurrence of glucose intolerance, high blood pressure, dyslipidemia, and also cardiovascular disease (CVD)" (Van der Heijden 2017). Due to its impact on CVD, BMI was found to have a significant correlation with endothelial dysfunction in three different diagnostic methods (Van der Heijden 2017). Outside of the risk factors, coronary artery disease, or CAD, was also studied in relation to endothelial dysfunction. It was found that patients with angiographic CAD showed a difference in endothelial function when compared to healthy individuals. However, when results from patients with CAD were further analyzed, they were found to be independent of the patient's BMI (Van Der Heijden 2017). Next, peripheral arterial disease, or PAD, plays a role in the development of arterial disease therefore affecting endothelial function. In comparison to healthy individuals, it was found in uFMD measurements that there was a significant decrease in endothelial function in patients with PAD. It is important to mention that the healthy population was on average, 28 years younger than the population studied with PAD. As mentioned before, endothelial dysfunction decreases with age which is another contributing factor in the study (Allan 2013).

### 1.3 Objective

Both uFMD and PAT diagnostic methods take continuous measurements during and after cuff deflation. When using cFMD, the data points are discrete values taken as the blood pressure cuff deflates. A mathematical model is proposed to generate a continuous curve for a beat-by-beat data set.

Despite their continuous data collection, uFMD and PAT methods only supply one number, FMD% or RHI, to determine endothelial function. It is proposed that with the combined use of cFMD and the mathematical model, a continuous curve of the artery's vasodilation percentage can be extrapolated. From these graphs, the model parameter's connections to percent dilation and the blood pressure cuff's effects on vasodilation can be studied.

# Chapter 2: Methods

To study endothelial function, two different computational models were created: one for the resting brachial artery and one for the endothelial dependent vasodilated state of the brachial artery. The model of the resting artery was used as a control to determine how much the artery dilates after cuff occlusion. The two models were then used to generate a percent dilation curve which can be used to study endothelial dysfunction.

Before gathering subject data, a preliminary model (Appendix section II) was generated using data points from Bank et al. (Bank 1999). Due to the nature of the data from Bank et al., only positive transmural pressure values could be evaluated, and the curve was simulated for negative transmural pressure values. However, human data points allowed for positive and negative transmural pressure values. Therefore, when switching to human data, the same best fit methodology used for positive transmural pressures in the preliminary model was applied to the negative transmural pressures.

## 2.1 Modeling Methods

The functional relationship between transmural pressure and lumen area was applied from Drzewiecki et al. who generated an equation from canine vascular measurements that describes the lumen area of the artery as it stretches and collapses (Drzewiecki 1998; WHO 2017). As the vessel expands, the shape is more circular while its collapse generates one that is more ellipsoidal. The pressure equation from Drzewiecki et al. is reproduced below (Drzewiecki 1997).

$$Pt = a\left(e^{\frac{b(A-A_b)}{A_b}} - 1\right) - E\left(\left(\frac{A_b}{A}\right)^n - 1\right) + P_b \quad (1)$$

Equation 1 was proved to be an accurate representation of the brachial artery's response curves in a broad variety of blood vessels with annotations given in Table 2.1 (Drzewiecki 1998; Whitt 2010). In the study, they tested model parameters for dependency on subject information and determined that the model determined only on systolic pressure (Drzewiecki 1998).

| **Variables** | **Definition** |
|---|---|
| **A** | Lumen cross-sectional area |
| **Pt** | Transmural pressure |
| **$A_b$** | Area value at vessel buckling |
| **$P_b$** | Transmural pressure value at vessel buckling |
| **a** | Constant of proportionality termed elastance scale modulus |
| **b** | Exponential rate constant termed elastance rate modulus |
| **E** | Arterial wall elastic modulus |
| **n** | Constant defining degree of curvature |

**Table 2.1:** Variable Definitions for Eq. 1 (Drzewiecki 1997)

The variables $A_b$, $P_b$, a, b, E, and n were manipulated to generate the best fit methodology.

To generate the model, Eq. 1 was split into two sections: one describing the arterial stretch and the second describing the arterial collapse. Once split, each was solved so that area was in terms of pressure generating Eq. 2 and Eq. 3. These solutions permit pressure to be the independent variable for better comparison with vascular data.

$$A_{Stret} = A_b * \left(1 + \frac{1}{b} * ln\left(\frac{Pt}{a} + 1\right)\right) \quad (2)$$

$$A_{Collapse} = A_b * \left(1 + \frac{Pt - P_b}{E}\right)^{-1/n} \quad (3)$$

## 2.2 Experimental Methods

*Study Protocol*

The protocol was submitted for approval from the local Institutional Review Board at Rutgers University (Study ID: Pro20170002078) and informed consent was obtained from all participants.

*Subject Information*

Within this study, there were 13 volunteers who participated but only 6 were used to understand endothelial dysfunction. Seven of the thirteen volunteers were unusable due to equipment failure. The six usable data sets were run through the automated algorithm and analyzed in this report.

## 2.3 Data Collection

Before any data was collected, the participants were asked to fill out a form with a few questions to ascertain demographic and current health information (Table 2.2).

Gathering data from volunteers was separated into three parts. The first part used was the Walgreens Automatic Arm Blood Pressure Monitor model WGNBPA-940 Ver. A to gather the blood pressure and heart rate information. This was done with the participant's dominant arm with the cuff placed above the elbow.

The second part used CuffSoft Data Acquisition Unit version 3 and the accompanying software created by AMP to collect the resting vessel data. The data was collected using the non-dominant arm supported at the elbow. The blood pressure cuff was placed above the elbow and inflated to above 200 mmHg for data collection to initiate data collection from the CuffSoft Data Acquisition Unit. After part two, the participant was given a 5-minute break.

The third part was performed with the non-dominant arm. The blood pressure cuff attached to the CuffSoft Data Acquisition Unit was inflated 15-20 mmHg past the participant's systolic pressure and was held there for 5-minutes. To prevent air loss, a metal tube clamp was used on the tube connecting the hand pump to the cuff. After the 5-minte occlusion, the cuff was immediately pumped past 200 mmHg to start data collection from the CuffSoft Data Acquisition Unit.

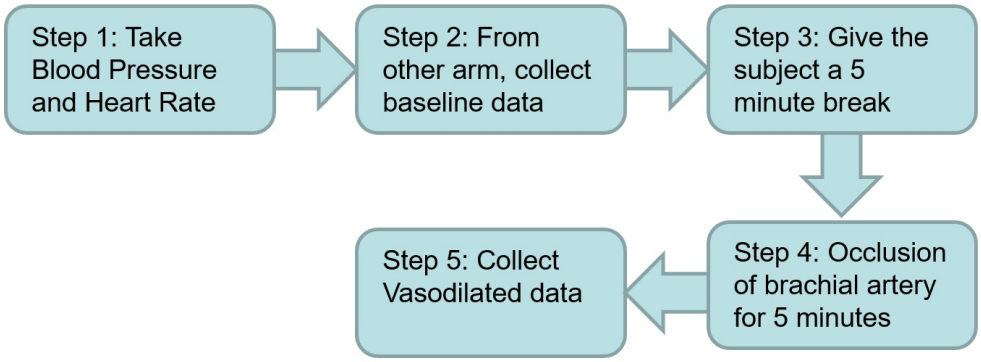


**Fig. 2.1:** Data Collection Process

After the subject filled out the consent form and questionnaire, they underwent the cFMD diagnostic method to gather their beat-to-beat output.

