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A Noninvasive Indicator for Cardiovascular Health

Abstract

One in four deaths in the United States can be attributed to some form of cardiovascular illness. Often, especially in the event of preserved ejection fraction, heart diseases are untreatable by the time significant symptoms arise or formal diagnoses are made. One of the most effective ways to combat these diseases is to prevent them by detecting vascular distress early.

Pulse wave velocity (PWV) is a widely researched and established indicator of vascular health. The metric measures the speed at which a pulse from the heart moves between specific points in the body, for example, the carotid and femoral arteries. Existing PWV measuring devices are explicitly used in research, require extensive training, and cost significant money and time to use. This innovative device is intended to improve upon the current technologies with a user-friendly and cost-effective design appropriate for the clinical setting.

The innovation boils down to three main ideas. First is the pulse wave detecting component, which typically comes in the form of a cumbersome stylus. The new design replaces the stylus with a glove. This provides the doctor with tactile feedback, removes the uncomfortable probing stylus, and reduces training and procedure time. Second is the user interface, which usually includes a separate software and computer. An Android tablet app will eliminate the currently bulky and inconveniently packaged software application.

If put into practice, this PWV measuring device has the potential to significantly impact the success rate of early heart disease detection. Regular PWV measurements over time will provide doctors long term insight into the vascular health of their patients. Consistent checkups from an early age onward could benefit many people and save lives.

TABLE OF CONTENTS

1 INTRODUCTION

Heart disease is the cause of one in four annual deaths in the United States [1]. It is often the case that once detected, certain types of heart disease, such as heart failure with preserved ejection fraction, have no cure. The best option in lieu of a cure is prevention, which means physicians must be equipped with the proper tools to detect at-risk patients early and in a convenient setting, such as regular office check-ups. Early identification of the at-risk population allows doctors to track the progression of risk factors, diagnose the type of heart disease, and treat the patient early with a much higher chance for success. There are currently very few simple, effective, and non-invasive methods of monitoring the most relevant cardiovascular health factors and even fewer methods are accessible in a clinical setting.

Over the past two decades, medical researchers have determined that a metric called pulse wave velocity (PWV) is a robust indicator for arterial stiffness and risk of heart disease. PWV is an attractive field of study because all necessary measurements are retrieved non-invasively. Unfortunately, the practice of monitoring PWV has not fully permeated the clinical setting due to the expensive and difficult to use existing technologies that measure PWV.

Our team has built a working prototype of a device to bridge this gap, which allow physicians to easily determine PWV and monitor changes in a patient's PWV over time in the clinical setting [2].

Our device is comprised of three technological components. First is the tonometer, which is a pressure sensor that measures the arrival of pulse waves in the arteries through small pressure changes detectable at the skin's surface. For our purposes the physician will wear the tonometer, which resembles a glove to allow for a more natural interface between the physician and the device. The second component is the three-lead electrocardiogram (ECG) that monitors the electrical output of the heart. Third is the software component, which is an Android application designed to work on any mobile device which runs the Android operating system. The application displays a live-graph of the data being collected by the ECG and tonometer. Once data has been completely collected, the application also analyzes the data to determine PWV. The Android application interfaces wirelessly with the tonometer and ECG over bluetooth.

In order to validate our device's functionality, we tested accuracy and usability in two ways. First, we completed an IRB application to test our device on real patients in clinical trials. We have used these trials to gather our own sets of PWV data, and we have collected data on the average amount of time physicians require to collect PWV samples using our device. The data collected on average measuring times will indicate the ease of use by averaging a reasonable ten

minutes or less for total procedure time.

Our device has a few constraints outside the inherent limits in the scope and design we chose. One constraint determined by the basic principles of our device necessitates making a noninvasive and safe instrument that does not put the doctor or patient at risk. Another requires our device to be intuitive and suitable to use without extensive training or prior experience. We have also defined a constraint on the ease of use: doctors must be able to determine their patients' PWV within ten to fifteen minutes.

Finally, our project has several financial constraints. We intended to limit our bill of materials to roughly $500 so that future products, if realized, could be commercially sold for less than the industry average of about $30,000. Lastly, the device must be both comparably accurate and precise relative to the existing technologies, as well as incite physician satisfaction and approval. To emphasize the point of our mostly self-imposed constraints, PWV is a proven indicator of heart disease, but current devices are not suitable for or available to general physicians without the resources or expertise. In its final form, our device must meet the above restrictions in order to be competitive with the existing technology.

2 DISCUSSION OF PREVIOUS WORK

To date, pulse wave velocity measurements have been approached in very few different ways. The least desirable method began with an invasive determination of PWV. The procedure involved catheters at two points of entry to measure pulse waves from within the arteries of interest. This approach is unacceptable for our purpose due to our desire to simplify the measurement procurement process. We want PWV to be easy to determine in a clinical and non-surgical, non-specialized setting.

