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CONTINUOUS NON-INVASIVE BLOOD PRESSURE USING METHOD OF PARTIAL APPLANATION TONOMETRY

by

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And approved by

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ABSTRACT OF THE THESIS

Continuous Non-Invasive Blood Pressure Using Method of Partial Applanation Tonometry

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The method of obtaining blood pressure with the use of a mercury sphygmomanometer, or the generic 'cuff,' is inaccurate, time-consuming, uncomfortable, lacks pulse waveform data and is not continuous. With these factors considered, the universal method for taking blood pressure yields unreliable measurements that put patients at a higher risk of misdiagnosis.

In this thesis, we introduce the Continuous Non-Invasive Blood Pressure Sensor (CNIBP), a cuffless blood pressure sensor. This new sensor incorporates the recent method of partial applanation tonometry as an alternative to CNIBP. Partial applanation tonometry is a method that determines blood pressure by means of converting arterial contact force, deflection and area to pressure. In this case, the radial artery is flattened using the CNIBP which provides the subject with a continuous arterial pressure waveform. Therefore, a thorough system to measure blood pressure is established.

In prior experiments, utilizing this method, failure to reproduce a computational method indirectly led to a downfall in the functionality of the sensor. In addition to this, a non-deflection corrected calibration method showed to have a higher percentage of error

when compared to our deflection corrected method. In the addressed experiment presented in this thesis, the use of raw data through an algorithm built into Matlab achieves to establish a pressure-area-deflection relationship, which results in accurate blood pressure pulse waveforms. Using this innovative calibration, we are able to retrieve values of force, in units of volts, from the arterial tonometer which are then easily converted into the common unit of blood pressure, millimeter of mercury (mmHg). In this research, the partial applanation tonometer pressure readings were compared with those from an automatic cuff pressure monitor.

It was found that continuous pressures and pulse waveforms are retrieved in about one-fourth of the time of the generic cuff. In the comparison of systolic pressures, it was established that continuous systolic blood pressure values are not statistically different than the cuff blood pressure. As compared to the cuff, our errors were less than ± 20 mmHg. These adjustments resulted in an overall, average blood pressure error of less than 5% when compared to the cuff and previous tonometer experiments expressing similar methods.

We can conclude that our partial deflection tonometer is capable of providing blood pressure accuracy comparable to the standard occlusive cuff monitor. At the same time, our device provides faster readings along with complete pulse waveform information in a continuous manner.

ACKNOWLEDGMENT

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I would also like to thank the senior design group (Christopher Coppola, Shyama Shah, and Shradha Suresh) that provided insight to certain parts of the project. Without their guidance, I would not have been able to achieve what I have achieved to date.

Thirdly, I would like to thank the various numbers of students (Alex Hirniak and Harrison McClarren) who have worked in the lab under my supervision. These students have also, provided a necessary amount of awareness to me about my own project which has eventually, helped me make the progress I have made up to date.

Lastly, I would like to thank the Biomedical Engineering facilities as a whole for providing me with a space in which I can conduct my experiments in full comfort. Without these facilities, it would be nearly impossible to have made progress on this project and for that, I am extremely thankful.

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INTRODUCTION

The human body undergoes many different types of pressures in order to remain under constant functionality. Without all the necessary pressures that the body faces, whether blood pressure, intraocular pressure, lung pressure, etc., the body would not be deemed as functioning properly. Computing readings for different types of pressure can eventually lead to the realization of underlying health conditions. What many do not see is that these readings are much more than just a set of numbers.

Blood pressure is one of the most common types of pressure taken in the body and is a measure of specific cardiovascular activity. Being able to understand what these readings entails is crucial in determining one's underlying cardiovascular health. With every beat of the heart, there is a contraction and relaxation that assists in the blood flow throughout the heart.

> "Blood circulation starts when the heart relaxes between two heartbeats: The blood flows from both atria (the upper two chambers of the heart) into the ventricles (the lower two chambers), which then expand. The following phase is called the ejection period, which is when both ventricles pump the blood into the large arteries. In the systemic circulation, the left ventricle pumps oxygen-rich blood into the main artery (aorta). The blood travels from the main artery to larger and smaller arteries and into the capillary network. There the blood drops off oxygen, nutrients and other important substances and picks up carbon dioxide and waste products. The blood, which is now low in oxygen, is collected in veins and travels to the right atrium and into the right ventricle" ("How does the Blood Circulatory System Work?", 2019)

Understanding this flow is crucial in order to comprehend where a systolic and diastolic pressure reading is received. As the heart beats, a force is exerted against the walls of the arteries.

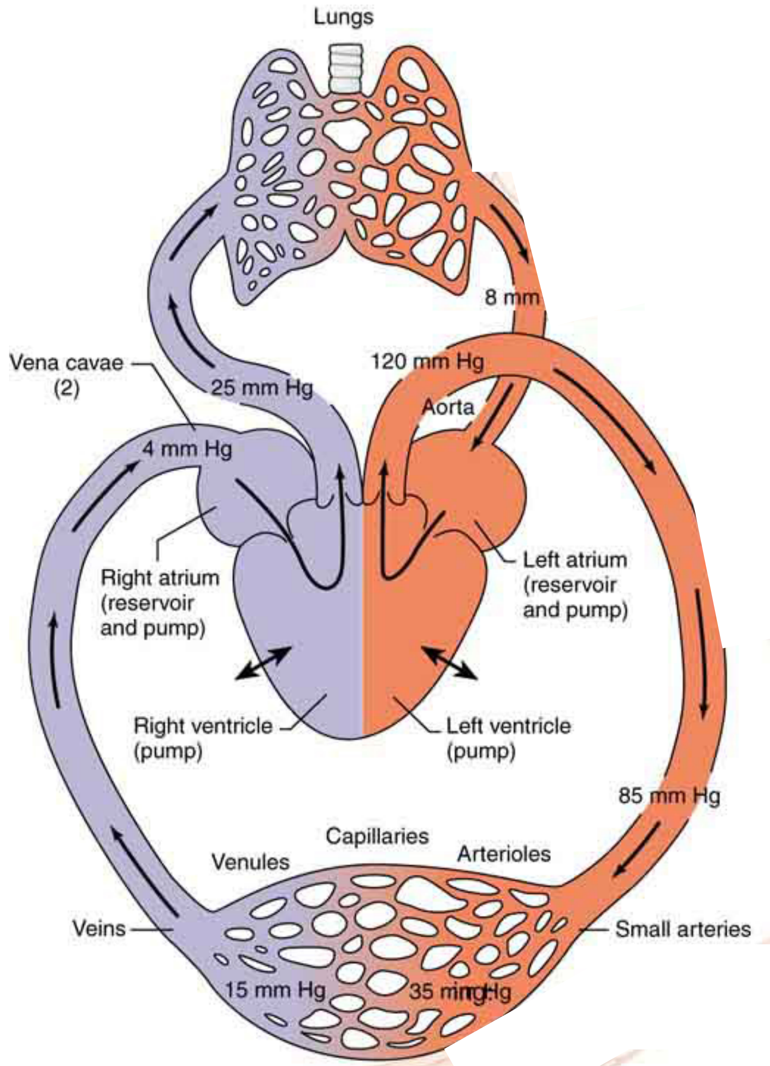

Figure 1. Understanding blood flow throughout the body helps us to understand the pressures in the body. After knowing how blood pressure comes about, we can figure out what factors affect the readings.
(Urone, 2012).
(Urone, P. P., & Hinrichs, R. (2012, June 21). Pressures in the Body - College Physics. Retrieved from https://openstax.org/books/college-physics/pages/11-9-pressures-in-the-body)

> "Systolic pressure (the top number) records the pressure as the heart beats and forces blood into the arteries. Diastolic pressure (the bottom number) measures pressure as the heart relaxes between beats" (Fernandez, 2017).

In the case of blood pressure, being able to determine a relatively high or low systolic or diastolic reading can eventually help diagnose a patient with a health condition. With an increased systolic pressure, one may be made aware of the functionality of their circulatory system. During exercise and rigorous types of activity, this value increases dramatically and shows a patient a way in which their blood pressure fluctuates. After this, the pressure returns to a normal range. On the other hand, an increase or decrease of diastolic pressure can help determine certain fluid imbalances that have occurred. An increased diastolic pressure may show…

> "ballooning of the blood vessels, which may be due to the transfusion of too much fluid into the circulatory system" (Urone, 2012).

In other words, if there is too much fluid in the blood vessels, the vessels will, in a sense, inflate and expand to abnormal measures. On the other hand, if we have a decreased diastolic pressure, we see that there is not enough fluid in the blood vessel. This can be cause by an internal hemorrhage in some cases. When a person is hemorrhaging, there is a lack of blood supply in the vessel, hence; the patient will potentially need a transfusion to compensate for lost blood. With this in mind, it is crucial to remember that there are many other factors that can affect a patient's blood pressure reading. Factors such as elasticity, which decreases with age, lack of physical activity, genetics, etc., all play a major role in blood pressure measurements. Without the appropriate machinery, it would be very difficult for a doctor or medical assistant to diagnose a patient the proper way.

As a matter of fact, being able to quickly and non-invasively take a blood pressure measurement would be ideal in today's day and age. A non-invasive method is more ideal because it is not realistic to invasively measure blood pressure, with the use a catheter, every time a patient needs something such as a blood pressure reading. A simple measurement, as such, should ideally be easy and quick to receive. Different types of digital and manual sphygmomanometers are used as ways of monitoring blood pressure. The mercury sphygmomanometer, a manual sphygmomanometer, also known as a blood pressure gauge, has been amongst the most common ways to receive a blood pressure reading. This machinery consists of an inflatable cuff that collapses and retracts with each pump given manually through an operated bulb. Although this is a common technique used at any doctor's visit, we see that many factors head to major variances in blood pressure readings. More specifically, factors such as a small cuff, the patient having their legs crossed, the patient speaking during a reading, an unsupported back, etc. all lead to a variance. This alone can be the determining factor as to whether or not a patient has hypertension.

More commonly with the upgrade of technology, a method of digital sphygmomanometer is used. This updated method, doesn't incorporate a stethoscope, but rather uses oscillometric measurements to help figure out blood pressure. We know that as blood is pumping in an artery, the arterial wall will vibrate hence, causing electrical signals that are then converted into blood pressure measurements.

More specifically, we've seen that factors such as no pulse waveform being provided has a major impact on diagnosis of a patient. As a matter of fact,

> "the arterial pressure signal provides two types of information that may help the clinician to interpret hemodynamic status better: the mean values of systolic, diastolic,

> mean and pulse pressures; and the magnitude of the respiratory variation in arterial pressure in patients undergoing mechanical ventilation" (Lamia, 2005).

With this taken into consideration, we understand that the pulse waveform does, indeed, possess additional information. There is a much bigger purpose behind the arterial waveform and can help much more than the generic results of a blood pressure measurement, hence, the cuff does not suffice patient requirements as much as it can.

Problem Statement

A main problem with the generic cuff in not just the amount of time it takes to receive a reading, but also, the fact that there is no pulse waveform and that it is not continuous from beat-to-beat. In the case of a patient's health, knowing more information is always better than knowing less and as mentioned earlier, blood pressure is an indicator to many underlying health conditions. Thus, being able to receive blood pressures alongside, with several waveforms. Although the most accurate method to receive blood pressure is an invasive method, in this research, we will be comparing our arterial tonometer measurements with the BD Assure Blood Pressure monitor. The BD Assure Blood Pressure monitor will serve as our standard of accuracy.

Unfortunately, we see that this new updated method, although good at giving accurate readings on mean blood pressure, does not do a good job at giving individual systolic and diastolic measurements. As stated earlier, being able to get an accurate and individual reading on both systolic and diastolic pressures is key in determining many underlying and serious condition that may be occurring in the body. Thus, methods such as digital sphygmomanometers should aim to be used at homes, where a doctor or trained practitioner is not there to properly perform an exam.

With all of these downfalls being taken into consideration, it is evident that change must occur. Hypertension remains as one of the easily most undiagnosed conditions due to “essentially ‘hiding in plain sight’” (Wall, 2014). The main reason for this is due to the fact that there are not many symptoms associated with hypertension. Many patients underestimate the strength and power that this health condition may have on one’s body. As a matter of fact, an “estimated 13 million people are neither aware of their hypertension nor taking antihypertensive medications” (Wall, 2014). This silent killer, if not controlled, can easily lead to many other serious health conditions such as heart disease and stroke.