**2.4 Data Analysis**

The non-linear parameter estimation functions of MATLAB version 2016b from MathWorks were then used to fit both the resting and vasodilated human data sets obtained from cFMD to Eq. 2 and Eq. 3. To generate a fit for each of the two equations, the collected data was split into two by identifying transmural pressure values that were positive for the arterial stretch and negative for the arterial collapse. First, the stretch equation was fitted to the data and the value for $A_b$ was saved and used for the fit of Eq. 3. This non-linear fit method generated the values for $P_b$, $A_b$, E, a, b, and n. After the parameter values were determined, the stretch and collapse equations were pieced together by finding their intersections (Fig. 2.2). These steps were performed to generate one curve for the stretch and collapse portions of the pressure-area curve.

From the resting and vasodilated curves generated from the model, a smooth and continuous arterial dilation graph was generated by obtaining the radius of both arterial

states from the resting and vasodilated areas using Eq. 4. From there, Eq. 5 was used to obtain percent dilation of the brachial artery.

$$R = \sqrt{A/\pi} \tag{4}$$

$$\%\ dilation = \frac{R_{dilate} - R_{rest}}{R_{rest}} * 100\% \tag{5}$$

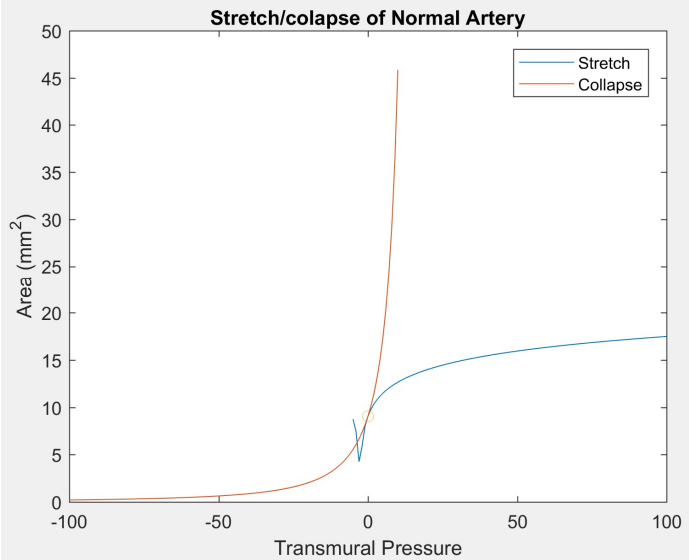


**Fig. 2.2:** Curve Fitting and Piecing Together

Equations 2 and 3 were used to generate best fit curves for the positive and negative transmural pressure ranges respectively. Next, the curves were pieced together at an intersection point to generate one continuous output curve.

| **Subject** | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| **Time** | 9:31 | 18:12 | 15:10 | 9:00 | 9:45 | 12:30 |
| **Systolic Pressure** | 103 | 116 | 123 | 116 | 121 | 110 |
| **Diastolic Pressure** | 64 | 73 | 87 | 79 | 83 | 76 |
| **Heart Rate** | 82 | 79 | 63 | 68 | 69 | 54 |
| **Gender** | Male | Male | Female | Male | Female | Female |
| **Age** | 19 | 54 | 20 | 23 | 22 | 21 |
| **Weight** | 140 | 172 | 125 | 180 | 155 | 120 |
| **Height** | 5'6" | 5'7" | 5'8" | 6" | 5'10" | 5'6" |
| **Do you smoke? How often?** | No | No | No | No | No | No |
| **Do you drink coffee? How often?** | Yes, none today | Yes, 1 cup today | Yes, 1 cup today | Yes, none today | No, 1 cup tea today | Rarely, none today |
| **Do you drink sugary drinks? How often?** | No | No | No | No | 2-3x a week | No |
| **Are you on heart disease meds?** | No | No | No | No | No | No |
| **Do you have a history of heart disease?** | No | No | No | No | No | No |

**Table 2.2:** Subject Specific Data

**2.5 Statistical Analysis**

To determine if the curve fitting methodology was accurate, a chi-square test was performed using MATLAB. The human collected data was considered the observed values while the model was the expected values. These calculated chi-squared values were compared to their critical values as determined by degrees of freedom of the model and alpha ($\alpha = 5\%$). If the calculated chi-square value was less than the critical chi-square value, the model and the collected data were statistically dependent.

Next, an iterative chi-square test determined if there was equivalence between subjects. To start, 2 computational models from two different subjects were compared using chi-square. In following iterations, two more models were added until all mathematical models were included. This was performed for both the resting and vasodilated curves from each subject. When the ratio of the calculated chi-square value and the critical chi-square value decreased below 5% was it determined there was no statistical difference between subjects indicating that the natural variation between subjects was statistically insignificant and the sample size was sufficient.

$$X^2 = \sum_{i=1}^{n} \frac{Observed_i - Expected_i}{Expected_i} \quad (6)$$

Lastly, a normalized RMSE, or root mean square error, percentage was calculated for each participant's vasodilated curve and used to generate a signal to noise ratio, or SNR. The vasodilated curve was the only one studied for SNR since it is the control curve meaning that there is no signal, or dilation. SNR was calculated using Eq. 7 where M and y represent the model and the collected data set respectively. The data points compared were done so at the same transmural pressure values.

$$SNR = \sum \frac{\%\ \text{Dilation}_i}{(M_i - y_i)^2 / n(y_{max} - y_{min})} \quad (7)$$

# Chapter 3: Results

## 3.1 Pressure-Area Curve

Data collected from each of the six subjects were run through the automatic algorithm to generate a best fit model to the resting and vasodilated states of the brachial artery. The models for each subject's arterial state was defined as a piecewise function due to separate analysis of the vessel's stretch and collapse defined in Eq. 2 and Eq. 3.

In Table 3.1, the six constant values for Eq. 2 and Eq. 3 are summarized for both the resting and vasodilated models generated for each subject. In Fig. 3.1, the best fit curves along with the collected data points are shown for each subject.

| Subject | Model | $A_b$ ($mm^2$) | $P_b$ (mmHg) | E ($Dynes/cm^2$) | a | b | n |
|---|---|---|---|---|---|---|---|
| **1** | Resting | 2.306 | -1.441 | 2.306 | 42.171 | 0.396 | 0.396 |
| | Vasodilated | 2.842 | 0.903 | 7,482.996 | 862.113 | 0.033 | 0.005 |
| **2** | Resting | 2.594 | -2.343 | 2.594 | 11.093 | 0.727 | 0.723 |
| | Vasodilated | 6.417 | 0.069 | 161.126 | 106.919 | 0.334 | 0.158 |
| **3** | Resting | 2.921 | -0.565 | 2.921 | 672.152 | 0.108 | 0.104 |
| | Vasodilated | 3.097 | -3.340 | 665.722 | -82.816 | -0.605 | 0.041 |
| **4** | Resting | 3.499 | 1.500 | 3.499 | 50.042 | 0.550 | 0.550 |
| | Vasodilated | 2.707 | -23.820 | 57,505.050 | 19.456 | 0.298 | 0.001 |
| **5** | Resting | 0.558 | -32.802 | 0.558 | 0.849 | 0.548 | 0.528 |
| | Vasodilated | 2.451 | 0.840 | 39,987.996 | 583.331 | 0.045 | 0.006 |
| **6** | Resting | 2.724 | -4.728 | 2.724 | 9.138 | 1.012 | 1.012 |
| | Vasodilated | 4.668 | -1.723 | 14,597.970 | 653.374 | 0.0464 | 0.003 |

**Table 3.1:** Generated Constants

The constant values were selected to generate a best fit for each participant's resting and vasodilated output curves.