Current competition in the market of noninvasive-PWV measuring instruments is small and includes few significant players with whom we are concerned. The main competitors are AtCor, Vicorder, and Complior, which share some similar key aspects that we intended to improve upon with our device. All three products have been colloquially referred to as the industry standard, by credible cardiologists, and they have successfully pervaded the clinical market more than other PWV measuring devices. Each device has its pros and cons, which provided our team some necessary inspiration for how to set our device apart from the rest and how to make sure our device meets the necessary standards for use in a practical setting.

SphygmoCor, manufactured by AtCor, is the most well known device and contains three distinct components including a pressure sensor, an ECG, and a software component [2]. The other two

devices also implement the pressure sensor and software components, but they do not require an ECG because they are designed to measure the carotid and femoral pulses simultaneously rather than relatively. The main difference between the competitors is in the design of their tonometers. The SphygmoCor's tonometer is designed as a stylus, which the doctor uses to probe around the patient's carotid and femoral arteries until a strong enough pulse produces a high-quality graph on the software display. This stylus is very difficult to use because it creates a significant physical boundary between the doctor and the desired signal that normally provides helpful haptic feedback. The Complior device uses a shorter version of a stylus for detecting the femoral pulse, which is also difficult to use due to the lack of feedback [4]. The Vicorder device eliminates the stylus by using a combination of cuffs that wrap around the body part containing the desired artery [5]. While the cuffs essentially remove the lack of feedback issue, they are difficult to place in the proper locations consistently and they are cumbersome to relocate frequently. Both the Complior and the Vicorder devices implement carotid tonometer cuffs, which generally look very uncomfortable for the patient because a tight device is clamped around the neck for the duration of the procedure.

There are benefits to using the cuffs and measuring PWV instantaneously rather than relatively; however, the multitude of accessories leads to a large number of wires that limit the device's mobility and may increase the setup and cleanup times of the procedure. Also, despite using an ECG, the SphygmoCor has the same number of potentially tangling connecting wires as the Vicorder and Complior devices. In addition to the wires between patient and device, each product requires another connecting wire between the device and a computer, which further limits the device mobility and convenience.

In terms of software, the three devices use similar applications that must be installed on in-office computers, but each uses slightly different visuals. The software used by SphygmoCor is poorly suited for the clinical setting because it encompasses more PWV detail than necessary for our purposes as it was originally intended for research use. The Complior and Vicorder softwares are generally well done and provide an appropriate level of detail as well as usability. The main issue with the current device softwares is the form they come in, such that they must be downloaded onto specific computers and are inaccessible from computers without the installation or appropriate system requirements.

3 STRATEGIC PLAN/ STRUCTURE

3.1 SYSTEMS APPROACH AND METHODOLOGY

Our project centers around the accessibility of pulse wave velocity as an indicator of cardiovascular health. Over the past fifteen years, a wealth of clinical data has linked pulse wave velocity with arterial stiffness, which is a robust indicator of cardiovascular health: the higher a patient's PWV, the stiffer his arteries, and the worse his health. As stated previously, most medical instruments that measure PWV have prohibitively high price tags and are difficult to use in a clinical setting.

The mechanism for measuring PWV is simple and straightforward. Blood that is pumped out of the heart and through the aorta generates a pressure wave through the arterial system. This pressure wave moves throughout the body's vascular system, including the carotid and femoral arteries. The resulting pressure changes are detectable at the skin's surface due to the size and location of the carotid and femoral arteries. The "velocity" component of the term "pulse wave velocity" refers to the speed at which this pressure wave travels through the body. By measuring the arrival of the pulse wave in the carotid and femoral arteries and measuring the physical distance between the carotid and the femoral, the speed of the pulse wave can be determined.

While the concept and relevance of PWV are well-supported and sound, measurement techniques are not. Our project is focused on improving the ease of use of measuring PWV. As stated above, current technologies are difficult to operate, such that physicians often require weeks of training and practice to gain the skill to comfortably and reliably measure a patient's pulse waveforms.

Our device's functional operation can be broken down into four distinct parts, including signal collection, signal processing, data analysis, and output. Together, these components encompass the design and capabilities of our device.

The first step, signal collection, involves acquiring the necessary information from a patient's body for PWV calculations. For detecting pulse waves from the carotid and femoral arteries, we constructed a tonometer using a force-sensitive resistor. We used an electrocardiogram to collect the electrical activity of the heart. To counter the lack of feedback and discomfort of existing technologies, our tonometer minimizes the distance between the desired signal, or pulses, and the doctor's sense of touch, or fingertip. We achieved this by creating a thin glove such that allows the physician to rely on tactile feedback from the patient's arteries like when normally feeling for a pulse. The pressure sensor lies flat against the doctor's index finger pad and the fabric is thin enough that the doctor can feel pulse waves at the surface of the patient's skin through the device. The glove design is intuitive for physicians who already know how to find a pulse and therefore saves them training time and frustration. The ECG in our device closely resembles existing ECG devices and does not require any new training.