“The Correct Way to Measure Blood Pressure”

1. Don’t eat or drink anything in the half hour before you take your blood pressure.
2. Empty your bladder before your reading.
3. Sit in a comfortable chair with your back supported for at least 5 minutes before your reading.
4. Put both feet flat on the ground, and keep your legs uncrossed.
5. Rest your arm with the cuff on a table at chest height.
6. Make sure the blood pressure cuff is snug but not too tight.
7. The cuff should be against your bare skin, not over clothing.
8. Do not talk while your blood pressure is being measured.

Figure 2. List of factors Affecting Blood Pressure Readings. Taking blood pressure in a doctor’s office has become such a careless action that one does not realize all the small factors that make a huge difference. Understanding these factors may help us get more accurate readings. (“Are You Wrong About Your Blood Pressure?”, 2017)
(Are You Wrong About Your Blood Pressure? (2017, May 15). Retrieved from https://www.cdc.gov/features/blood-pressure-tips/index.html)

<u>Hypertension: More Common Than You Think</u>

- 1 in 3 adults worldwide have high blood pressure
- 1 in 4 adults have prehypertension (a risk factor for high blood pressure)
- 1 in 5 adults have high blood pressure and aren't even aware of it

7% more Americans will have high blood pressure by 2030.

Figure 3. Hypertension. More Common Than You Think. This underlying health condition is extremely underestimated. As stated in the figure above, 'although it poses serious health risks, high blood pressure typically has no symptoms- so it often goes untreated" ("Getting a Handle on Hypertension", 2016).
(Getting a Handle on Hypertension [Infographic]. (2016). Retrieved from http://www.nwpc.com/getting-a-handle-on-hypertension)

As one can see, the cuff-based measurements do not meet the need of a hypertension diagnosis. A new method of arterial tonometry can potentially solve this problem, but one slight issue is the position sensitivity that comes with this method. Taking this into account, a new device must be brought into attention in order to improve how current blood pressure devices have been taking measurements.

<u>Thesis Statement</u>

This thesis will continuously show my solution to this terrifying problem. I have proposed the idea of a non-invasive fixed-deflection arterial tonometer with an adjusted calibration method specifically targeted towards systolic blood pressure values. With this adjusted calibration method, we are able to pick up values of force and relay them back to the patient in pressure measurements. The method of a tonometer incorporates a sensor which receives readings of force. With this reading of force, we can integrate the constant area, that we receive from the size of the force sensor, and eventually, receive a reading for pressure. After receiving this pressure from the tonometer, a calibration curve is created with respect to pressure, area, and deflection.

$$Arterial\ Pressure = f(Pressure, Area, Deflection)$$

Formula 1. The given formula stated above is a key component in order to ensure that the device is correctly calibrated.

Due to hypertension and other underlying heart conditions, a proper device to quickly and accurately take blood pressure is needed. We've seen that the method of applanation tonometry and incorporating force and area is an ideal alternative to current methods of taking blood pressure. Thus, we propose that the method of tonometry should be incorporated in a device in which we receive more accurate readings in a lesser amount of time and also, picking up waveforms that may assist in further diagnostic outcomes in a patient.

CHAPTER 2

LITERATURE REVIEW

Recent studies show that about one in every five people have hypertension and are not even aware of it. The root of this problem comes from the fact that the instruments that takes these measurements are inaccurate, time-consuming and extremely sensitive. As shown in Figure 2, there are many factors that affect blood pressure measurements. Although these factors are very slight, a huge variance can be caused by them which can then alter the proper diagnosis of a patient. In this literature review, we will see how different blood pressure techniques have developed over the years and how we have adjusted certain factors of these different devices to come up with our ideal device – the non-invasive arterial tonometer.

The first technique for blood pressure…

> "originated in 1733, when Sir Stephen Hales introduced a brass pipe connected to a glass tube into a horse's leg artery, and observed the rise of the blood column to "8 feet and 3 inches above the level of the left ventricle" (Rader, 2017).

It wasn't until "1855 [where a blood pressure could be taken non-invasively]" (Rader, 2017). This is a crucial time period due to the fact that although taking blood pressure non-invasively is the most accurate method, it is not ideal. As a matter of fact,

> "Intra-arterial measurement of BP is the most accurate method, capable of giving a continuous picture. Indirect recordings give a rough estimate of intra-arterial pressure but less information about the relationship between individual subjects and their environment" (Littler, 1989).

Taking blood pressure should be a quick, easy-to-perform procedure that can be done in less than a minute. As a matter of fact, it is crucial to get these readings in a short amount of time in certain emergency situations. The generic ‘cuff’ was not developed until 1901 which infers that this method may very well be outdated. With this taken into consideration, a method of radial artery applanation tonometry has been developed.

In a recent study, we see that the radial artery applanation tonometry was compared to using an arterial catheter, also known as, the most accurate method of receiving blood pressure. Once again, we cannot use this method due to the invasiveness this procedure requires. We see that this study was performed in a cardiac intensive care unit. With this in mind, it is good to see that the tonometer is extremely responsive and can receive readings in a timely manner. In conclusions, we see that…

> “In ICU patients, MAP and DAP measurements obtained using radial artery applanation tonometry show clinically acceptable agreement with invasive AP determination with a radial arterial catheter. While the radial artery applanation tonometry technology allows SAP measurements with high accuracy, its precision for SAP measurements needs to be further improved” (Meidert, 2014).

With these results taken into consideration, we are made aware that radial arterial applanation method is very much accurate when it comes to mean arterial pressure and diastolic arterial pressure. Unfortunately, when it comes to systolic arterial pressure, slight improvements are needed. Therefore, the goal of our device is to ensure precision in systolic measurements.

In an experiment performed by Meidert along with, other researchers, we will see the comparison between radial artery applanation tonometry, the same concept we are incorporating compared with an invasively-assessed radial arterial pressure. As mentioned earlier, we are made aware that an invasive measurement of blood pressure is the most accurate way to take a reading yet is not realistic due to the strenuous steps required for it. As the systolic arterial pressure (SAP), diastolic arterial pressure (DAP), and mean arterial pressure (MAP) are closer to the slope, we see a large correlation between the two methods. Each patients' results are shown individually and provide information about MAP, SAP, and DAP. We see that the MAP, SAP, and DAP measurements are closer to the line which infers that there is a higher amount of correlation between the invasive and non-invasive measurements. This helps support our claim of arterial tonometry with its definitive results.

In another study, we see how noninvasive measurements are taken through the method of radial artery applanation tonometry also known as, arterial tonometry. Breaking apart this statement, we see the concept of applanation tonometry applied to a radial artery which leads us to wanting to know what applanation tonometry actually is. Applanation means the irregular flattening of a convex surface, for example, an artery, a cornea, etc. Tonometry is a test that measures pressure inside a given surface.

> "Applanation tonometry is based on the Imbert-Fick principle, which asserts that the pressure (P) inside a sphere equals the force (F) necessary to flatten its surface divided by the area (A) of flattening, P=F/A.1 In practice, multiple methods use this concept of flattening the [radial artery] to measure [arterial] pressure" (Townsend, 2015).

$$\text{Pressure} = \frac{\text{Force}}{Area}$$

Formula 2. The following equation is based on the Imbert-Fick principle. This formula incorporates the concept of pressure and area which is what we are applying

In Figure 4, we see how the sensor (C), gets oriented over the radial artery (B) and how the perfect balance between applanation and arterial pressure is necessary in order to get a precise waveform.

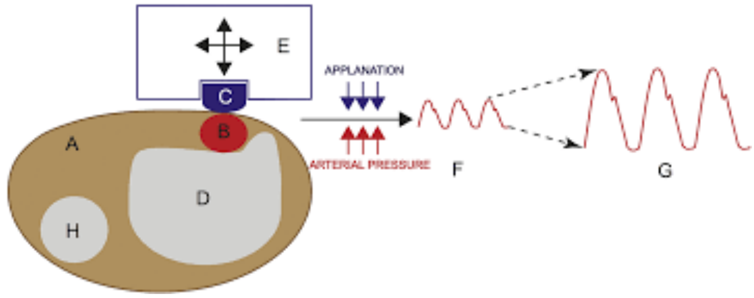

Figure 4. Partial Applanation Technique. Shown above is B → radial artery, C → Force Sensor, D → Radius Bone. We see that without correct placement of the sensor, it is difficult to get an accurate waveform. If the sensor hits the radius bone, pressure will be much higher than expected so one must be careful when using this device. (Prechtl, 2018)
(Prechtl, L. M. (2018, May 3). Applanation Tonometry for Continuous, Non-Invasive Blood Pressure Measurement in Intensive Care Medicine. Retrieved from http://mediatum.ub.tum.de/doc/1432555/1432555.pdf)

The sphere, in this case, is the cylindrical shape that the radial artery partakes. As the artery flattens, we see that the cylindrical shape that the radial artery expresses becomes more circular. As the artery is at its maximum deflection, we can see that the artery becomes a hemi-spherical shape where the circular region on top becomes the region of contact area. Given the force that the sensor picks up and the contact area that the device lays on, we are able to receive readings of pressure.

With these results also taken into consideration, we see that, as long as the correct pressure-area relationship is made, then values of blood pressure will come out accurate. In this case specifically, and while incorporating the proper pressure-area relationship, studies have shown that a pulse pressure only had a difference of 3 mmHg compared to an invasive measurement. This is a huge improvement to the original blood pressure cuff which at times, results in an "error in systolic blood pressure between 4 mmHg and 33 mmHg" (Berg, 2019). As mentioned before, with an error that big, it is important to adjust the device accordingly or to create a new one.

Understanding these reviews helps us confirm that our methods, which will be further explained, are justified. In our first review, we see that the method of arterial applanation is also a valid once. We see a slight restriction when it comes to the calibration of the device, so with our model, not only will we incorporate this pressure-area-deflection relationship with the use of the arterial tonometer, but we will also be sure to calibrate it the correct way in order for this device to remain compatible for all users. Incorporating different force sensitive resistors, we will be able to calibrate the device appropriately which will eventually lead us to a well-functioning device.

With this being said, we realize that there is an aspect of this arterial tonometry that is lacking. We see that without the proper fixed-deflection, the tonometer is extremely difficult to calibrate. Considering that we are manually applying force on the artery with the tonometer, we have developed a consistent method of calibration that will help resolve many issues that opposing arterial tonometers express. My thesis aims to develop a fixed-deflection tonometer with an incorporated calibration formula that incorporates factors of force, area, and deflection that may allow for more rapid Non-Invasive Blood Pressure by arterial tonometry.

After grasping the physiology behind blood pressure and incorporating different types of literature reviews, we are able to get an idea as to where we would like to gear our project. The method of a continuous non-invasive blood pressure device using the method of partial applanation tonometry has been seen as a reliable one and can be used as a more dependable device when compared to the generic cuff. As we have stated in the introduction, the generic cuff has many flaws to it. Unfortunately, the mercury sphygmomanometer has been the most common device that occurs at any doctor's visit due to its easy-to-use and relatively fast nature. We have seen that without proper precautions, this device will not take measurements accurately. This ultimately, will lead to many issues such as misdiagnosis of blood pressure and such. With this being taken into consideration, we see that many patients are now at risk for hypertension and many blood pressure related problems and will not even be aware of it. With blood pressure being known as the silent killer, it is crucial to ensure that we have devices that can perform the job that they are supposed to perform accurately and without fear that it will fail.

CHAPTER 3

METHODS

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a. Overview

The methods behind this thesis are split into a computational and experimental section. In the computational section, we create an accurate modeling as to what the arterial pressure pulse looks like. We incorporate raw data through an algorithm created in MatLab in order to see a visual comparison between what our raw data produces versus what our tonometer will produce. Through this, we are able to understand the pressure-area-deflection relationship. By seeing this comparison, we are able to identify certain functionality in our device, hence, are able to determine whether or not certain parts of the arterial tonometer needs adjustments.

The second part that will be described in these methods section is the experimental part. In this portion, we model the tonometer force during deflection. We are made aware of the components of the sensor and take a deep look into the properties behind a force sensor. We see that the force sensor receives readings that are picked up in volts which are then converted to millimeters of mercury through a calibration method that's established. Combining both the computational and experiments part are important in order to get the full picture as to what is expected and asked for from the arterial tonometer that we have made.

b. Part 1: Modeling of Arterial Pressure Pulse

To begin building our prototype, we begin by incorporating raw data in using an algorithm in Matlab. The reason why it is important to do this is due to the fact that with this algorithm, we will be able to get an idea as to what our signals should look like. There are many pros that Matlab has that we should take advantage of. Being aware of these various advantages will help in ensuring an accurate representation of what is expected of us with the physical tonometer.