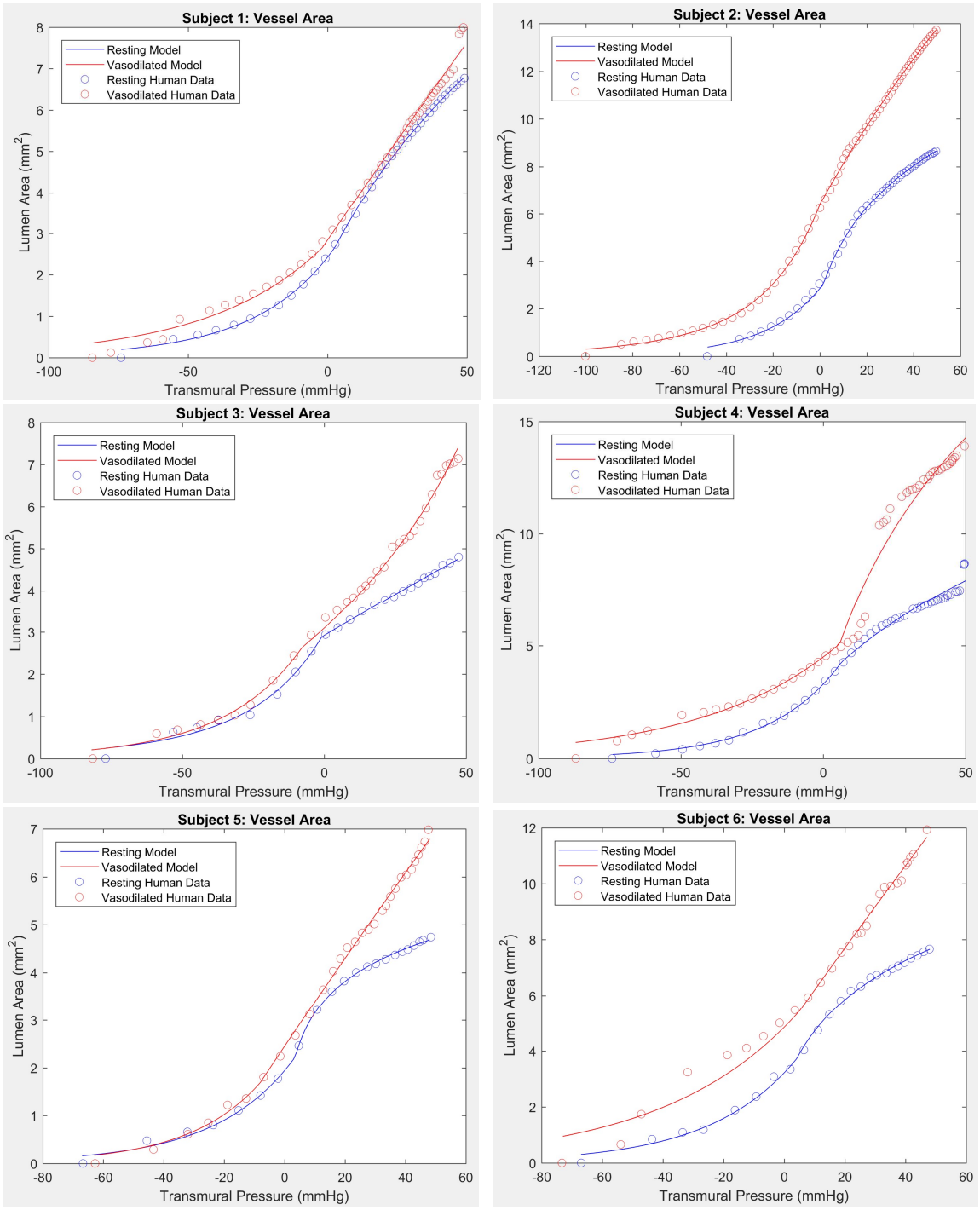


**Fig. 3.1:** Area-Pressure Curves

Each subject had a resting and vasodilated area-pressure curve seen in blue and red respectively.

### 3.2 Percent Dilation Curve

Using Eq. 5, percent dilation from the model curves were calculated for each subject and graphed against their transmural pressure. At very low transmural pressures, there is a higher percent dilation which corresponds to very small, almost zero, areas. As transmural pressure increases, the percent dilation decreases to smaller values. Once passing zero transmural pressure, the percent dilation increases again. This trend has an exception for subjects 3 and 5 where the percent dilations are lower and increase before dropping at pressure values near zero before increasing again.