Second, the raw data collected from step one are processed to isolate the desired signals. Because the pulse wave and ECG data are collected directly from the human body, both are acquired at very low voltages and contain a relatively high signal-to-noise ratio. Moreover, the resulting signal also contains Mains hum noise at 60hz which needs to be removed. To isolate the desired signals, filtering and amplifying circuits have been implemented to provide live processing capabilities. Analog, rather than software, filters are used to reduce potential latency in signal transmission.

In the third step, the processed signals are then transmitted to the Android application through a microcontroller and Bluetooth module. Because the user interface contains a live graph of the collected signals, the ECG and pulse wave data needed to be aggregated and transmitted concurrently with each other. A microcontroller is used to digitize, collect the analog signals, and package them and then implement the Bluetooth module to deliver the signals wirelessly to the final output stage.

Lastly, the Android application receives the pulse and ECG data, generates a visualized output, and performs data analysis. During signal collection, the Android application also generates a live graphical output of first the ECG and then the appropriate tonometer data so the physician may see if the pulse is properly detected. After all the data is collected, determined by when the physician chooses to capture a good-looking signal, an algorithm calculates PWV with the numerical data from the signal plots. The algorithm detects the feet of the pulse waves and compares their times relative to a common point on the ECG wave. The “foot” of each wave will be identified as the lowest points before the upstrokes on the pulse waves. Any consistently recognizable point on the ECG is adequate for the relative timing point. Ideally, a physician will be able to record the calculated PWV value for future reference and therefore track a patient’s cardiovascular health over time.

3.2 SYSTEM SPECIFICATIONS

Table 3.2-1 Old vs New System Specifications

Characteristic	AtCor Sphygmocor	New Device
Cost	$25,000	B.O.M. < $500
Enclosure Size	16.0 x 26.4 x 5.8 cm	Match
Time of measurement	15-30 min	< 10 min
Power Source	USB connection	Batteries

Software Platform	PC specific	Platform Agnostic
Hardware Complexity	USB and laptop connection	Wireless Communication and Mobile Application

3.3 HARDWARE AND SOFTWARE REQUIREMENTS

3.3.1 Hardware Requirements

The main component of the tonometer system is the pressure sensor. This piece is integral to the accuracy and overall quality of the whole system and required several trials until a specific list of characteristic requirements could be compiled. For one, the sensor had to be small, thin, and flexible enough to fit comfortably on the fingertip of a glove without significantly impairing sense of touch. A force sensing resistor was most effective because the sensor inevitably experiences pressure on both sides: our sensor must have only one active side so that it remains unaffected by the force of the doctor's hand. The sensor also required a specific sensitivity due to the range of forces generated by pulses. After some testing we found the best results were obtained with a sensitivity range between 100 grams and 10 kilograms. In future designs, this sensor must be modified to account for the initial pressure required to press down on the artery during pulse wave collection, but for the prototype, our chosen component was sufficient.

To extract the signal from the ECG, an instrumentation amplifier was used for its differential amp capabilities while providing more precision than bridges or typical op-amps. For the instrumentation amplifier, the INA129 from Texas Instruments was chosen as an initial option. This amp is low-power, provides a large range for gain (1-10000 V/V), and was able to be obtained cheaply for testing purposes. Given that an amplifier was needed to create an initial prototype, the cost and accessibility of the INA129 were important factors in our decisions to use it.

In order to generate quality data to be analyzed on the Android application, the signals from the ECG and the pressure sensor had to be filtered to remove undesirable frequencies. Due to the nature of the human body and the desired signals, versions of a robust Butterworth lowpass filter worked to preserve the low frequency signals and eliminate the higher and undesired frequencies. The lowpass also serves to remove the hum noise at 60Hz. For the ECG, we accomplished this frequency removal with a cutoff of about 35 Hz, however, for the pressure sensor, we required a cutoff frequency of about 7 Hz. In future designs, high-pass filters will be added to remove any DC voltage and the existing filters will be improved to isolate cleaner

signals.

A microcontroller was needed for signal digitization and transmission to the Android. For this purpose, the Arduino Duemilanove microcontroller was chosen for its wifi extension capabilities. Moreover, it has sufficient typical microcontroller capabilities for our usage, including I/O pins, voltage requirements, and ADC capabilities. For the wifi extension, we decided on a Bluetooth module that could send data at an appropriate frequency and minimize lag for optimal live-stream data feedback.