We begin part one of our algorithm in Matlab by plotting pressure versus time. With this initial graph, we are able to see the general waveform a pulse creates when being recorded from the artery. We set constants for the average radius of a human artery and for the diameter of the sensor which will eventually be used to determine the area of the deformed artery. Incorporating these constants, we are able to find the general pulse pressure while including the mean arterial pressure (MAP).

$$P\ (1{:}\,length(time)) = MAP + A1.* sin(w.* time(1{:}\,end)) + A2.* sin(2.* w.* time(1{:}\,end) + PHI);$$

Formula 3. Array of Simulated Pulse Data.

- MAP→ Mean Arterial Pressure
- A1 & A2 → Fourier Series Generation of Pulse
- W→ frequency

Incorporating these constants and arrays, we are then able to generate a general waveform made from raw data.

The second important relationship to visualize is the contact area versus deflection. We make contact area known as the amount of area that is converted by the force sensor, which we will revisit later when speaking about the equipment that this tonometer consists of.

The last relationship that was established through all of this was a pressure versus deflection graph. We see that when we incorporate our first relationship of pressure and time to our second relationship of contact area and deflection, we receive our third relationship. This third relationship of force versus deflection is then automatically correlated to our fourth relationship of pressure versus deflection which essentially is the pulse waveform once again. We see that we have made a full circle in terms of the relationships that are expressed using the following raw data. With this taken into consideration, we are now able to get a very good idea as to what waveforms should be expected when receiving measurements from our waveforms. Attached in the Appendix are the core algorithms that were taken into consideration while incorporating Matlab. All images can be seen in the Results section.

c. Part 2: Modeling of Tonometer Force

After fully grasping and understanding the methods behind the simulation portion of this research, we are then able to move on to the more electrical and mechanical components of this research.

The final prototype of the arterial tonometer consists of a Honeywell FSG Force sensor (FSG005WNPB), a D-Sub Connector, and a tube casing.

Force Sensors have a wide variety of applications and are used for their noted high accuracy and ability to be customized to different systems. As far as medical applications, force sensors have been used in

> "infusion pumps, ambulatory non-invasive pumps, occlusion detection, kidney dialysis machines, and enteral pumps" (Hoske, 2011).

The FSG Series force sensor is…

> "uncompensated and unamplified, they offer infinite resolution on the pressure signal. The frequency response is limited only by the end user's system" (Hoske, 2011).

The Force Sensing Resistor used is the FSG005WNPB, manufactured by Honeywell Sensing and Productivity Solutions. This product can be found on the Digikey website by searching the Digi-Key Part Number 480-5692-ND. It can also be found in the manufacturer's catalogue.

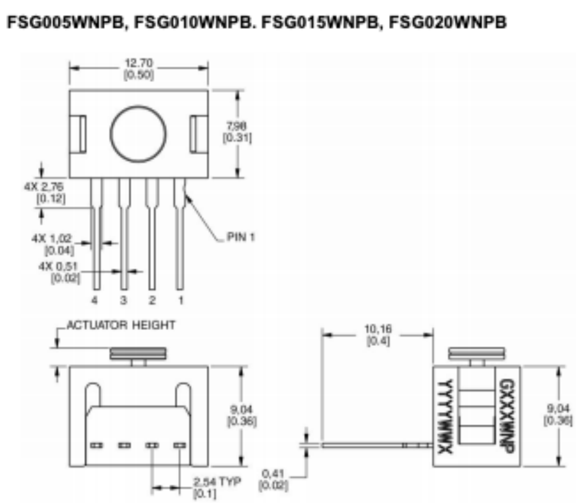
The FSG005WNPB, or FS5 for short, works on an operating force between 0 and 5N with a resolution to 0.0098 N for improved accuracy. The product also features extremely low deflection, about 30 μm (which aids to reduce measurement error). This low deflection allowed for the calculation of the precise deflection required in order to get a consistent and accurate blood pressure reading. Other features of this device that make it a consistent and reliable device include a “low repeatability error (±0.2% span) along with a low linearity error (±0.5% span)” (“FSG Series: Force Sensor”, 2013) which adds to improved accuracy over the entire force range measured. The Product Sheet also cites a “low off-center loading errors improves system accuracy due to mechanical misalignment” (“FSG Series: Force Sensor”, 2013) which continues to indicate a reduced possibility of user error and improved readings. Overall, the FS5 is highly accurate and allows for consistent and continual force readings, perfect for this application.

The FS5 was chosen not only for its accuracy, but for its fast, efficient and compact design. The FS5 has a typical response time of 0.1 milliseconds and a maximum recorded response time of 0.5 milliseconds. This allows for immediate force readings, which, when compared to the typical time it would take for a user to apply a sphygmomanometer (manual blood pressure cuff), is far superior in an emergency setting. The FS5 has “low power consumption allows use in battery applications” (FSG Series: Force Sensor) which would allow the device to be transportable and reduces the need for additional equipment. The device also has a “high ESD resistance of 8 kV [which] reduces special handling during assembly” (“FSG Series: Force Sensor”, 2013). Which allows for more user error without recourse during assembly.

The FS5 does have an overforce value of 15 N, which means the sensor should not withstand a force of 15 N without damaging the device. This is not an issue for the application of the device for this paper as no force readings would be expected above 5 N, however it should be noted as the device will not withstand rugged use, such as being thrown against the ground, plunger down. This only indicates that the device should be cared for as any other medical equipment would. The device is also limited in the temperature that it can be stored at, with a range from -40 °C to 100 °C, but for this application it will always be well within the range and is not cause for concern.

This series of force sensors has the flexibility of self-calibration which evidently has the benefit of being unique and specific to our system. This sensor is mainly known for its piezoresistive properties. This simply implies that there are miniature silicon sensing elements inside the sensor. With this kept in mind,

> "force sensors operate on the principle that the resistance of silicon-implanted piezoresistors will increase when the resistors flex under any applied force. The sensor concentrates force from the application, through the stainless-steel plunger, directly to the silicon-sensing element. The amount of resistance changes in proportion to the amount of force being applied" (Hoske, 2011).



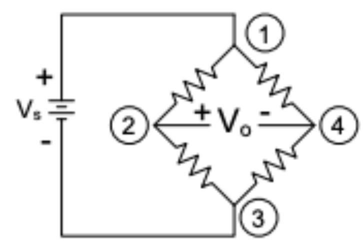


Figure 5 (left) & & 6 (top right) & 7 (bottom right). Figure 5 displays the sensor mounting dimensions in mm/ [in]. The key dimension that is important is the area of the sensor. Incorporating the area with force will give us our pressure. Figure 6 is a schematic of the excitation expressed by the internal wiring of the system where pin 1 is the supply voltage (+), pin 2 is the output voltage (+), pin 3 is the ground voltage (-), and pin 4 is the output voltage (-). Figure 7 is an image of the force sensor we are using. We see that the sensor is a circular shape and will be picking up force readings which will get transferred with the D-Sub connectors into Biopac.

After adjusting aspects of the tonometer, we came to find out that having it in one fixed position is a better route to take in terms of precision and accuracy. Without this extra component of variable deflections, we are able to ensure a more stable device which plays in the users favor. Ensuring the relationship between pressure and deflection would not be possible without the motor being incorporated into the device.

The primary purpose for the D-Sub connectors is to build an electrical connection between the tonometer and the Biopac. The Biopac provides power as well as the signal processing . Without these connectors, it would be nearly impossible to receive our force readings that would be later converted into our pressure readings. We insert our 9-pin D-Sub connector into Channel 1 in the Biopac where we begin our process our receiving blood pressure recordings.

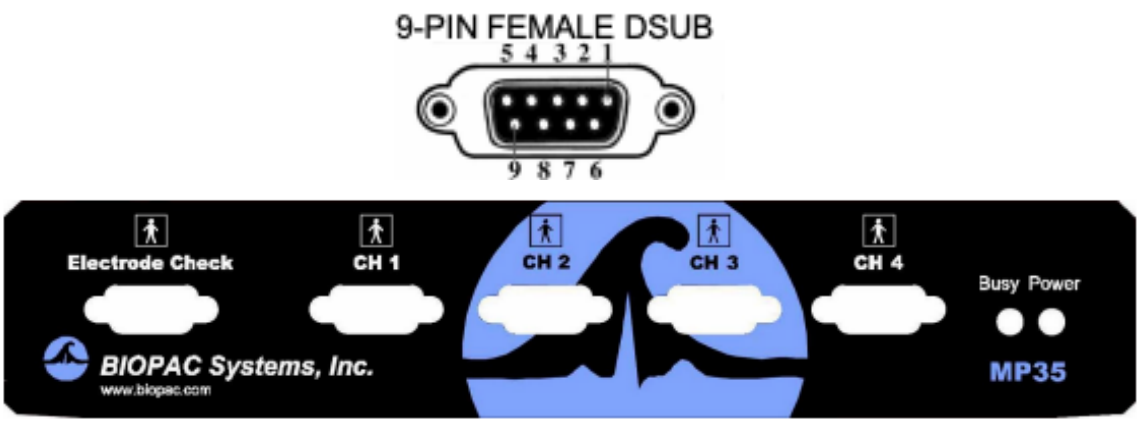


Figure 8. The D-subminiature ("D-sub") connectors may vary in different size. We specifically used a 9-pin D-sub connector (shown under layout of the Biopac machinery) which got connected to the Biopac MP35 into Channel 1.

Lastly, the purpose behind the tube casing was essentially to provide a protection to all wires and parts that made up the tonometer. Its very basic function is necessary to the functionality of the product.

Figure 9. In the image above, we are able to see how the casing in the tonometer helps hold everything together and in place. This is key in order to ensure no loose ends come out and that our tonometer stays functioning.

All in all, with the appropriate combination of all of the above-mentioned parts, along with the Biopac MP36 Device, we receive a functioning tonometer. Confirming the performance of this device and it's consistent and anticipated behavior, we are able to move on the receiving our desired force readings. We begin this process by performing various types of calibration processes. After proper verification of the desired calibration procedure, we can finally move onto the final goal of this research which is to receive the blood pressure measurements.

With this final design, we are able to confirm functionality in our prototype. Shown below is the fixed-deflection tonometer setup at its top view, side view, and front view.

In order to study the effect of using a fixed positioning tonometry, the following apparatus was designed to provide various degrees of fixed deflection as shown in figure 10. Understanding this sort of positioning will help in the long-term process of this tonometer.