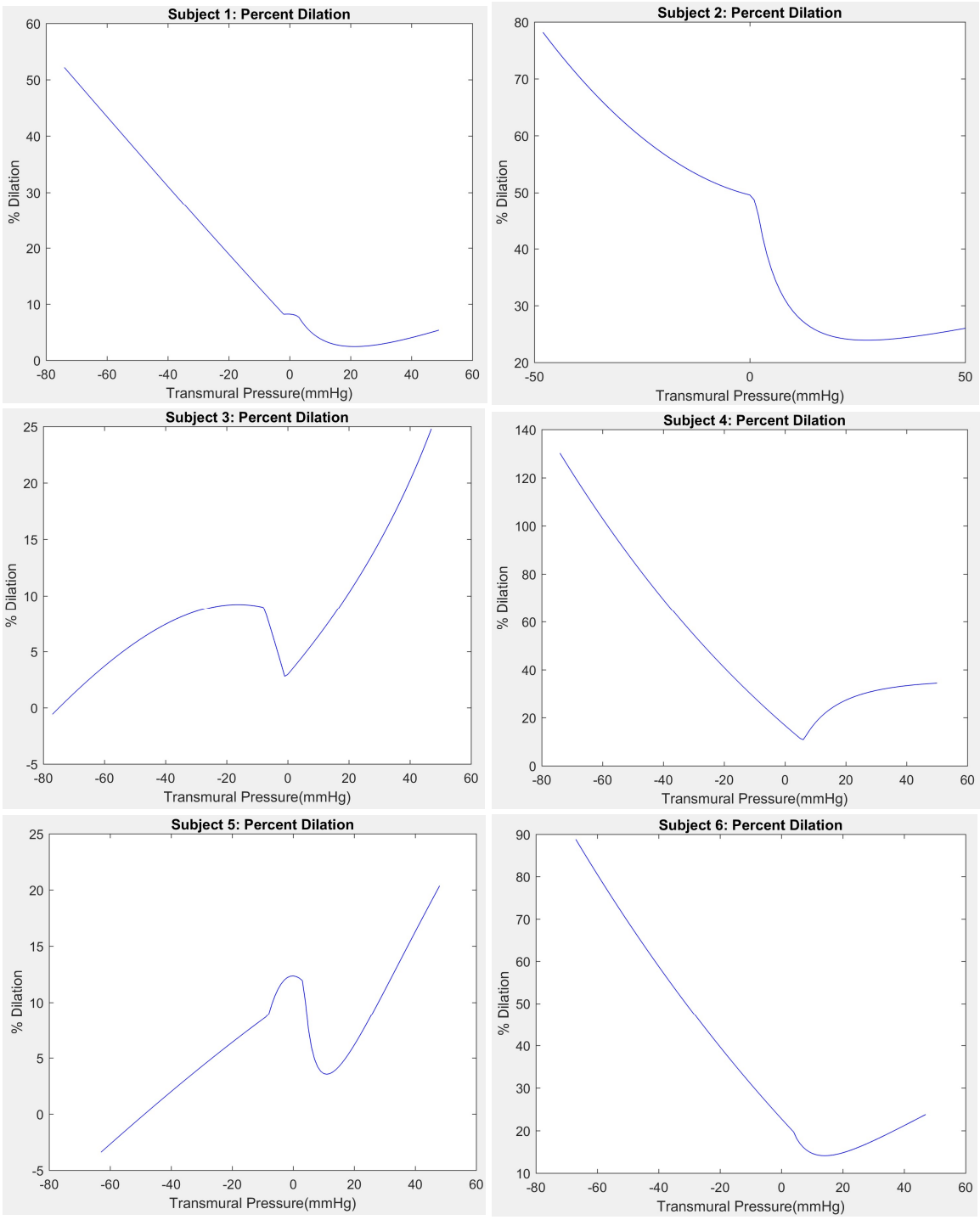


**Fig. 3.2:** Vessel Dilation Curves

The percent dilation curves for each subject as calculated from the area-pressure curves using Eq. 4 and Eq. 5.

### 3.3 Statistical Evaluations

Each of the twelve models went through a chi-square test to determine if the curve generated fit the data. In Table 3.2, statistics for each of the 12 curves are shown. Since the $X^2_{calculated}$ values are less than the $X^2_{critical}$ values, all models fit the collected data.

| **Subject** | **Model** | **$X^2_{calculated}$** | **$X^2_{critical}$** | **Degrees of Freedom** | **α** |
|---|---|---|---|---|---|
| **1** | Resting | 0.238 | 50.998 | 36 | 0.05 |
| | Vasodilated | 0.846 | 61.656 | 45 | 0.05 |
| **2** | Resting | 0.468 | 60.481 | 44 | 0.05 |
| | Vasodilated | 0.466 | 83.675 | 64 | 0.05 |
| **3** | Resting | 0.346 | 35.172 | 23 | 0.05 |
| | Vasodilated | 0.351 | 46.194 | 32 | 0.05 |
| **4** | Resting | 0.644 | 61.656 | 45 | 0.05 |
| | Vasodilated | 3.825 | 67.505 | 50 | 0.05 |
| **5** | Resting | 0.226 | 29.615 | 21 | 0.05 |
| | Vasodilated | 0.253 | 42.557 | 29 | 0.05 |
| **6** | Resting | 0.396 | 35.172 | 23 | 0.05 |
| | Vasodilated | 1.996 | 40.113 | 27 | 0.05 |

**Table 3.2:** Model Statistics

This table shows the calculated and critical $X^2$ values for each of the twelve models. The critical values were extracted from a $X^2$ table using the degrees of freedom and the α value.

After the six subjects' resting and vasodilated model curves were generated, the iterative chi-square test was performed by adding 2 subject curves at a time. As the number of models increased, so did the degrees of freedom. In Fig, 3.3, the statistical analysis from left to right show the analysis between 2, 4, and 6 models for the resting and dilated curves. It was determined there were enough subjects since for the last addition with all 6 models included, both the vasodilated and resting models have chi-square percentages less than 5%.

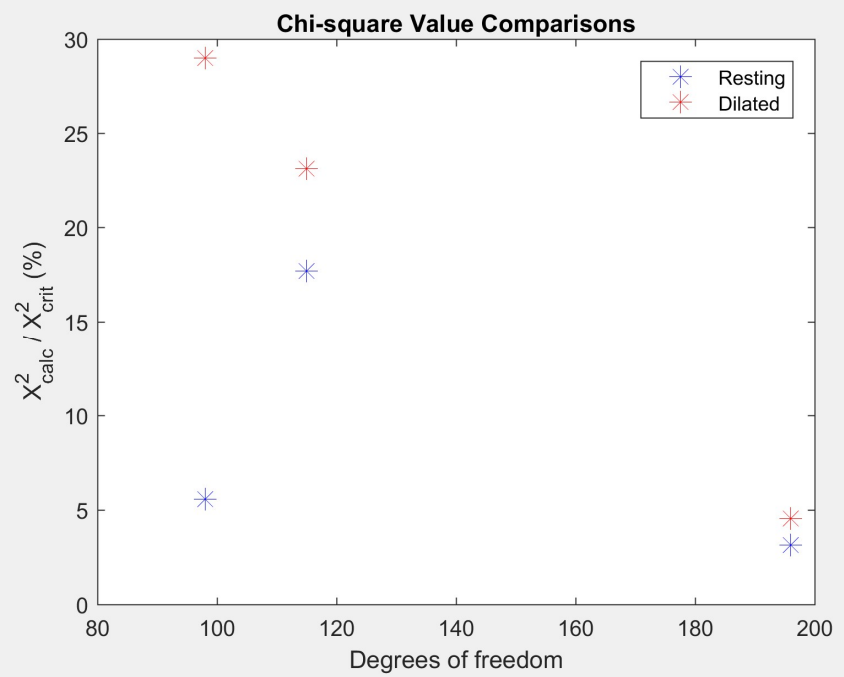


**Fig. 3.3:** Iterative $X^2$ Test

The iterative $X^2$ test was performed by randomly selecting models to perform the $X^2$ test on. Each iteration added two more models for comparison. From left to right: 2 subjects, 4 subjects, 6 subjects.

For each subject's generated model constants, the average percent change between the resting and vasodilated models was calculated to examine which variables changed the most during vasodilation (Table 3.3). Then for the stretch variables ($A_b$, a, and b), the variable's percent change for each subject was plotted against the radius dilation percentage at zero transmural pressure.

| **Variable** | **$A_b$** | **$P_b$** | **E** | **a** | **b** | **n** |
|---|---|---|---|---|---|---|
| **Average % Change** | 94.1 | -291.3 | 541,127.2 | 13,054.4 | -172.8 | -89.5 |
| **Average % Standard Deviation** | 134.0 | 725.7 | 607,842.3 | 27,361.9 | 238.7 | 16.0 |

**Table 3.3:** Percent Change of Constants

The six generated constants were analyzed to identify if any directly corresponded to vasodilation. Variables E, or the elastic modulus, and a, the elastic scale modulus, were found to increase when going from the resting to the vasodilated models.

Lastly, SNR for the vasodilation curves were calculated using the vasodilated curves. Starting at negative values of transmural pressure, SNR decreases and starts increasing again for positive transmural pressure values. This trend exists for all participants except for subjects three and five where SNR increases, decreases, then increases again as transmural pressure increases.