Table 3.3-1 Tonometer Pressure Sensor Subsystem Requirements

Characteristic	**Requirement**
Type	Force Sensing Resistor
Force Sensitivity Range	< 100g to > 10g
Active Area	0.5” diameter
Unloaded Resistance	>10 MOhms
Force Repeatability	+/- 2.5% to +/- 5% of established nominal resistance
Rise Time	1-2 msec
Sensitivity to Noise/Vibration	~0

Table 3.3-2 Pressure Sensor Filtering Subsystem Requirements

Characteristic	**Requirement**
Type	Lowpass
Design Method	Butterworth
Order	1st
Cutoff Frequency	7Hz
Number of Inputs	1

Table 3.3-3 ECG Filtering Subsystem Requirements

Characteristic	**Requirement**
Type	Lowpass
Design Method	Butterworth
Order	2nd
Cutoff Frequency	35Hz
Number of Inputs	1

Table 3.3-4 Signal Processing Sub-System: Arduino Microcontroller Requirements

Characteristic	**Requirement**
Number of inputs	2
Input Voltage Range	0-5V
Supply Voltage	6V
Sampling Frequency	500 Hz
Signal to Noise Ratio	~21dB
Analog to Digital Conversion	12-bit
Wireless Capability	Compatible with Bluetooth Module

Table 3.3-5 Final Bill of Materials: Overall Hardware Requirements

Item	Cost
1 Arduino Microcontroller	$30.00
1 Bluetooth Module	$20.00
1 Force Sensitive Resistor	$6.95
1 Cotton Glove	$1.13
Assorted Electrical Components	$10.00
1 Sheet ¼ Acrylic	$7.32
2 9V Batteries	$5.99
Total:	**$81.39**

3.3.2 Software Requirements

Producing a successful final prototype requires several software-related components. First, our hardware device must integrate seamlessly with our android application. The efficacy of our project relies on providing real-time data graphs to physicians using our device. In order to stream data real-time, the Arduino microcontroller must interface with our Android application via bluetooth.

Second, our application must be accessible from a variety of mobile devices and tablets, to provide physicians with the flexibility to collect data in the field. This flexibility requires that our application be hosted on Android, and available on the Google Play store.

Finally, our prototype must be extremely user-friendly. We consulted with several cardiologists and researchers who have experience with the SphygmoCor, and we have created several design mockups for a click-and-go process. The user experience must be very intuitive, which requires a well-designed Android application and user interface.

Table 3.3-6 Software Requirements

Characteristic	**Requirement**
Real-time data stream from hardware device	Hardware/software bluetooth integration
Accessibility from an assortment of mobile devices	Application must be deployable on any Android-powered device
Three-step click-and-go process, mapping out which measurements physicians should take during the PWV-measurement process	Well-designed Android front-end interface with descriptions and photos of steps and ECG lead placements
Hospital-compliant data transfer protocols	Using well-documented data transfer protocols via bluetooth

3.4 TEST AND DEMONSTRATION

3.4.1 Test

The accuracy and consistency of the measurements made by our tonometer and ECG are integral to the success of our project. Therefore we must test the system in two distinct ways. To determine the accuracy of our PWV readings we will need to test the system as a whole against one of the existing technologies that is considered the industry standard. We would most likely use the AtCor SphygmoCor, which is available in our advisor's hospital and nicely displays both the pulse wave and ECG graphs while recording their data as pairs of voltages and times, like our system.

Our final prototype will measure each of our PWV values using both our system and the SphygmoCor, then compare the final outputs as well as the data sets. Ideally, our PWV values will measure on average within a +/-5% error relative to the industry standard and our initial data will compare with a similar margin of error. If our results continue to compare within our desired margin of error after repeated tests on the same patients, we will be able to confirm the consistency of our hardware and the robustness of our PWV algorithm.

In order to test the quality of the synchronization between the ECG and tonometer we will have to determine if there is a lag between the sampling frequencies of two separate analog input pins on the mbed. This can be achieved by running two known signals, such as those generated by a function waveform generator, through the pins of interest and observing the resulting waveforms

in LabView. If there is no noticeable lag between the readings of the two signals, our signals should be clean. If a lag exists, we will have to determine if it is significant and, if so, how to counteract the issue. A significant lag would be a delay greater than a few milliseconds, which could be resolved either by configuring the sampling frequencies of the mbed in some way or by compensating for the lag in the PWV calculations through the software directly.