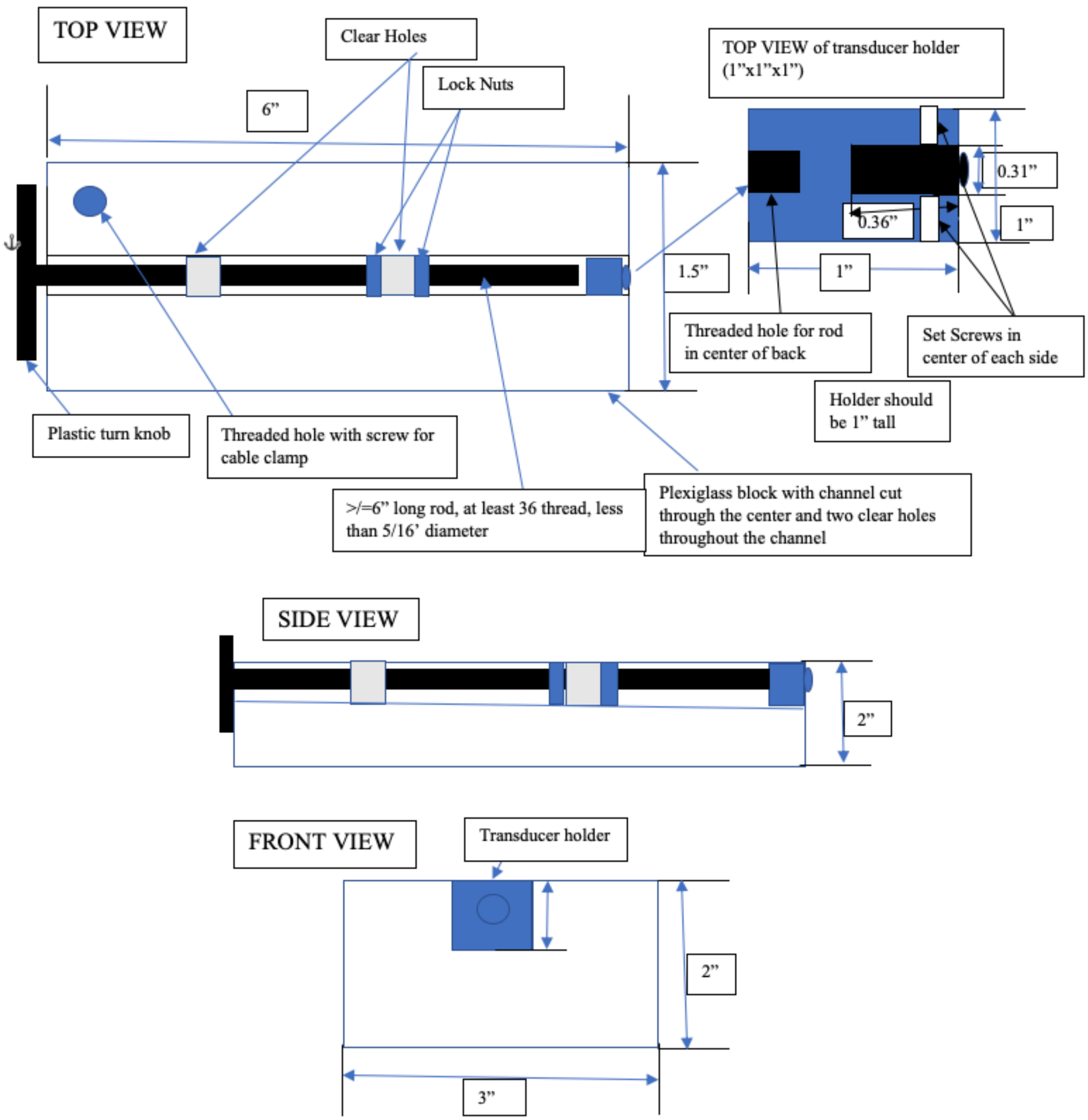


Figure 10. The top half of this diagram shows the top view of how the tonometer would look. It includes all the different screws, holes, materials, etc. that are used in this tonometer. The bottom half of this diagram shows the side and front view of the tonometer. Here we not only see dimensions for the tonometers, but we also get the full image of what the tonometer would look like. Understanding the effect of the fixed-positioned tonometer is crucial in ensuring results from our tonometer.

a. Force Calibration Procedure

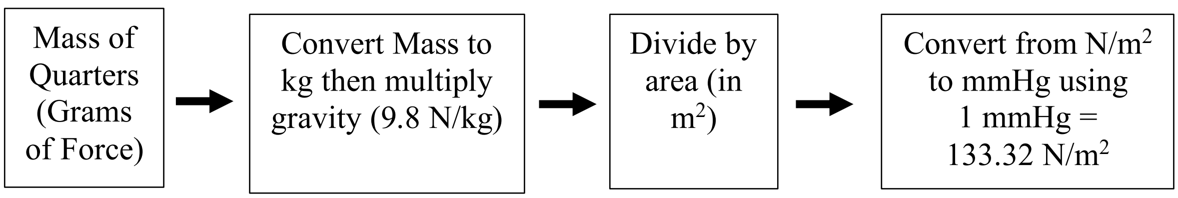
The noninvasive blood pressure monitor is a device designed to measure cardiovascular behavior and display the activity on a computer screen. It does so by detecting changes in blood pressure associated with pulse in a patient's radial artery. The device, which utilizes a pressure-sensitive transducer, is applied to the distal end of a patient's wrist, above the radial artery, and held there for a period of time, during which the device measures changes in pressure in the radial artery. The device converts these pressure measurements to voltage. The device is wired to a Biopac MP35, as mentioned prior, which can assess the change in voltage correlating to the changes in pressure and displays this voltage as a continuous waveform over time on a computer monitor.

The device is calibrated by using quarters, of consistent mass (5.67 g.), which are stacked one atop the previous on top of the device. This eventually records the spike in voltage and is displayed on the screen. The spike in voltage, as expected, was decently consistent each time, so we used a linear regression model to create a line of best fit, which turned out to be $V = 33.1F - 1.41$, where V equated to voltage in units of Volts and F equated to force in units of Newtons.

As we are aware, a common blood pressure reading in giving in units of millimeters of mercury. Considering these standard units, a conversion process must be incorporated in order to receive our pressure in these units.

b. Pressure Calibration Procedure- Conversion of Voltage to Pressure

From there, we needed to convert the equation to a function of pressure in terms of voltage. In order to convert from force to pressure, we needed to divide by the area of the sensor that was found on the spec sheet and equated to about 1.735×10^{-5} m^2, and convert to mmHg, our common unit of pressure, from $\frac{N}{m^2}$. Our final equation equates to ***P = 12.95V + 18.257***, where P equates to pressure in units of mmHg and where V is our input voltage that the Biopac receives.



c. Procedure for Tonometer versus PPG Experiment

The second component of our device is a measurement of pulse. To measure pulse, we used a Biopac compatible photoplethysmography (PPG) sensor and fastened that to the patients left thumb.

> "PPG is a non-invasive technology that uses a light source and a photodetector at the surface of skin to measure the volumetric variations of blood circulation" (Castaneda, 2018).

With this device, we are able to receive a signal that essentially resembles a blood pressure wave. This device alongside, with the arterial tonometer may be used as a means of justification and verification towards our device. We set the transducer, as usual against the patient's left radial artery, and compared the pulse frequency measured by the PPG and by the transducer. We assumed that since the thumb and radial artery are close in proximity, and connected vascularly, that the results should be quite similar, and they proved to be so.

CHAPTER 4

RESULTS

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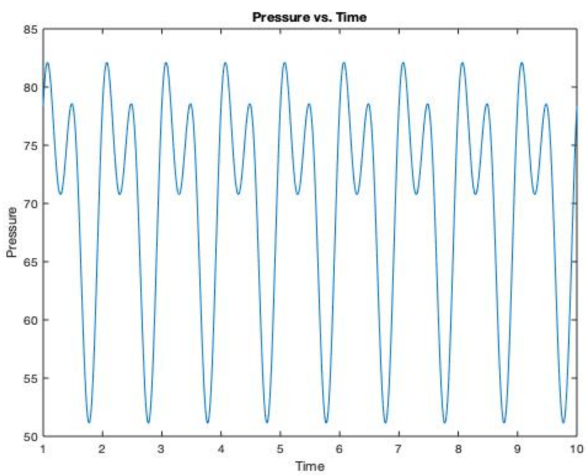
a. Results- Computational

Post developing an algorithm in Matlab, we receive results from the raw data that we implicated in our code. Being able to decipher a clear relationship between pressure, area, and deflection is crucial towards our findings of blood pressure with our improved device.



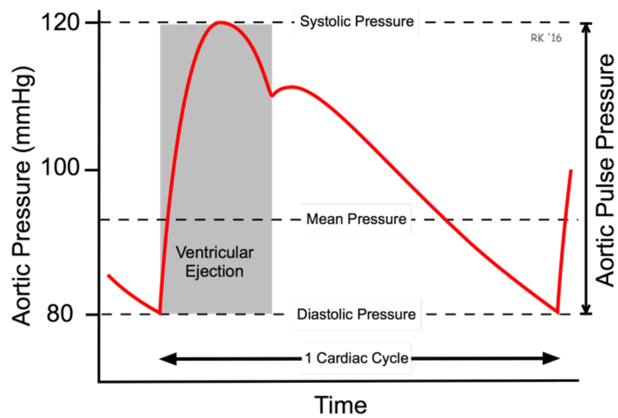


Figure 11 (left) and Figure 12 (right). On the left, we see the results of a pressure versus time graph produced through raw data in MatLab. On the right, we see that breakdown of each cardiac cycle and how we can confirm that the graph of raw data that we have made is accurate.

(Klabunde, 2016)

("Klabunde, R. E. (2016, December 8). Arterial Blood Pressure. Retrieved from https://www.cvphysiology.com/Blood Pressure/BP002)

From the image above, we see that the simulation in MatLab is a similar to the behavior that the cardiac cycle expresses. Being able to understand the basics in the pressure recordings is essential and leads us to getting one step further in fully understanding our pressure, area, and deflection.

The next relationship that is of importance is the contact area versus deflection relationship. We are made aware that as the tonometer is more deflected into the surface of the skin, the radial artery flattens and contains a larger surface area. The contact area stays at a constant value due to the fact that this is solely based on the diameter of the attached force sensor. Using the formula for the area of a circle (the shape of the sensor), we receive the desired value. We see that are deflection increases, that is, the deeper that the device penetrates the skin into the artery, we get more accurate readings as expected. Contact area and deflection express a linear relationship which means that as we deflect the device deeper into the artery, our contact area is slowly increasing to the ideal size. At a certain part of this graph, we see a linear jump. We came to find out that this jump is where the artery is fully flattened. When the artery is full flatten, we are made aware that the most accurate reading is taking place. This is due to the fact that when the artery is fully flattened, we ensure that the full contact area of the sensor is touching the area, hence picking up as much signal as it can be.

After establishing this relationship, we integrate the component of force. We receive these components of force by incorporating the pressure and area relationship that was discussed prior. Using the same raw data, we are able to establish an extremely significant relationship between low and high deflection along with force. We see that this graph ultimately becomes the perfect combination between the pressure versus time graph alongside with the contact area and deflection relationship. Similar characteristics such as the ‘jump’ that occurs in the graph are also present after the combination is established.

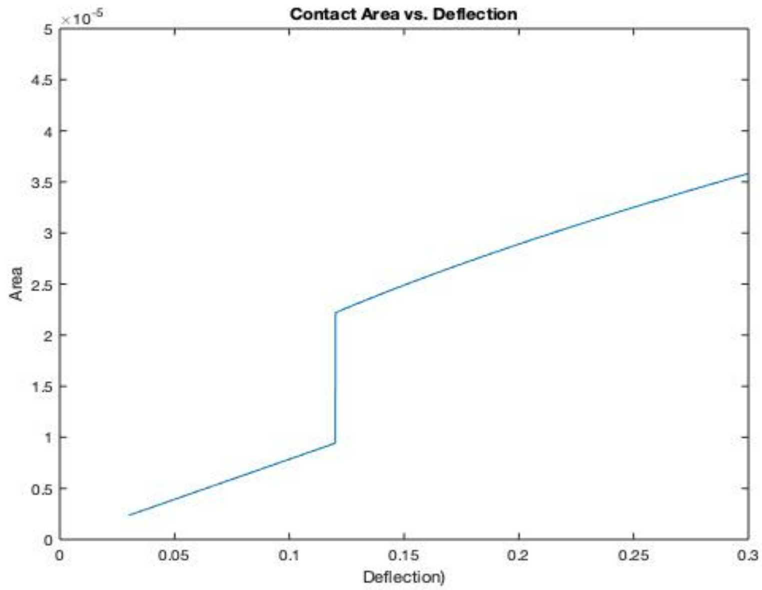
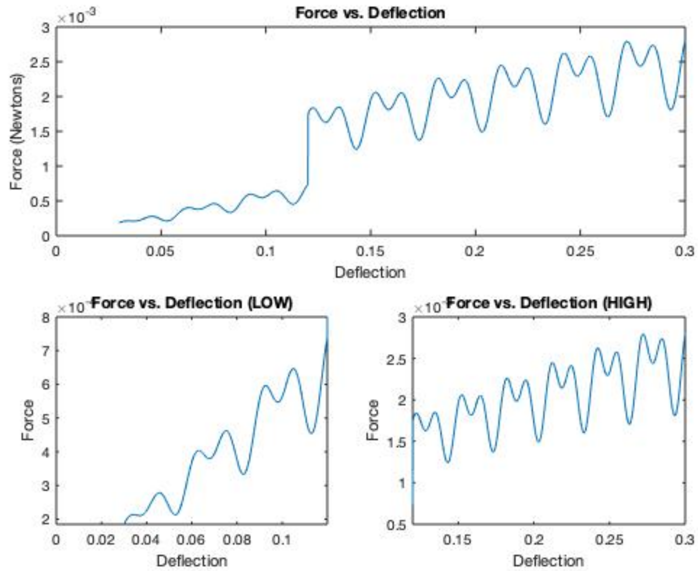


Figure 13. Above, the results to contact area versus deflection are shown. As deflection increases, as does contact area.