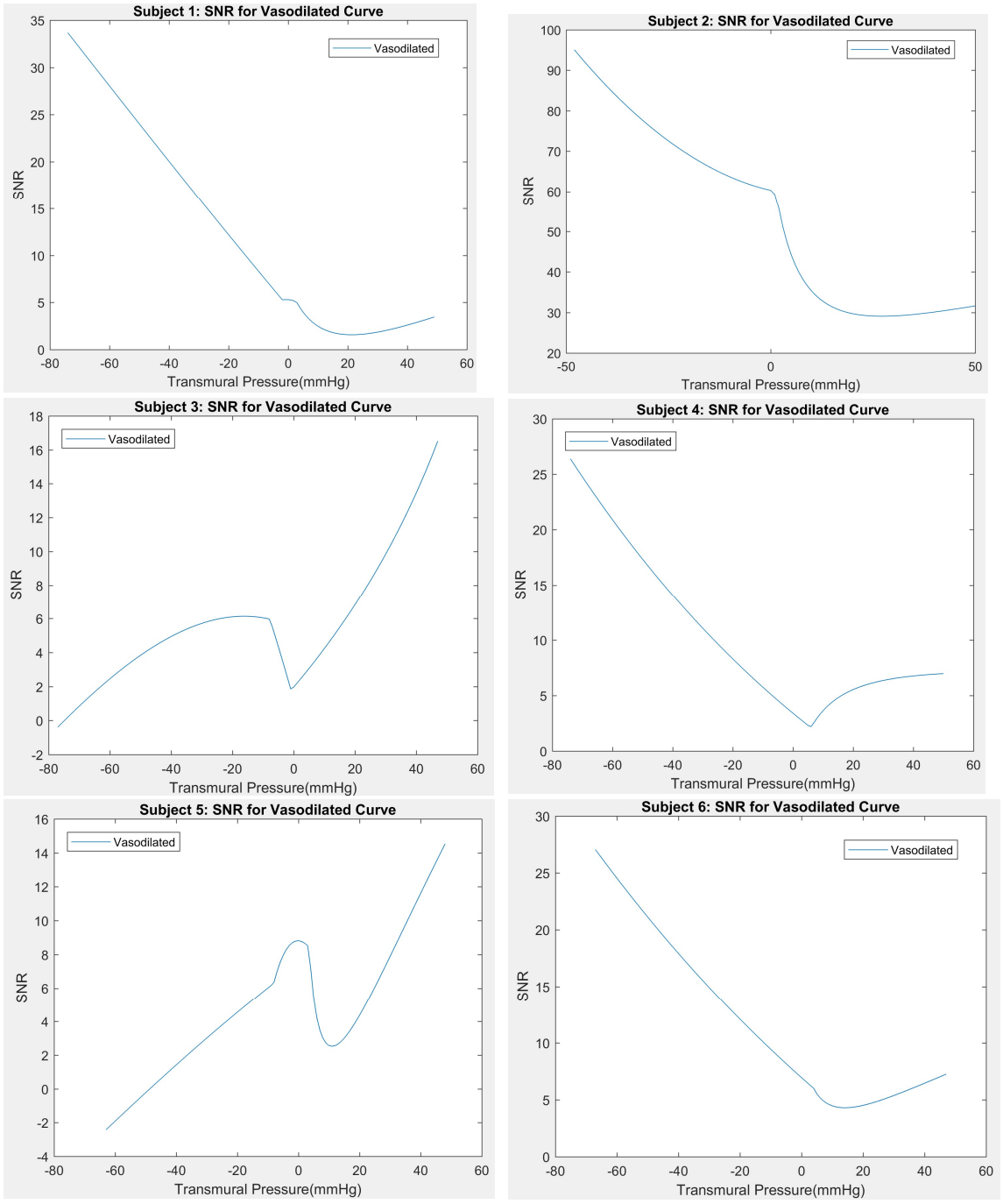


**Fig. 3.4:** SNR Curves

Signal to noise ratio values as transmural pressure changes.

# Chapter 4: Discussion

The objective of this study was to study the effects of transmural pressure on brachial artery vasodilation. This was performed by combining cFMD with a mathematical model to generate a smooth continuous curve for analysis. The model fitting methodology was generated using data points from Bank et al. and then applied to the data sets of six subjects (Bank 1999).

For all subjects, except subject three, the automatic algorithm had no issues identifying intersections and piecing together the vessel's stretch and collapse for the resting and vasodilated curve. When subject three's vasodilated data was analyzed in terms of collapse and stretch, the two curves generated did not intersect and the stretch portion of the curve didn't appear to be as stiff as the data collected. To account for the limitations of the automated model, this subject's data was analyzed differently from the rest. First, the stretch portion was fit to the whole data collection set. Second, the collapse curve was generated in the same manner as the other models and fit to the collapse data collect from the subject. For the stretch portion of the curve, adding the extra data points allowed for a better fit and more accurate representation of the subject's data points.

Each subject tends to have vasodilated model that has a smaller rate of slope change than their respective resting model. The effect of this can be seen in value increases of constants "a", the proportionality constant for elastance scale modulus, and "E", the arterial wall elastic modulus. This indicates that as the vessel vasodilates, the change in vascular tone, as dictated by the endothelial cells, is observed directly.

When observing the pressure-area curves of each subject, the models are generated using separate equations for the stretch and collapse of the brachial artery. One study suggested that many techniques cannot separate the direct effects from vasodilation and the changes in blood pressure. They suggest that since "vessels are not as stiff at pressures below their physiological range, it may be easier to separate disease form normal vessels by studying the vessels at low transmural pressure" but it is unclear what they define as low transmural pressures (Bank 1999). In looking at the vessel dilation graphs in Fig. 3.2, the collapse of the brachial artery is a geometric change in vessel shape solely due to the force that is applied by the blood pressure cuff. Since the collapse of the blood vessel does not help us understand endothelial function, only the area equation for vascular dilation (Eq. 2) is needed for diagnosis. It is suggested that at transmural pressures $\geq 0$ mmHg should be used to understand endothelial function.

Comparing the percent dilation results to the gold standard, uFMD, we observe that when transmural pressure is positive, there is a correlation between percent dilation ranges. In healthy blood vessels, uFMD has percent dilation ranges between 10-20% on average when looking at different study results (Pyke 2005). Looking at Fig. 3.2, these percent ranges are observed typically when transmural pressure is between 0-60 mmHg for most, but not all volunteers. This again reinforces that when looking at the pressure-area curves and vessel dilation percentages, transmural pressures $\geq 0$ mmHg are needed to understand endothelial function.

Vessel dilation curves (Fig. 3.2) have the same negative then positive slope trend except for subjects 3 and 5 where the curve's slope had a period of positive values before

being negative. This difference can be explained by observing the transmural pressure-area curves for each subject. For the four subjects with the negative then positive slopes, the vasodilated area values are clearly above the resting area values whereas with subjects three and five, the curves overlap and even intersect so that the resting area values are greater than the vasodilated values. This intersection at low transmural pressure values generates negative percent dilation before increasing. For all curves, as transmural pressure increases, surrounding the subject's value of $P_b$, the two area curves become closer before diverging. This accounts for the dip in vessel dilation that occurs before the percent dilation increases in all dilation curves. This dip is thought to be due to the competition between the smooth muscle cells and collagen fibers that dictate vascular tone. In a majority of the subjects, the resting area curve is less stiff than the vasodilated curves. The difference in rate slope change attributes to the vessel dilation graphs by generating a polynomial like curves. In subject five, this difference is the most pronounced.