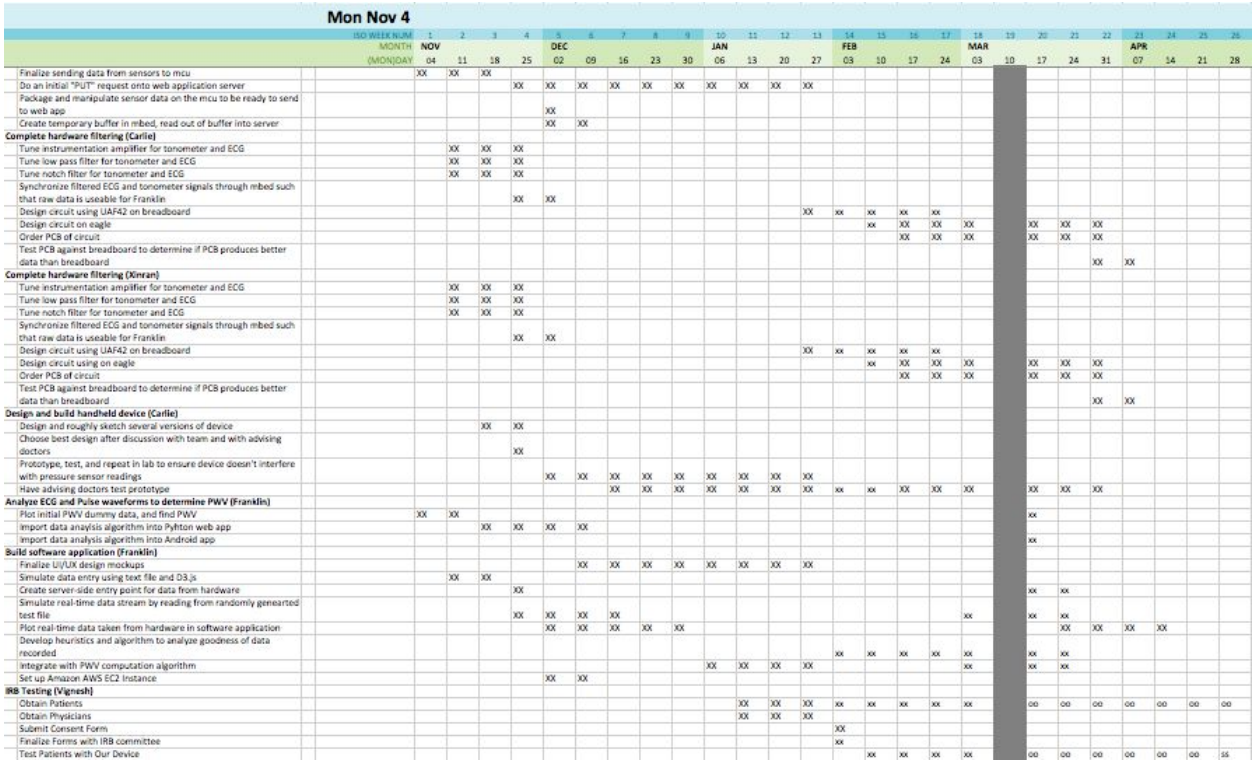
A second, but equally important, aspect of our system we must test is its usability and ease of use. Because it is hard to quantify ease of use, we intend to go about gathering information in a few specific ways. First, we believe we may characterize usability by examining training time and average procedure time; the faster the device is to learn and to use, the easier it is to use overall. During our accuracy tests, we will also time the procedures for both the Atcor device and our system. The total time will be useful as well as the segment for collecting pulse waves specifically because that will help us focus on the usability differences between types of tonometer. Second, we will collect user testimonials via a standardized survey that specifies level of medical expertise and PWV background and that targets opinions on experience with PWV systems, including ours, on the impact of our system, and on areas of improvement. The survey results will provide useful feedback for future modifications of the user interface.

3.4.2 Demonstration

Our project is composed of several distinct steps that are best demonstrated by performing the full procedure for measuring PWV. Still frame visuals and verbal explanation in combination with a live demonstration of the device in action accurately and clearly represent the process behind our project to even the least technical audience. When we are also able to produce a live PWV reading at the end of the demonstration, we have successfully exhibited the point and purpose of the device. We used one team member as the “patient” and another as the “doctor” while the other two supported the demonstration with further verbal explanations and poster exhibition.

3.5 PROJECT SCHEDULE

3.5.1 Schedule



3.5.2 Schedule Discussion

Throughout the year the project has been on schedule. However we ran into setbacks when it came to testing our product, mostly because our device was not in a state to be presented to a physician to test. The Institutional Review Board Application is been complete for a long period of time, meaning we have permission to test our device on patients at the Penn's hopsital. We were unable to use the approval to test our device during the amount of time allotted to us, but we plan on using it in the near future. Many of the schedule setbacks were due to changes in the software components of the project. We originally set out to use python and the cloud for our device, but we switched to an android platform in order to make this device more accessible to clinicians. This caused some major user interface and hardware changes. A minimum working prototype was created several weeks before demo day, and we plan on continuing testing and refining our minimum product as physician provide us feedback.

4 RESULTS

We have successfully built a prototype of a PWV measurement device, alongside a fully functional Android application. The system was tested on several human subjects and the ease of use was evaluated by several medical professionals with experience in existing technologies. Initial findings indicate comparable accuracy to the industry standard and significant improvements in ease of use. To demonstrate our accomplishments we will walk through each of the components of our device individually and discuss how our system compares to the industry standard.