The jump that is seen here represents the deflection at which we receive the most accurate force readings. When understanding this value, we are able to move one step forward in establishing the fixed-deflection aspect of our problem statement. The next relationship we will take a look at involves a combination of pressure mixed with deflection and area. This is the main relationship we much truly get a grasp on in order to move further in the process of getting an arterial tonometry with full functionality.



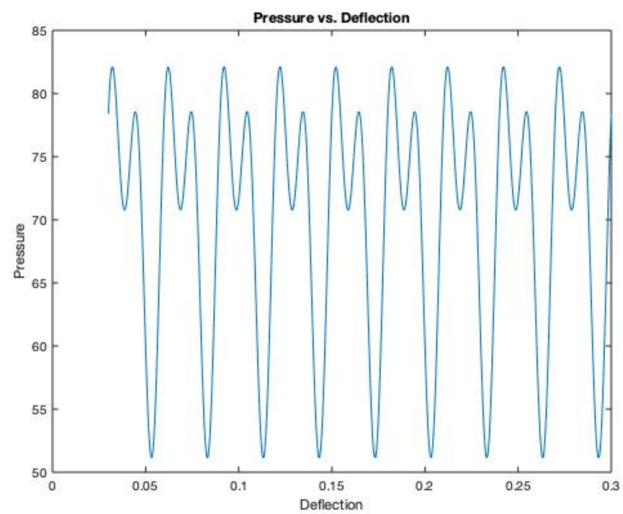


Figure 14 (top) and Figure 15 (bottom).
The following figures display the results received from our algorithm that was produced with the Matlab software. As we can see here, our first and last graph are almost exact replicas of each other. This is the prime example of how we've made a full consensus on how all our relationships are connected and related to each other.

Seen above is the relationship between force versus deflection. Considering this relationship, we now know what waveform we should expect when taking recordings with our arterial tonometer.

b. Results- Experimental

The theoretical data supports our experimental results; however, the patient's blood pressure was measured to be between 140/120 mmHg, which is abnormally high, since it was known that patient has a healthy blood pressure (120/80 mmHg), from previous doctors' visits. The explanation for this, however, is that the patient did not properly rest prior to taking a measurement. Initially, the blood pressure was shown to be 238/225 mmHg, an impossibly high measurement which should have corresponded with the patient suffering a fatal stroke, but as time progressed, the measurement decreased until it almost reached the standard range, when we stopped measuring. We simply did not measure for a long enough period of time for the patient to have fully rested and for their blood pressure to subside to a resting rate. In the future, a worthwhile experiment would be to calculate the time which it takes for the patients blood pressure to subside, so that the proper blood pressure can be measured and so that future calculations can then be made quicker and more efficiently.

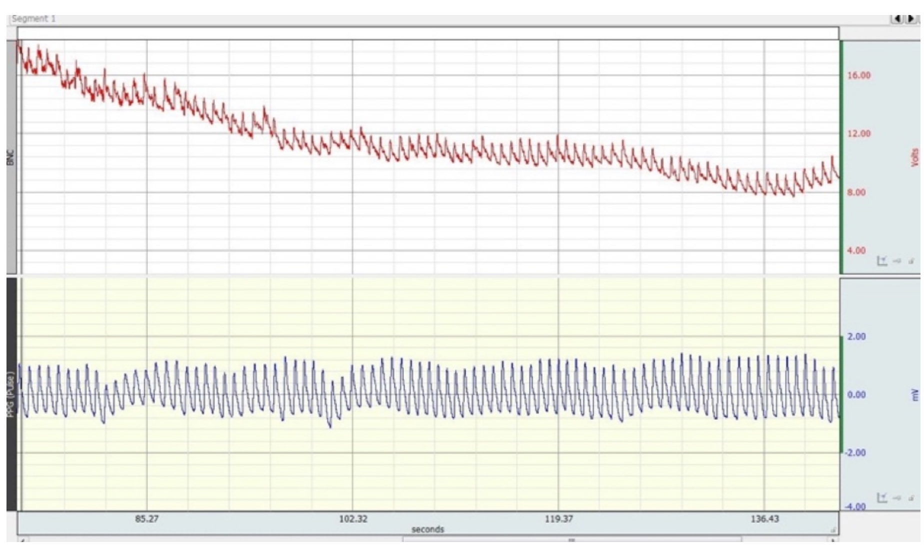


Figure 16. The voltage measurement, on top in red, clearly decreased, demonstrating the patient resting over a period of time.

After establishing the relationship between pressure, area, deflection and taking on a genuine understanding of how each are related, we were able to move on to further calibration through using the quarters. After establishing the final formula of ***P = 12.95V + 18.257***, we are able to take these pressure measurements that are read in volts, and automatically convert it to a more common unit of pressure, which in this case would be millimeters of mercury. While we are aware that a blood pressure reading comes with both a systolic and diastolic blood pressure reading, we set our main focus on readings from the systolic part. This is mainly due to the fact that the systolic value

> "measures the force of blood against your artery walls while your ventricles — the lower two chambers of your heart — squeeze, pushing blood out to the rest of your body… [The diastolic blood pressure] measures the force of blood against your artery walls as your heart relaxes and the ventricles are allowed to refill with blood. Diastole — this period of time when your heart relaxes between beats — is also the time that your coronary artery is able to supply blood to your heart" (McDermott, 2018).

With these factors taken into consideration, we may see why it is a much better idea to focus on the systolic part of our blood pressure reading. In the table below, column 1 represents readings that are picked up and converted through our methods using arterial tonometry and the Biopac. Whereas in column 2, we see readings that we picked up from the BD Assure Blood Pressure Cuff. After receiving several readings from several subjects, we are able to test the correlation between the two devices, which will tell us how similar each result is to one another and the p-value. With a p-value less than 0.05, we can be assured that our data is of statistical significance. In this research, we would like to stick to a two-tailed t-test due to the fact, that the direction in which these values may vary does not matter hence, having a more flexible range for potential readings.

During recordings for this test, we make the patient perform Valsalva maneuvers, that is pinching one's nose and forcefully exhaling out.

> "The compression of the aorta initially causes the blood pressure to rise. A sensor in the carotid artery, called the baroreceptor, detects the increased blood pressure. This activates parasympathetic fibers, which quickly reduce the heart rate and blood pressure. Doctors sometimes refer to this effect as vagaling. The Valsalva maneuver reduces cardiac output, which is the amount of blood that the heart puts out with every beat. The individual may feel lightheaded or dizzy as a result. Once the baroreceptor senses the decrease in heart rate and blood pressure, it will stimulate the sympathetic nervous system. This can cause a person's heart rate and blood pressure to increase, offsetting the parasympathetic effects" (Nall, 2018).

Those who performed the maneuver will be highlighted in red in the table found in the Appendix.

The pulse waveforms were almost perfectly in phase, which demonstrated worthwhile pulse measurement comparable to a simple PPG.

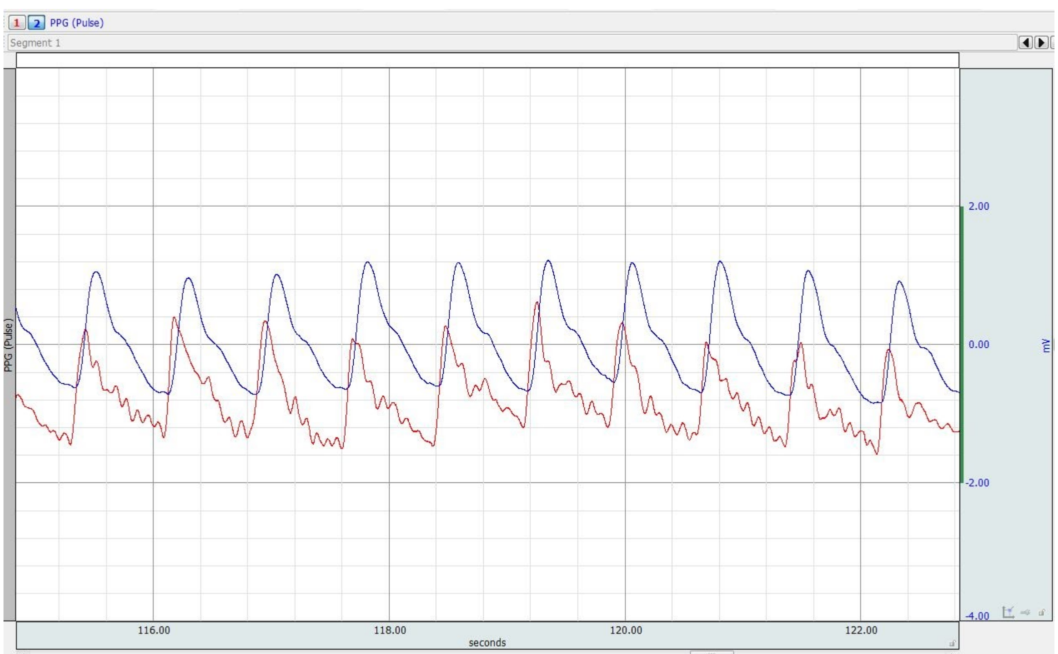
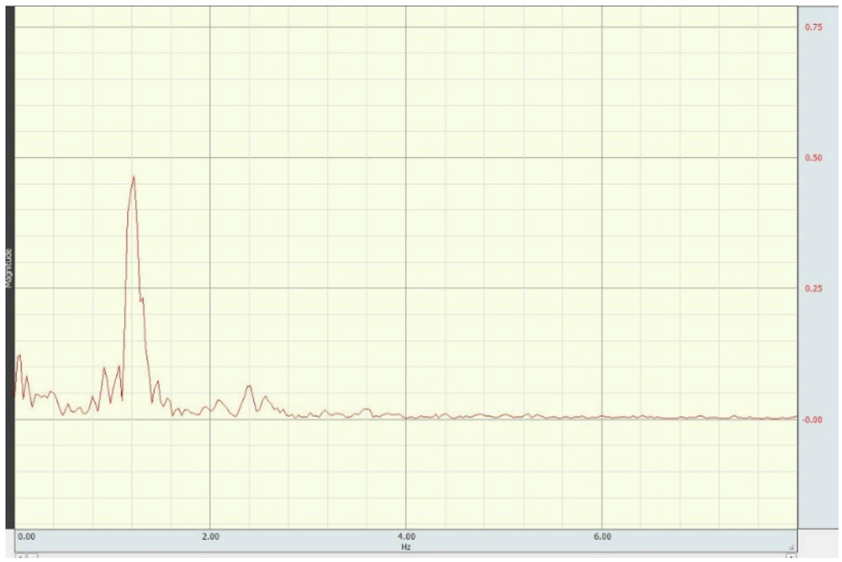


Figure 17. PPG (blue) and Transducer (red) pulse measurements nearly in phase.

After putting both waves through a Fast Fourier Transform (FFT) algorithm, which essentially transfers our function of time into a function of frequencies, we see that out the pulse frequencies were further shown to be nearly equal.