Each participant's SNR curves generated for the vasodilation model look exactly like the vessel dilation curves but scaled. Since only positive transmural pressure values are indicative of endothelial function, only those portions of the curve will be studied for significance. As transmural pressure increases, SNR increases therefore giving good resolution. For half of the subjects, SNR even reaches above 10.

The mathematical model along with cFMD allows for a continuous curve to understand endothelial function. This combination methodology helps account for the effect the blood pressure cuff creates during occlusion by providing a continuous vessel

dilation curve. The other diagnostic methods, uFMD and PAT, generate a singular number to determine if there is endothelial dysfunction. In understanding the effects of the blood pressure cuff, the timing of collecting data for the results for uFMD and PAT methods can be questioned. For example, collecting the blood vessel's data at a transmural pressure value might more indicative than current methods and help diminish the effects of subject specific influencing factors such as BMI.

# Chapter 5: Conclusion

The automated model has been determined to generate a good fit to the data collected from cFMD. Like most models, there are a few limitations. First, the model could not be produced for subject three's data until there was a minor change in the algorithm. This change was not universal and did not work for the rest of the models. In a future model, a conditional statement can be included in the code to account for situations like this and the model that fits best would be accepted.

The vessel dilation curves demonstrate the effects that transmural pressure have on percent dilation that have not been previously studied. For diagnostic methods that provide a singular value output like uFMD and PAT, there are ambiguities to the mapping between transmural pressure and its respective collected output. In this study, dilation was calculated using radius values at the same transmural pressure. uFMD collects the vasodilated diameter of the brachial artery 45-60 seconds after the cuff is released (Sorsen 1995). The values used in PAT methodology is not clear. There should be additional data collection to determine transmural pressure as a factor in normal and diseased arteries. Answering the question of which area points should be used for analysis of endothelial function might allow for an effect minimization of subject informational factors such as BMI.

In using an automated algorithm for the data collected by the cFMD, the transmural pressure area curve can be used to derive many different analytical curves. For example, adding pulse data to the transmural pressure can generate pulse waveforms in

the area curve and simulate real data collected from the patient. Also, the derivative of the vessel's area can be taken to generate a compliance curve of the brachial artery. There are multiple uses for the model that have yet to be explored and each function can help examine the endothelial function of the brachial artery.

*Future Work*

In addition to generating an algorithm that can automatically generate a best fit for all individuals, cFMD used with the model should be used to determine its ability to detect cardiovascular disease. This should be performed using a control group of healthy participants and an experimental group with participants diagnosed with cardiovascular disease. If the percent dilation graphs are statistically different between the two groups, then the methodology can detect cardiovascular disease. The results should also be compared to the gold standard, uFMD, to further validate the process.

*Significance and Summary*

With the addition of a model to cFMD diagnosis methods, there are a few improvements that were made. First, using cFMD allows medical practitioners to perform FMD analysis without the use and expense of ultrasound. Second, the model helps increase the signal to noise ratio while still generating a best fit to the data points gathered with cFMD whereas uFMD is biologically noisy due to multiple clinical factors that influence results (Vogel 2008). Lastly, the model allows for FMD analysis at various values of transmural pressure as opposed to one pressure value. These improvements allow for an alternative diagnostic method that is cheaper but comparable.

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# Appendix

## I. Data Collection Form

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**CONSENT TO TAKE PART IN A RESEARCH STUDY**

**TITLE OF STUDY:** *Noninvasive Brachial artery function*
**Principal Investigator:** *Gary Drzewiecki, PI and Kristin DiStefano, MS Grad Student*

This informed consent form provides information about a research study and what will be asked of you if you choose to take part in it. If you have any questions now or during the study, if you choose to take part in it, you should feel free to ask them and should expect to be given answers you completely understand. It is your choice whether to take part in the research. Your alternative to taking part is not to take part in the research.

After all of your questions have been answered and you wish to take part in the research study, you will be asked to sign this informed consent form. You are not giving up any of your legal rights by agreeing to take part in this research or by signing this consent form.

**Who is conducting this research study?**
Dr. *Gary Drzewiecki* is the Principal Investigator of this research study. A Principal Investigator has the overall responsibility for the conduct of the research. However, there are often other individuals who are part of the research team.

Dr. *Gary Drzewiecki* may be reached at Rutgers University, *Biomedical Engineering Dept. 848-445-6688, garydrz@soe.rutgers.edu.* .

*Gary Drzewiecki* or another member of the study team will also be asked to sign this informed consent. You will be given a copy of the signed consent form to keep.

**Why is this study being done?**
*The research will collect normal brachial artery physiological function to be used to validate a computer model of the artery. The model may then be used to later aid in the detection of vascular disease.*

**Who may take part in this study and who may not?**
*Anyone who is a healthy adult may participate. Any one with known cardiovascular disease should not participate.*

**Why have I been asked to take part in this study?**
*You have been asked to participate in the study as a healthy individual*

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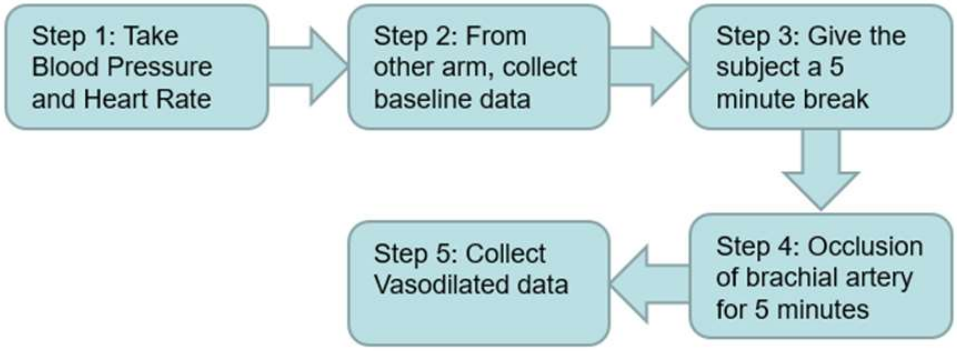
**How long will the study take and how many subjects will take part?**
*We expect to record about 10 volunteers in this study. The study will be during the course of the Spring semester 2018.*

**What will I be asked to do if I take part in this study?**
*During this study we will place an arm cuff on your arm. The cuff will be inflated by an automatic pressure monitor to obtain your blood pressure. The cuff will w be replaced on your arm to allow a different automatic instrument to measure the size of your artery. The cuff will be once again inflated and allowed to remain for a time of 5 minutes. The pressure will be released and your artery size will be recorded again. That concludes the test. This test is commonly used in research testing of the artery size with the exception that ultrasound instruments are used. Our instrument that measures you artery size using a cuff is new.*

Data Collection




**What are the risks and/or discomforts I might experience if I take part in this study?**
*During the time that your arm is occluded there may be some discomfort in the form of an ache. This is only during the occlusion step. Following occlusion the cuff is deflated and the arm refills with blood as our desired vasodilation response occurs. You may notice a nerve tingling at this time as well as red dots may appear on your skin as the capillaries dilate.*

*Reproductive Risks: N/AThis study is similar to that of a routine blood pressure test at your Doctor's office. It has no relation to the reproduction system and thereby no effect on it.*

***For Women:***
*There are no drugs involved in this study*

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***For Men:***
*There are no drugs involved in this study*

*Suggested language for drug studies where it is expected that the drug may cause harm to an unborn fetus:*
*IF APPLICABLE:* NA

*IF APPLICABLE:* NA
*LIST METHODS:*

NA

*Suggested language for studies involving a blood draw:*
None

*Suggested language if study drug may interact with other medications the subject is already taking:*
NA

**Are there any benefits to me if I choose to take part in this study?**

The possible benefit of taking part in this study is learning your blood pressure reading or levels, especially if you were not aware of it previously.