4.1 PULSE-WAVE DETECTION GLOVE

The tonometer functions well and provides significant tactile feedback to physicians. The material does not interfere with pressure sensor readings or the comfort of the user or patient. Pulse wave data from the carotid artery was successfully collected using this tonometer glove prototype. The signal was displayed on LabView, as seen in Figure 4-1, through USB connection after amplification by an instrumentation amp and rough filtering by a first order lowpass with cutoff frequency of about 40Hz. The spectral graph specifically showed what frequency of noise was still most prevalent, which allowed us to determine the need for a more robust filter and an instrumentation amp better suited for low frequency signals.

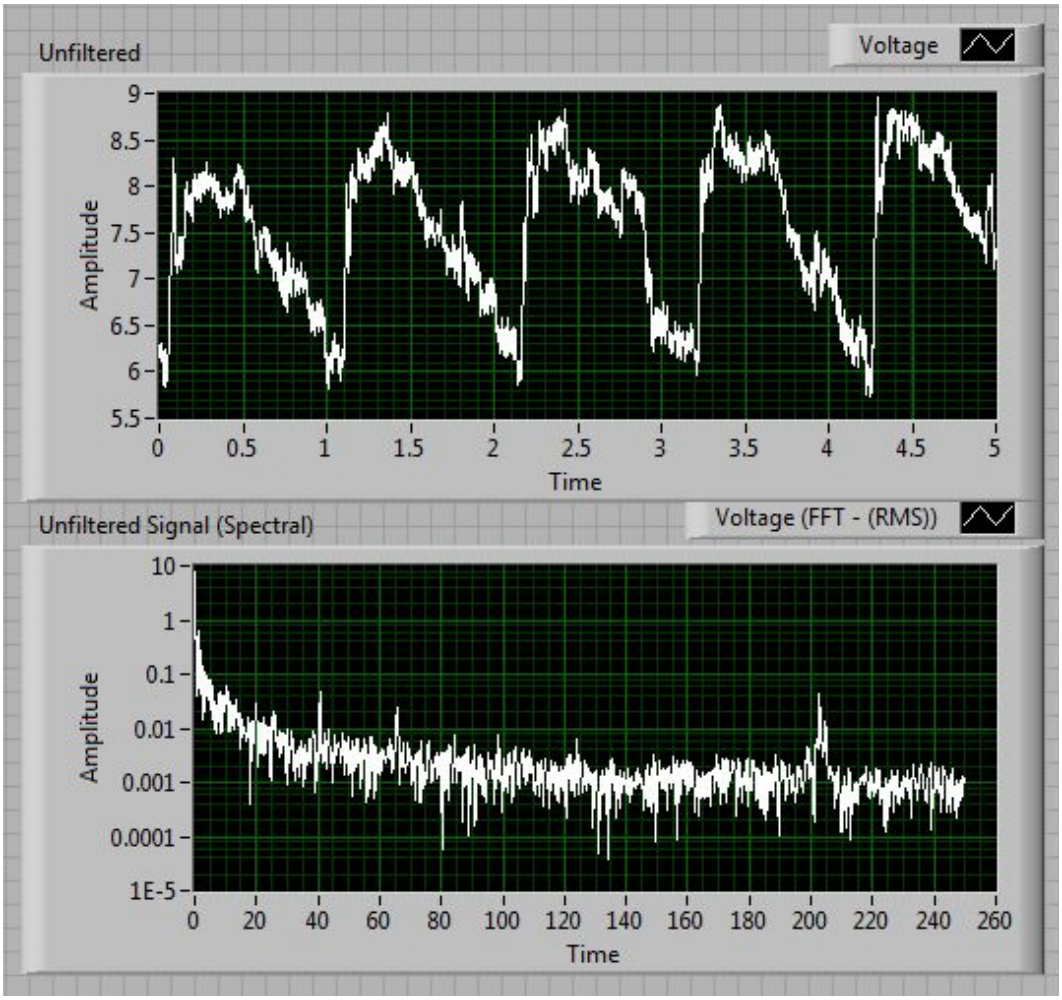


Figure 4-1 Tonometer Data in LabView

After tweaking the hardware filters we implemented, and implementing software filters in Matlab, the pressure sensor data was markedly improved. The newly filtered data is provided in figure 4-2, below.