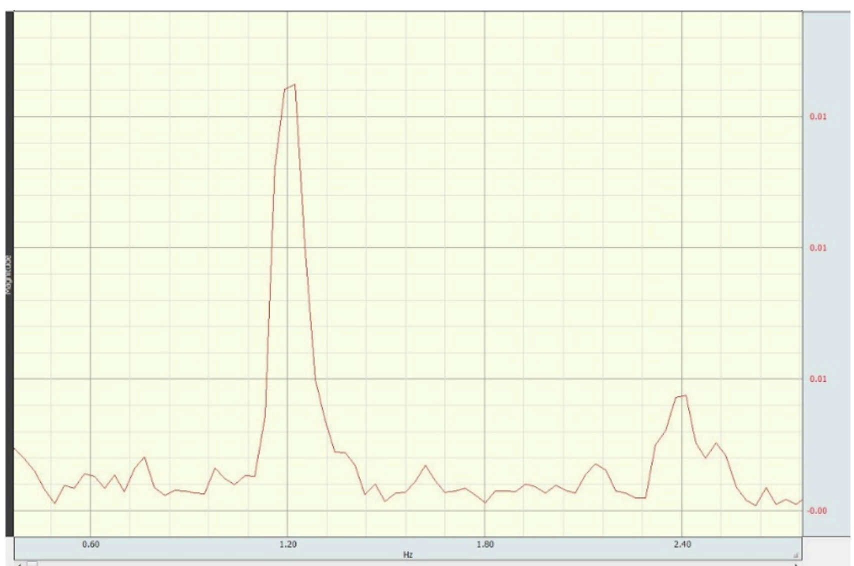


Figure 18.
(Top) PPG FFT with a peak at ~1.2 Hz (72 BPM).
(Bottom) Tonometer FFT with a peak at ~1.2 Hz (72 BPM)

c. Experimental Data Analysis Section

With this calibration set in place, it evidently becomes shown that accurate results can be taken and that the functionality of our product is very much legitimate. We can now proceed to receiving final results and performing several analysis methods on them.

t-Test: Paired Two Sample for Means		
	Variable 1	*Variable 2*
Mean	121.6291	115.7
Observations	10	10
Pearson Correlation	0.833191389	
Hypothesized Mean Difference	0	
df	9	
t Stat	2.639256382	
P(T<=t) one-tail	0.013473304	
t Critical one-tail	1.833112933	
P(T<=t) two-tail	0.026946608	
t Critical two-tail	2.262157163	

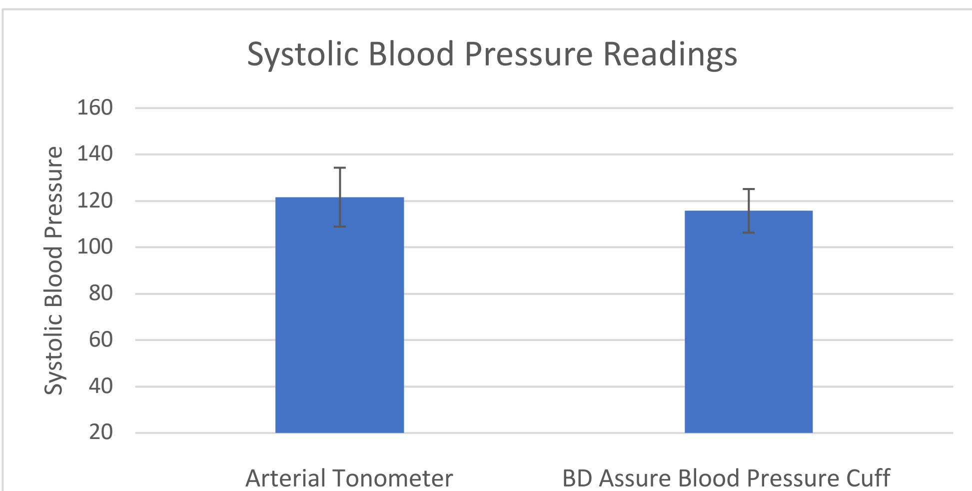


Figure 19. The above graph shows the average values of systolic blood pressure received from the arterial tonometer and from the BD Assure Blood Pressure Cuff. We see a very similar average and relatively low standard deviations.

As we can see from the following data above, the values between our arterial tonometer and the blood pressure cuff we're highly correlated and have very similar means. We state our null hypothesis to be that the values between the tonometer and the cuff are similar. After performing a two-tailed t-test, we receive a p-value of 0.026 which is less than 0.05. With this being said, we reject our null hypothesis and are made aware that our values from the tonometer is different than the values of the cuff pressures. We see that the tonometer reads higher by about 5 mmHg. This is what we expect due to the pulse wave effects from the brachial, the artery from the cuff readings, to radial, the artery from the tonometer readings, propagation.

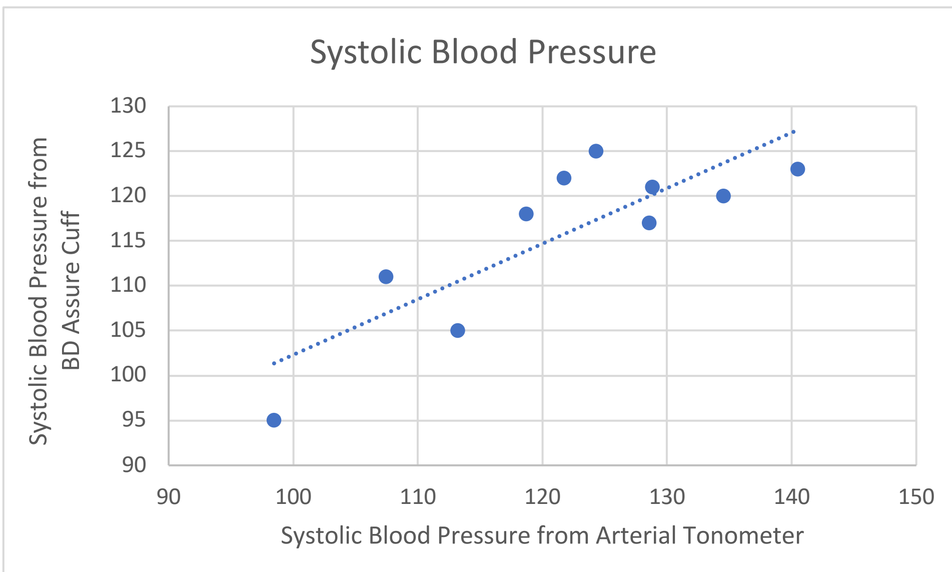


Figure 20. Shown above is a scatterplot with all systolic measurement given from the BD Assure Cuff versus the arterial tonometer. As stated either, the closer these data points are to the line, the higher correlation that is present in the experiment.

In the graph shown above, we see that when values given from our arterial tonometer are compared to values given from the BD Assure Cuff, there is a similar correlation amongst the two values. More specifically, post-running a t-test for a pair of sample means, we see that our correlation is about 0.83! This is extraordinary and very similar to some of the early research that we have done. With this, we have confirmation that the methods that we use and incorporate are significant and reliable.

One final type of error analysis that was performed on the data presented in the Appendix is a Bland-Altman Plot. The purpose of the Bland-Altman plot, also known as, a difference plot, is used in order to analyze the agreement between two different sets of the data. In this case, the two different sets of data consist of the difference between the arterial tonometer systolic blood pressure and the BD Assure blood pressure cuff along with, the mean of the same components. A bias was then calculated through the mean of all the differences found and equated to about 5.9291. The standard deviation of the differences was then used to calculate a lower and upper limit of agreement.

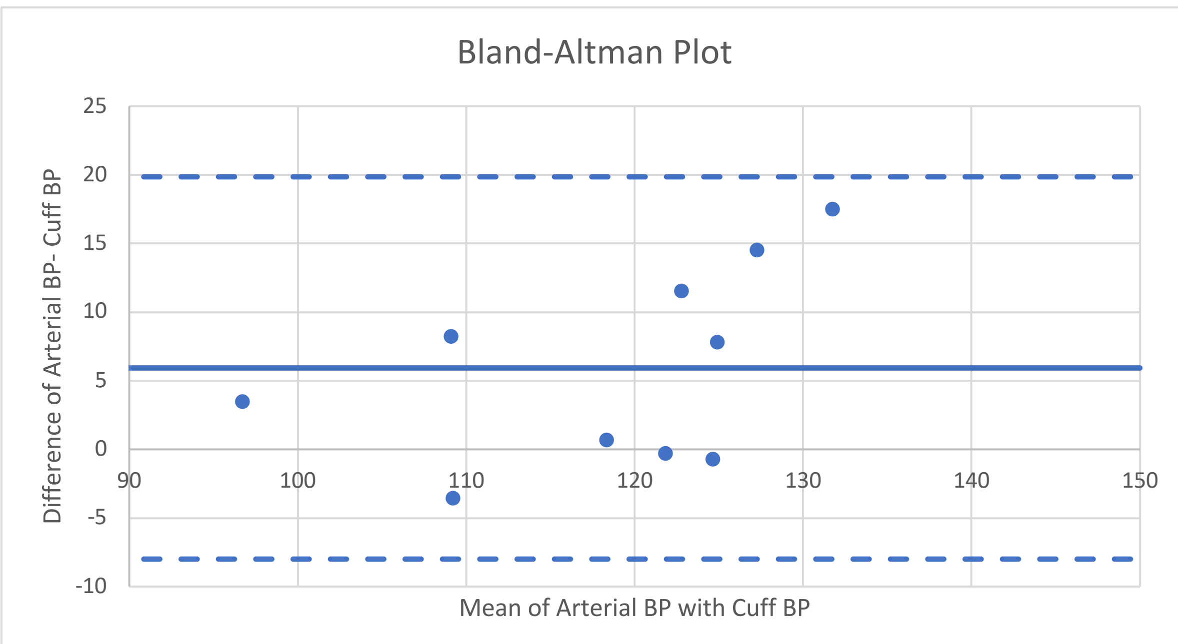


Figure 21. The Bland-Altman Plot for all data points collected during the arterial applanation tonometry with fixed-deflection is shown above. As we can see above, all of our values fall in between both the lower and upper limits of agreement.

CHAPTER 5

DISCUSSION

As discussed earlier, the radial artery applanation tonometry method has been attempted before but has had faulty results due to many distinctive factors. Amongst these factors lies calibration. Without our easily simplified method of calibration and without plotting the corresponding linear regression, the final formula that we had ended up with would have not been able to be made. We are easily able to take our readings that are picked up in volts and convert them to millimeters of mercury within seconds of getting a reading. On average, we take about ten to fifteen seconds per reading which is extraordinary while the cuff took at least forty-five seconds. With this time delay, we can see that a lot of time may be wasted on a patient that much be more quickly diagnosed. Blood pressure is a very good indicator of underlying health conditions so this method of quickly being able to take a better blood pressure will be crucial in the long run for the patients' survival.

When comparing our results to the first article in our literature review, "Radial Artery Applanation Tonometry…." By A. Meidert, we see that our correlation to the generic cuff alongside with the arterial tonometer resulted in high correlation. We are aware that the closer the correlation is to one, the more correlated the two values are. With a correlation value of 0.83, it is confirmed to say that our results are promising. The problem that this article initially faced was the fact that systolic arterial pressure was not accurate, yet, values such as diastolic arterial pressure and mean arterial pressure were.

Therefore, the goal of our device was reached by ensuring precision in systolic measurements.

In another study, “Accuracy of a Continuous Blood Pressure Monitor Based on Arterial Tonometry” by Takayuki Sato, we see that methods such as the Valsalva maneuver were similar just as in our experiment. Similarly, to this experiment, we see that our results are still statistically significant when comparing to the two methods. Also, similar to this experiment, we had two main focuses that were directly aligned with another. One being that there is a correspondence of the waveforms of blood pressure, as shown in Figure 16. This correspondence was well-established from the origins of the calibration. As anyone is aware, in order to have strong results in anything, the roots must be strong as well. Thus, confirming that our calibration was precise and favorable led us up to our promising results.

The second focus of this project was the correlation and agreement between the blood pressure values that were being displayed. The gold standard for accuracy is an invasive method, the catheter, which was used as a method to compare the blood pressure received from Sato’s device. Taking into account the limitations to our research, we are unable to use the catheter as our comparison device, but instead, are able to use the BD Assure Blood Pressure Cuff, an automatic cuff that also, gets readings of blood pressure. Shown below, we see that the level of accuracy exhibited by the cuff when compared to the arterial tonometer was acceptable, thus served as a valid comparison with our device.

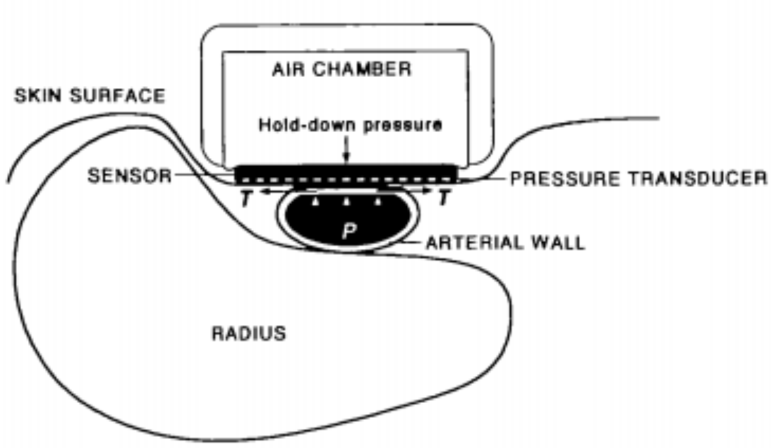


Figure 22. Above is the image of the arterial tonometer. We see that arterial pressure is measured by applying a force over the artery which causes it to flatten.

As we move further in our research , we consistently see many similarities between our experiment and the similar experiment that was performed by Sato as well.