**What are my alternatives if I do not want to take part in this study?**
NA – participation strictly voluntary

**How will I know if new information is learned that may affect whether I am willing to stay in the study?**

NA

**Will there be any cost to me to take part in this study?**
None

**Will I be paid to take part in this study?**
You will not be paid to take part in this study.

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**How will information about me be kept private or confidential?**

This research is confidential. Confidential means that the research records will include some information about you and this information will be stored in such a manner that some linkage between your identity and the response in the research exists. Some of the information collected about you includes age, sex, height, blood pressure. Please note that we will keep this information confidential by limiting individual access to the research data and keeping it in a secure password protection on a laptop.

The research team and the Institutional Review Board at Rutgers University are the only parties that will be allowed to see the data, except as may be required by law. If a report of this study is published, or the results are presented at a professional conference, only group results will be stated. All study data will be kept for three years.

**What will happen if I am injured during this study?**

Subjects in this study will be exposed to certain risks of personal injury in addition to those associated with standard forms of treatment, which include: *none.* In addition, it is possible that during the course of this study, new adverse effects of that result in personal injury may be discovered. The University will make appropriate referrals for medical and/or dental treatment for subjects who sustain personal injuries or illnesses as a direct consequence of participation in the research. The subject's health insurance carrier or other third-party payer will be billed for the cost of this treatment; provided that the University shall not submit to federally funded programs, e.g., Medicare, Medicaid or CHAMPUS, for reimbursement first if submission to such programs is prohibited by law. No financial compensation will be provided by the University and no other type of assistance is available from the University.

**What will happen if I do not wish to take part in the study or if I later decide not to stay in the study?**

It is your choice whether to take part in the research. You may choose to take part, not to take part or you may change your mind and withdraw from the study at any time.

If you do not want to enter the study or decide to stop taking part, your relationship with the study staff will not change, and you may do so without penalty and without loss of benefits to which you are otherwise entitled.

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You may also withdraw your consent for the use of data already collected about you, but you must do this in writing to *Dr. Gary Drzewiecki, Biomedical Engineering Dept. Rutgers University, Biomedical Engineering Building, Room 213,Piscataway,NJ., 848-445-6688, garydrz@rutgers.edu.*

**Who can I call if I have questions?**

If you have questions about taking part in this study or if you feel you may have suffered a research related injury, you can call the study doctor: *Dr. Gary Drzewiecki, Biomedical Engineering Department Rutgers University, garydrz@rutgers.edu; 848-445-6688.*

If you have questions about your rights as a research subject, you can call the IRB Director at:

Institutional Review Board
Rutgers University, the State University of New Jersey

Liberty Plaza / Suite 3200

335 George Street, 3rd Floor

New Brunswick, NJ 08901

Phone: 732-235-2866
Email: humansubjects@orsp.rutgers.edu

**Who may use, share or receive my information?**

The research team may use or share your information collected or created for this study with the following people and institutions:

- Rutgers University investigators involved in the study;
- The Rutgers University Institutional Review Board and Compliance Boards
- *The subject's arterial pulse data will be reproduced for scientific publication articles but only in non-identifiable manner.*

Those persons or organizations that receive your information may not be required by Federal privacy laws to protect it and may share your information with others without your permission, if permitted by the laws governing them.

**Will I be able to review my research record while the research is ongoing?**

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No. We are not able to share information in the research records with you until the study is over. To ask for this information, please contact the Principal Investigator, the person in charge of this research study.

**Do I have to give my permission?**

No. You do not have to permit use of your information. But, if you do not give permission, you cannot take part in this study. (Saying no does not stop you from getting medical care or other benefits you are eligible for outside of this study.)

**If I say yes now, can I change my mind and take away my permission later?**
Yes. You may change your mind and not allow the continued use of your information (and to stop taking part in the study) at any time. If you take away permission, your information will no longer be used or shared in the study, but we will not be able to take back information that has already been used or shared with others. If you say yes now but change your mind later for use of your information in the research, you must write to the researcher and tell him or her of your decision: *Dr. Gary Drzewiecki, Rutgers Biomedical Engineering Dept., Biomedical Engineering Building, Room 213, Piscataway, NJ. garydrz@soe.rutgers.edu.*

**How long will my permission last?**

Your permission for the use and sharing of your health information will last until your *recordings are used in the study that will be published in a scientific journal. We would anticipate this to be by December 2018.*

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## AGREEMENT TO PARTICIPATE

### 1. Subject consent:

I have read this entire consent form, or it has been read to me, and I believe that I understand what has been discussed. All of my questions about this form and this study have been answered. I agree to take part in this study.

Subject Name:_____

Subject Signature:_____ Date:_____

### 2. Signature of Investigator/Individual Obtaining Consent:

To the best of my ability, I have explained and discussed all the important details about the study including all of the information contained in this consent form.

Investigator/Person Obtaining Consent (printed name):_____

Signature:_____ Date: _____

*SURROGATE OR LEGALLY AUTHORIZED REPRESENTATIVE CONSENT: N/A*
*Use of a surrogate or legally authorized representative to consent for a research subject must have prior approval by the IRB. Information about the surrogate consent process is available on at the HSPP website https://orra.rutgers.edu/hspp or contact your local IRB office for assistance https://orra.rutgers.edu/contactus.*

*CONSENT ADDENDA: N/A*
*Investigators who wish to develop consent addenda seeking permission to audio or visually record aspects of the research, take photographs, store information or biospecimens for future research secondary to a main study may find recommended consent addenda language at the HSPP Guidance Page https://orra.rutgers.edu/formsandtemplatesirb.*

## II. Preliminary Model

# Computational Model of Vascular Biomechanics with Smooth Muscle Function

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***Abstract*— Understanding the brachial artery during functional dilation testing can allow physicians to noninvasively determine if the arterial wall has smooth muscle that has been damaged by disease. Since many other mechanical properties of the artery affect smooth muscle response a computer model would be useful to help interpret vascular smooth muscle function. In this article a biomechanical model of the human brachial artery was programmed using MATLAB to represent both the resting and vasodilated conditions of the brachial artery. The model results were evaluated in comparison with canine in vitro vessel data and human brachial artery intravascular ultrasound data. The model was found to accurately represent both vessels including the vasodilated and resting conditions.**

### I. Introduction

One of the main causes of health concern in both men and women in the United States is heart disease. It is the cause of death in one of every four cases [1]. A source of heart disease is systemic hypertension which can be caused by arterial wall hypertrophy [2]. Systemic hypertension can lead to left ventricular hypertrophy, diastolic dysfunction, intracerebral hemorrhage due to medial degeneration, and accelerated atherosclerosis which is a cause of ischemic heart disease, stroke, and peripheral vascular disease [3]. Early diagnosis and treatment of systemic hypertension can decrease the health concern of heart disease. Vascular smooth muscle dysfunction is an early indication of vascular disease and damaged endothelium. The flow mediated dilation test with ultrasound imaging is a noninvasive measure of endothelial and vascular function. Unfortunately, the results of this test can be variable due to the multiple geometric and mechanical factors that affect dilation. We suggest that a computational biomechanical model may be useful to improve the interpretation of vascular dilation data.