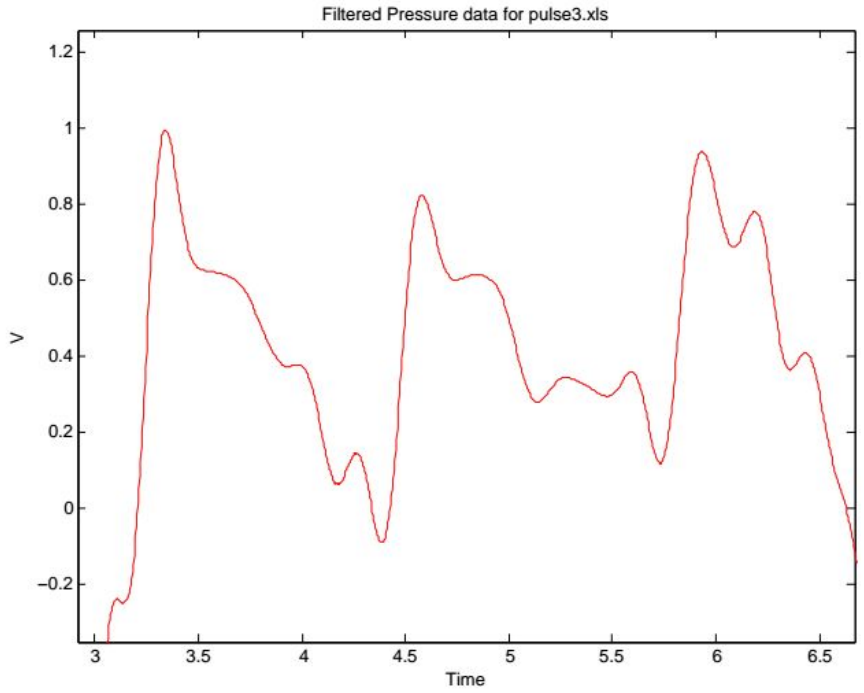


Figure 4-2 Filtered Tonometer Data in MatLab

4.2 3-LEAD ELECTROCARDIOGRAM

Rough ECG data was also collected using a three-lead system. The signal was also displayed on labview after passing through a nearly identical instrumentation amp and lowpass filter circuit. Spectrum analysis revealed that most body signals occur at under 10 Hz. The data, as shown in Figure 4-3, resembled the desired form of an ECG signal with its distinctive peaks. The signals provided in 4-3 are clean and show clear maxima and minima.

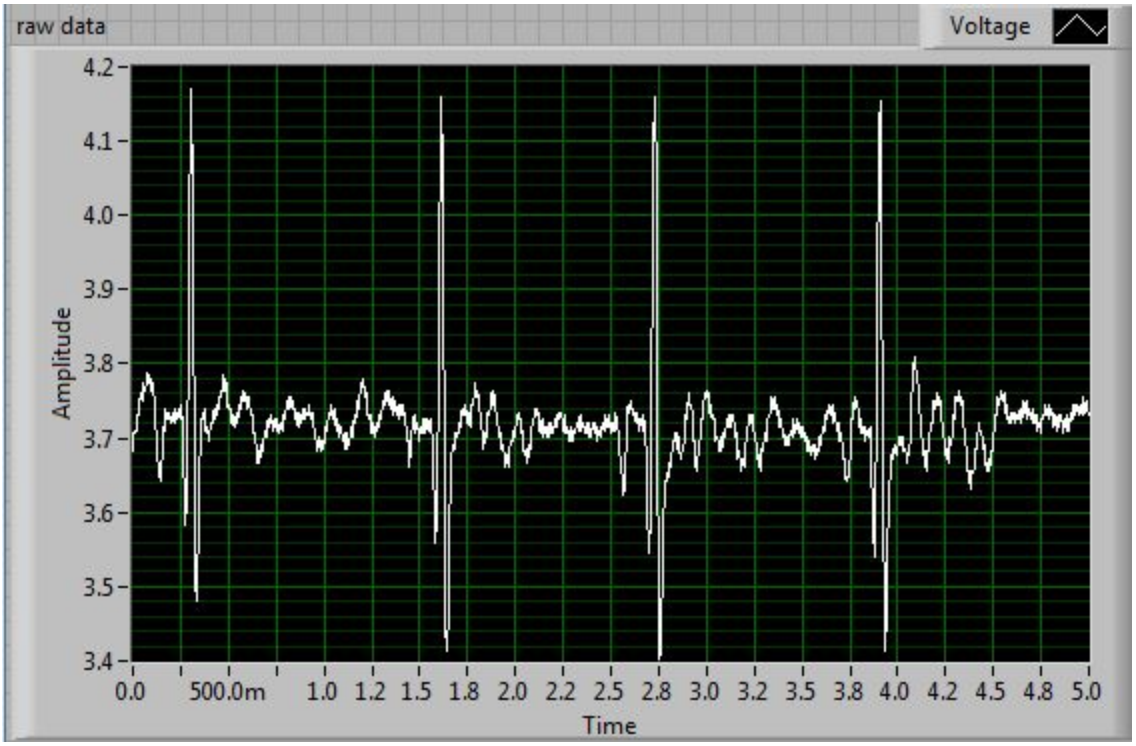


Figure 4-3 ECG Data in LabView

4.3 ANDROID APPLICATION

The Android application receives the synchronized pulse wave and ECG data which is collected and streamed live from the Arduino. The Android application guides the user through three main steps. First, the electrocardiogram leads must be set up and ECG data collected. Second, pressure wave forms must be collected from the carotid and femoral arteries. Finally, the application analyzes the captured ECG and pulse wave data to calculate PWV. The steps are shown below.