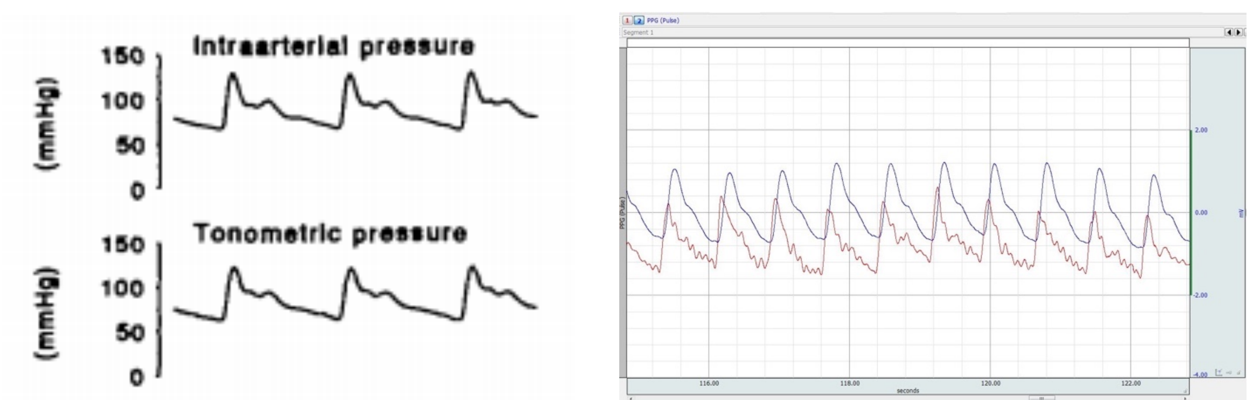


Figure 23. We confirm similarities in our results with results shown in a similar experiment. In the two images above we see how Sato's experiment (left) compared to my experiment (right). The waveforms that are expressed are almost identical which proves initial functionality in calibration methods.

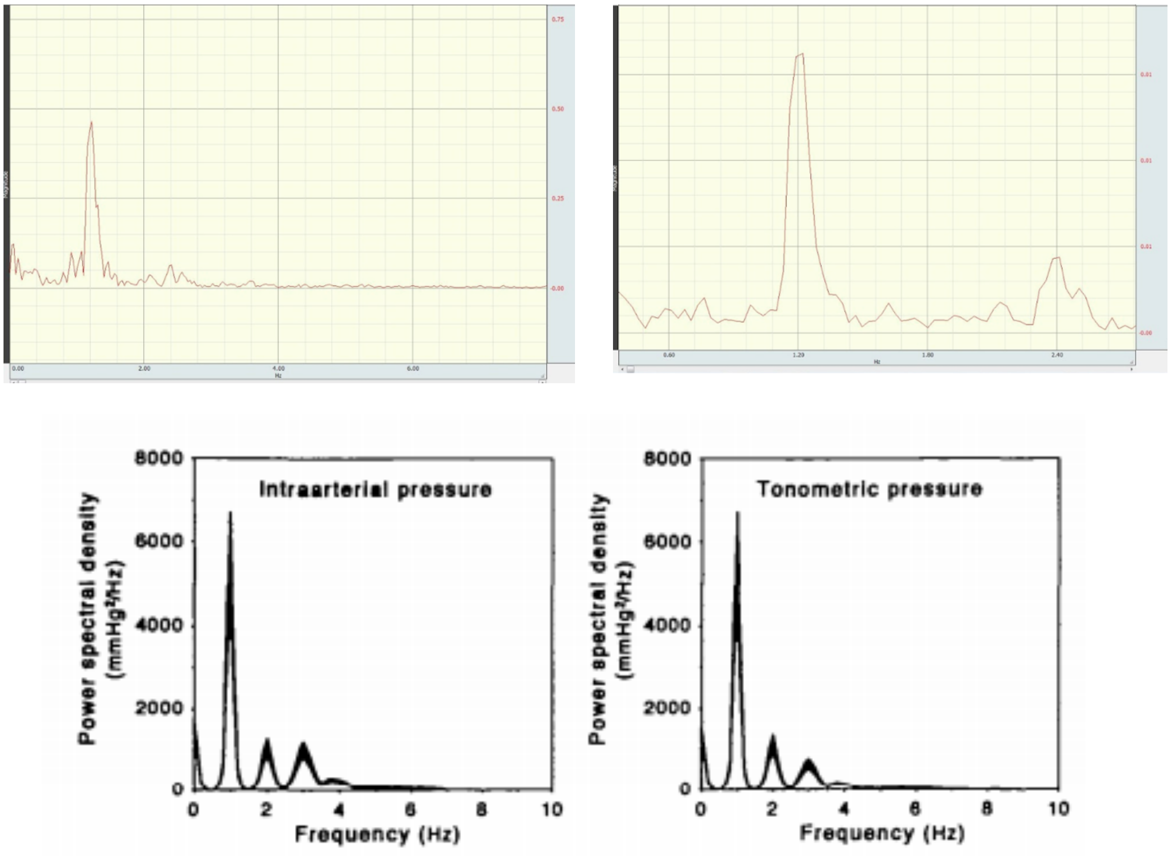


Figure 24. We confirm similarities in our results with results shown in a similar experiment. After careful incorporation of FFT, we see that our waveforms (top) are once again, very similar to the waveforms that Sato (below) had received.

After carefully following the appropriate protocols, we are still made aware that they will realistically be limitations to some of the practical use of the tonometer. The tonometer, consisting of a resistive sensor, may be sensitive to certain motions and forces. With this being said, under certain conditions, the tonometer may pick up extra movement artifacts. In the following article, we read that

> "shown that the tonometric sensor is less sensitive to subject movements than a photoplethysmographic, quadrupolar impedance plethysmographic, or sphygmomanometric sensor" (Sato, 1993).

We found a way to enforce a just enough force onto the patient without causing any pain or discomfort. Ensuring this resulted in accurate pressure recordings.

As discussed nearing the end of Sato's paper, he states how the overall frequency response of the blood-pressure monitoring system ranged from about 0 to 5 Hz. In our case, the same exact range was exhibited hence, showing that our new and improved calibration was valid and that it did not flaw any results.

He then, goes on to state how similar the waveform between the tonometric waveform and the intra-arterial waveform were. When looking back at figure 17, we see that there is almost an identical representation of both waveforms. Being able to replicate this trend once again, shows that our calibration method is not flawed and that our results are reproducible even with different calibration methods. Not only were the calibrations different, but we must also remember that Sato was consistently comparing his results with a catheter. The catheter as we mentioned before, is the most accurate method to calculate blood pressure. The reason we do not use this method once again, is due to the invasive nature of it.

The third and final point that Sato reinforced was the fact that while the body was not performing different maneuvers, the correlation between values stayed relatively high. Whereas, during certain maneuver mechanics, the correlation between the values would still be high but not as relatively high as the rest. Shown below we see that after eliminating the maneuver values, we receive a higher correlation factor. Although, this is something we aim for, there is an importance in establish a basis for these measurements that are taken during maneuver methods. This is due to the fact that a doctor or physician that is using this in their office or in a hospital setting, cannot ensure the relaxation state of a patient, especially if being put in a setting where an emergency has risen. In certain circumstances, it is crucial for the medic personnel to receive this blood pressure reading within second of a patient's arrival.

t-Test: Paired Two Sample for Means		
W/o Maneuver Blood Pressure		
	Variable 1	*Variable 2*
Mean	116.7067	112.7142857
Observations	7	7
Pearson Correlation	0.874326	

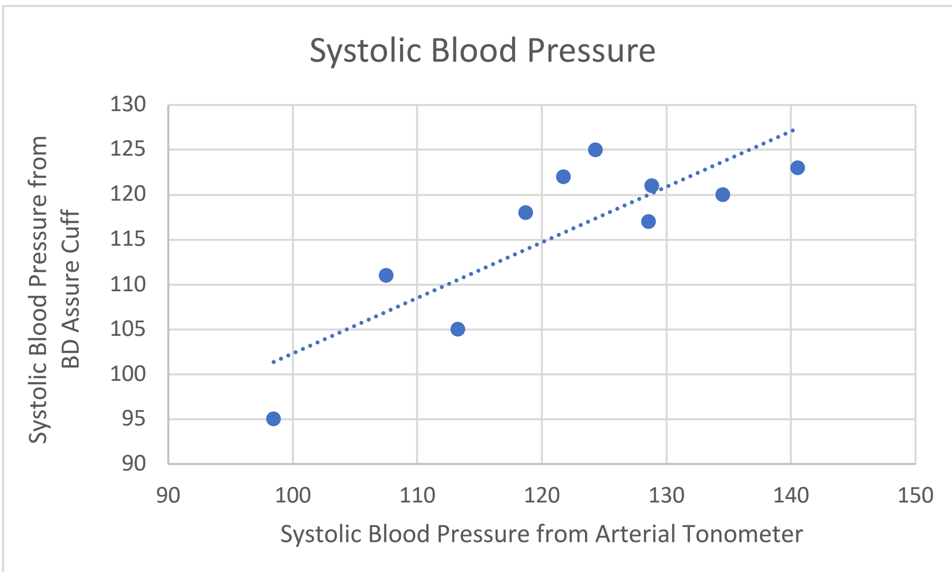
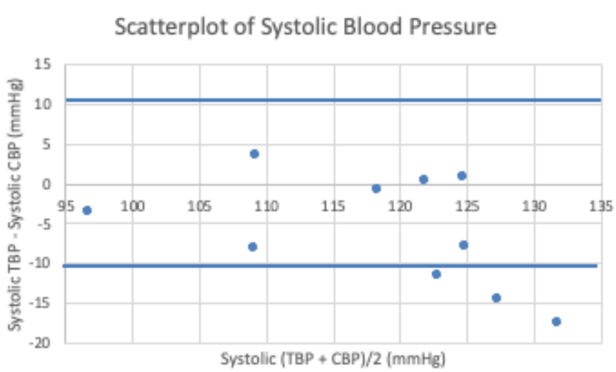


Figure 25. Shown above are the statistics that are shown between the subjects that did not perform any Valsalva maneuvers. We see a correlation factor of 0.87, thus being higher than all the subjects combined regardless of maneuver or not.

Given this, we are able to conclude a very similar conclusion to Sato. That is, that change occurs during the Valsalva maneuver are small but significant at the same time. There is a much bigger ideology associated with these Valsalva maneuver as explained further up above.

In another experiment by Dr. Normal R. Searle, we see his methods as he assesses the arterial tonometer for a continuous blood pressure measurement in rapid atrial fibrillation. The N-CAT, a newly developed arterial tonometer, was established and compared to invasive blood pressure methods to confirm accuracy and reliability. When being able to reproduce results from experiments compared to invasive methods, such as this one, we become confident that our thesis has been confirmed and proven.

After plotting a scatterplot with the difference between systolic tonometer blood pressure (TBP) and systolic cuff blood pressure (CBP) versus the average systolic TBP and CBP values with the average bias line lying at the x-axis. The two standard deviation limits are set to be about 10.5 units of mmHg on each side. We verify promising results by seeing that our maximum error was less than Searle's.