Our model begins with the derivation of the arterial pressure-lumen area relationship. The pressure-area curve of a vessel incorporates most aspects of the vessel biomechanics in one data function for example, the pressure–area curve may be used to find the derivative of vessel area with respect to pressure [2].

### II. Methods

#### A. Computational

To generate the model for the brachial artery, MATLAB 2016b was utilized.

#### B. Mechanical Modeling

The functional relationship between vessel Pressure and lumen area was applied from Drzewiecki et al. who generated an equation from canine vascular measurements that describes the lumen area of the artery as it stretches and collapses [2]. As the vessel expands, the shape is more circular while its collapse generates a more elliptical shape. The original pressure equation is reproduced below:

$$Pt = a\left(e^{\frac{b(A-A_b)}{A_b}} - 1\right) - E\left(\left(\frac{A_b}{A}\right)^n - 1\right) + P_b \quad (1)$$

Where Pt is the transmural pressure, or the pressure difference between inside the artery and the external pressure, $A_b$ and $P_b$ are the area and pressure at vessel buckling (Pt=0), E is the elastic modulus of the vessel, and A is the area. Parameters a, b, and n are specific values for the equation to fit the data.

Equation (1) was solved so that area was in terms of pressure and then it was split into two, one for the stretch Eq. (2) and one for the collapse Eq. (3) of the artery. These solutions permit pressure to be the independent variable for better comparison with vascular data. The parameter set was chosen to create the complete area versus pressure curve.

$$A_{stretch} = A_b * \left(1 + \frac{1}{b} * \ln\left(\frac{Pt}{a} + 1\right)\right) \quad (2)$$

$$A_{collapse} = A_b * (1 + \frac{Pt - P_b}{E})^{-1/n} \quad (3)$$

The nonlinear parameter estimation functions of MATLAB were then used to fit human intravascular ultrasound data from the area versus pressure curves from Banks et al. to obtain the values for $P_b$, $A_b$, E, a, b, and n for the resting and dilated states [4].

Compliance is defined as the derivative of volume with respect to pressure. In this study, the derivative was taken with area instead of volume so the units are $mm^2/mmHg$:

$$\frac{dA}{dP} = \frac{A(Pt + h) - A(Pt)}{h} \quad (4)$$

Further comparisons with the in vitro vessel data of Drzewiecki et al. and Banks et al. were made to ensure the model's accuracy [2,4].

## I. Results

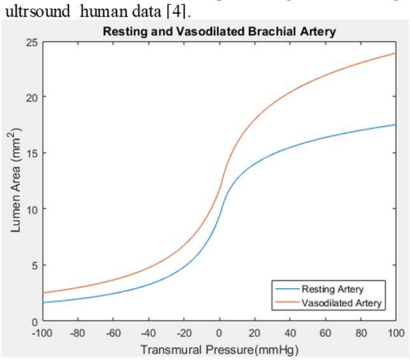
### A. *Area versus Pressure for Rest and Dilation*

Data for the area versus transmural pressure curves obtained from Banks et al. was used to generate a best fit Eq. (2) and Eq. (3) from above [4]. Below are the generated values for both the resting and dilated models of the brachial artery. Next are the generated graph containing both models after Eq. (2) and Eq. (3) were pieced together.

TABLE I. Generated Constants

| Model | $A_s$ | $P_s$ | E | a | b | n |
|---|---|---|---|---|---|---|
| Resting | 9.0569 $mm^2$ | -0.7 mmHg | 22 Dynes/$cm^2$ | 2.667 | 3.9206 | 1 |
| Dilated | 11.4219 $mm^2$ | -0.7 mmHg | 28 Dynes/$cm^2$ | 5.1741 | 2.7657 | 1 |

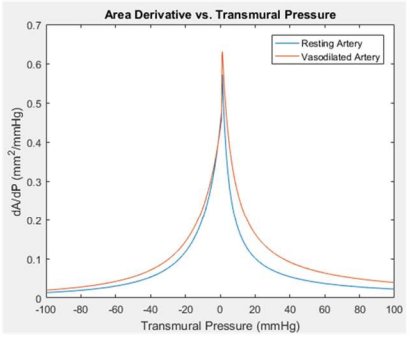
Fig. 1. Vessel area versus transmural pressure generated using best fit to invascular ultrsound human data [4].




### B. *Vessel's Area Derivative*

To model the derivative, a step of h=0.25 was utilized.

Fig. 2. Brachial artery area derivative computed using Eq. (4).




### C. *Comparison of Models*

For model verification, data points from the human brachial artery study that evaluated vessel stretch from Banks et al. was graphed on the pressure-area curve with the computational model for both resting and vasodilated vessel states [4]. For the derivative curve, only the resting vessel model was graphed with the canine data from Drzewiecki et al. for verification [2].

Fig. 3. Pressure-area curves from human data with computational model [4].

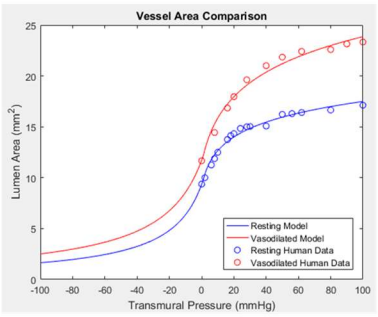
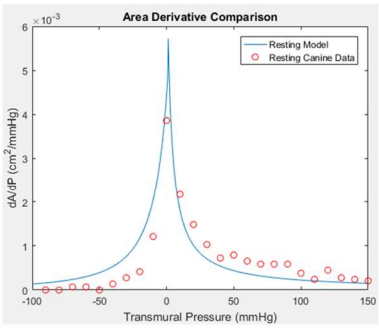



Fig. 4. Derivative curve from canine data with computational model [2].




Looking at the two graphs above, the compuational model closely represents the human data but the collapse of the vessel in the pressure-area curve doesn't reach zero at -100 mmHg. The derivative curve for a resting artery appears to be a shifted version of the canine data which is expected since canine physiology is different from that of humans.

## II. Conclusion

Describing the human brachial artery's collapse and expansion by using the mathematical model derived from the canine study is possible [2]. The equations fit the human data obtained from the invasive ultrasound study performed by Banks et al. [4]. Future work will include further model validation by examining the stress-strain curve of the artery and the change of elastic modulus with transmural pressure and smooth muscle function. Current model results have shown that it can successfully represent canine and human in vitro arteries intravascular measurements for both the resting and dilated conditions.

## References

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