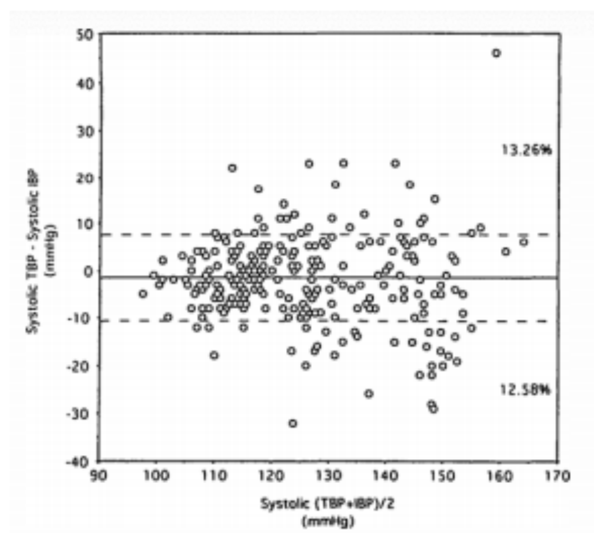
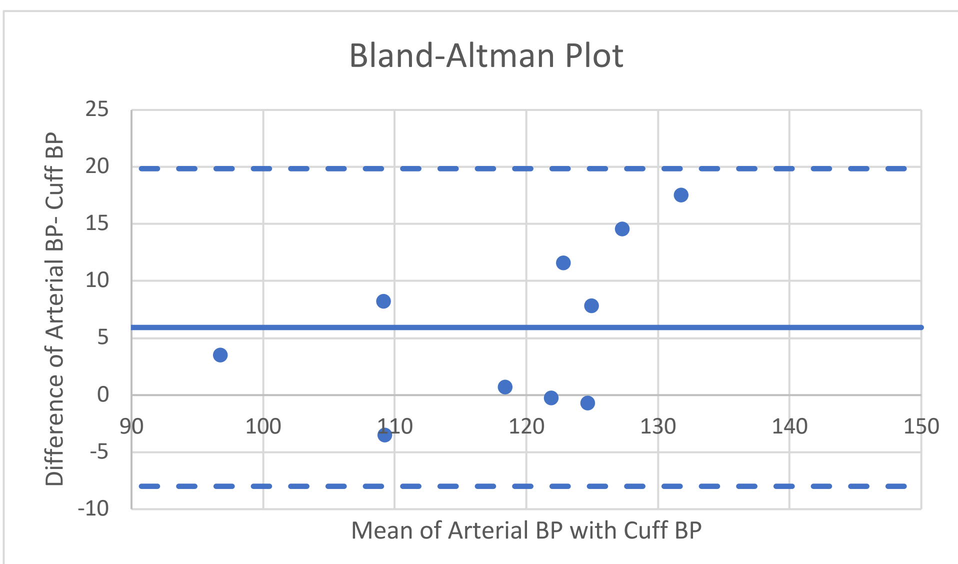


Figure 26. Being able to compare results from our experiment and the experiment assessed by Dr. Searle helps confirm that our results are reliable. Having the factor of this invasive method helps prove that our thesis and deem it as a solution to the problem. (Figure reproduced from (Searle, 2014))

In the final experiment that we compare to by Dr. Gary Drzewiecki, we see how a very similar method of tonometry compares to mine. In this experiment, he performs a method of deflection corrected tonometry. In this experiment, we see a very similar amount of trials performed and very similar methods, hence leading this experiment to be reliable one to compare to. The main error analysis that we compare to is the Bland-Altman Plot. As explained earlier, the Bland-Altman plot, also known as, a difference plot is a dependable way to compare between the difference and the mean of the arterial blood pressure measurements along with the standard method of blood pressure taken. We can justify that our methods are better due to the fact that instead of placing all values with two standards deviations, as the image below shows, we plot all of our points within one standard deviation of each other hence giving a more restricted limit of agreement. With this, we still see all of our values fall in between these two lines, hence, insuring precision and accuracy.



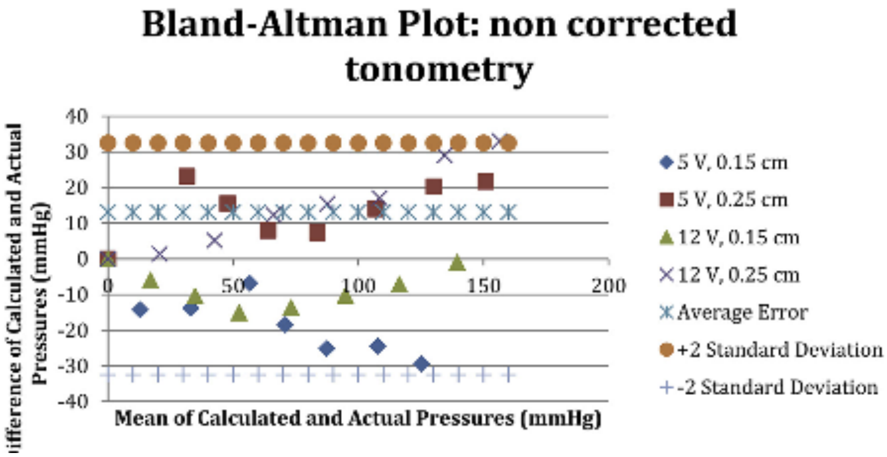


Figure 27. As stated above, we see that the Bland-Altman Plot that was performed in Drzewiecki's experiment has a limit of agreement within two standard deviations of one another. Whereas, the error analysis I had performed, we show all data points within one standard deviation of each other. This results in our data being reliable and accurate. (Figure reproduced from (Drzewiecki, 2018))

Although there are many similarities between my improved methods and other comparable experiments, much of the same errors show up in this experiment as others. A main type of error that occurs is measurement error. As a matter of fact,

> "arterial tonometry relies on the special condition of arterial applanation such that the vessel wall contact area becomes approximately equal to the sensor area. For this condition to be met, the artery must be deflected to a large extent. Moreover, the tonometer operator must maintain the deflected position very carefully so not to introduce measurement error" (Drzewiecki, 2018).

Maintaining this deflected position precisely over the radial artery is the most crucial part of the measuring process. Through much practice and repetition, a consistent method of how to precisely do this was established hence, ensuring that much of the measurements that we had picked up were accurate. This alone shows how the error in our fixed-deflection-tonometer had decreased in comparison to other experiments who had performed similar experiments. In truth, not being able to use the adjustable position device had many more pros. Keeping the tonometer at a fixed-deflection eliminated another factor of measurement error. If the tonometer had to pulse inwards or out, another measurement would be taken into consideration and therefore, leaving more room for error to occur. This alone, implied that our results are left unambiguous and dependable. After, establishing this method, a source of measurement error was decreased yet, other sources of error such a human error and pressure error. Pressure error occurs from our pulse sensing approach that was used for comparison earlier in the procedure. In this experiment, the photoplethysmogram, or PPG, is…

> "based on optical or capacitive deflection sensors. While these methods are capable of providing pulse timing and waveform information, they typically require another method such as a cuff to provide an indirect calibration. Moreover, Plethysmographic records are subject to pulse wave distortion due to nonlinear arterial wall properties. Arterial tonometry has been shown to provide true CNIBP with pressure error of less than 5%" (Drzewiecki, 2018).

In order to solve this issue, implementing a fixed-tonometer-deflection method can ensure that the issue of applanation tonometry can be reduced. As mentioned prior, with improvements in our Valsalva maneuver, we can see results become much more accurate. Even with these Valsalva maneuvers, we see that our percent error is still very much acceptable and impressive. This is found to be better than similar experiments where the "deflection corrected tonometry method is found to be less than 25% for all data" ((Drzewiecki, 2018). Given this large range, it is safe to say that the results and error I have shown has been much improved with the fixed-deflection method of tonometry.

Alongside with the new positioner, we will be able to adjust the deflection. This is crucial for the sole purpose of making sure that the transducer flattens the artery at a calculated deflection. After several types of experiments, it will be possible to find a specific value of deflection based on results we received already. With this value, we ensure that the artery is flattened to its full extent. Our goal with this is to find at what level of deflection gives the best reading. When finding this, we will then know what to set the deflection at.

Overall, we see that our method compared to others have very similar principles which can confirm the functionality of our tonometry. As stated before, even with a different and more comprehensive calibration in place, we are still able to reproduce results to the length that our competitors have reached. The reproducibility and comparison between our arterial tonometry and the BD Assure Blood Pressure monitor alongside with Sato's and Drzewiecki's tonometer with the catheter and cuff, respectively, help confirm my thesis.

CHAPTER 6

CONCLUSION

My thesis aimed to develop an alternative calibration method to a non-invasive blood pressure measuring device. Due to several downfalls of the mercury sphygmomanometer, we found it more necessary to lead into a more dependable method of applanation tonometer.

Applanation tonometry is a method of temporality flattening a part of a convex surface in order to measure pressure. In this case specifically, we use the radial artery as our point of contact. This is the artery we chose due to the fact that the radial artery is neighboring the surface of the skin, hence, easily picked up by a tonometer. When the tonometer is made in contact with the radial artery, values of force are transmitted and then relayed through the Biopac to recordings measured in volts. Through our newly, developed calibration method, we are able to devise a formula which helps us convert force, by the sensor attached to the tonometer and relayed in units of volts, to units of millimeters of mercury. This unit of millimeter of mercury, or mmHg, is the generic unit for blood pressure hence, developing this formula is essential in order to provide results that are well-understood by the researcher and the patient involved in the experiment.

The fixed deflection tonometer study produced impressively low errors. With this being said and in comparison the cuff method, our arterial tonometer showed a 5.12% error without the implementation of the Valsalva maneuver and a 3.54% error without the implementation of the Valsalva maneuver. Another advantage of the fixed deflection tonometer was that it did not require a full arterial applanation. With this, we were able to record blood pressure within 30 seconds, which is less than half the time, of an automatic monitor. This alone, resolved an initial issue of being able to receive a blood pressure reading in the case of an emergency situations.

As discussed above, we are able to not just get reproducible results, but we also are left with extremely high correlation between three different methods of blood pressure methods. The best of these methods, the catheter, is seen as the most dependable, due to its invasive and precise nature. Given circumstances, being able to invasively record blood pressure methods for the purpose of this thesis was out of range of the project requirements, but being able to go back and confirm my results with multiple researchers who have compared it to the catheter showed that my results were not flawed at all. My new calibration method and the formula that is associated with this calibration method proved to be reproducible and dependable.

APPENDIX

Computational Methods- Algorithm Developed In MatLab

```
%% A. Pressure vs Time Graph
tic
radius = 0.4; % Radius of a human artery
sensordiameter = .005; % factor which is used to determine the area of
the deformed artery

d = [.002:1.98*10^-7:.2];
b = radius-d;
low_deflection = pi/2 .* (radius- b/0.7185);

area = (sensordiameter)*(2*low_deflection); % diameter of the sensor
multiplied by 2 *time, % Area is of a rectangle formed when the contact
stress is measured on the planar surface
% Force is related to pressure and area
size(b);
time = [1:.005:10]; % model time
k=.03;
diameter=k.*time;
A1 = 10.0; % Fourier series generation of pulse
A2 = 9.0;
PI = 3.1415926;
PHI = 1.2;
F = 1;
size(F);
size(time);
w = 2.0*PI*F;
MAP = 70; % MAP is normally around 70-100 mmHg
P (1:length(time))= MAP + A1.*sin(w.*time(1:end)) +
A2.*sin(2.*w.*time(1:end) + PHI); %array of simulated pulse data
P=P(1:length(time));
figure(1)
plot(time,P)% plot of the simulated pulse data         %%%%%GRAPH
NUMBER 1
title('Pressure vs. Time')
xlabel('Time')
ylabel('Pressure')


%% B. Low vs High Deflection and Contact Area

for I = 1:length(diameter)
if (diameter(i)>0.12)
LD=radius.*(pi-2.*(asin(1-(diameter(i)/(2.*radius))))); % Large
Deflection
AreaL=LD.*sensordiameter; % sensor diameter times the large deflection
a(i)=AreaL/100;
else
SD=pi*(diameter(i)/2); % Small Deflection
AreaS=SD.*sensordiameter;
a(i)=AreaS/100;
end
```

```
end


figure          %%%% FIGURE 2 THAT WORKS
plot(diameter,a)
xlabel('Deflection)');
ylim([0 1*10^(-4)])
ylabel('Area[m^2]')
title('Contact Area vs. Deflection');
F=zeros(1,length(diameter));

%% C. Low vs. High Deflection and Force

for I = 1:length(diameter)
    if (diameter(i)>0.12)
    FL=P(i)*a(i);
    F(i)=FL;
    else
    SD=pi*(diameter(i)/2); % Small Defletion
    FS=P(i)*a(i);   %deflection vs p-p force
    F(i)=FS;
    end
end

figure;
subplot(2,2,[1,2])
plot(diameter,F);
title('Force vs. Deflection')
xlabel('Deflection')
ylabel('Force (Newtons)')

subplot(2,2,4)
plot(diameter,F);
title('Force vs. Deflection (HIGH)')
xlabel('Deflection')
ylabel('Force')
xlim([.12,diameter(end)])

subplot(2,2,3)
plot(diameter,F);
title('Force vs. Deflection (LOW)')
xlabel('Deflection')
ylabel('Force')
xlim([0,.12])

%% D. Pressure vs. Deflection (should look like the pulse)


figure;
plot(diameter,P);

title('Pressure vs. Deflection')
xlabel('Deflection')
ylabel('Pressure')
```

Results- Data Taken from 10 Patients

- *Red values refer to Valsalva maneuver being performed on certain patients*

Sample Number	Systolic Blood Pressure from Tonometer	Systolic Blood Pressure from BD Assure Cuff
1	140.51	123
2	121.72	122
3	124.304	125
4	107.465	111
5	98.462	95
6	134.53	120
7	128.56	117
8	128.83	121
9	118.69	118
10	113.22	105

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