4.3.1 Electrocardiogram Set-up

The patient is hooked up to leads, positioned in a formation identical to the image on the left of figure 4-4. Once hooked up, ECG data begins streaming live onto the graphical display on the right. After seven seconds of data are captured, the physician can move on to collecting pulse wave data. During the entire procedure, ECG data will continue being collected in the background of the application.

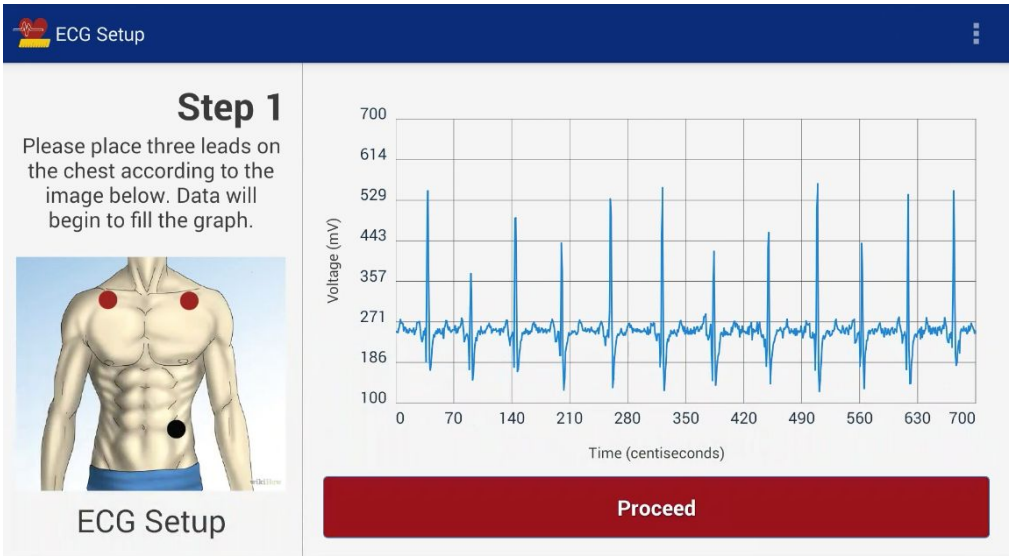


Figure 4-4 ECG Set-up Screen Capture

4.3.2 Carotid and Femoral Measurements

Once ECG data has been collected, physicians move on to the collection of carotid and femoral pulse waveforms. These steps correspond to Step 2 and Step 3 in the application respectively. The screenshots for steps 2 and 3 are captured below in figure 4-5.

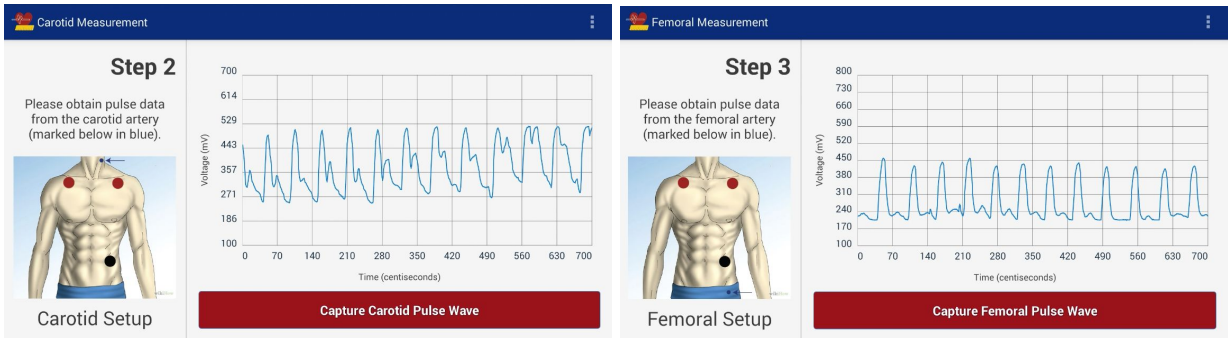


Figure 4-5 Carotid (left) and Femoral (right) Real Data Collection Screen Capture

4.3.3 PWV Calculation

Once femoral and carotid waveforms have been captured, the pressure waveforms are plotted against the corresponding sets of electrocardiogram data. The Android application runs a PWV-calculation algorithm, which identifies the foot of each of the pressure waves. These points are plotted in green in Figure 4-6. The physician then enters the distance between the carotid and femoral arteries (measured in millimeters), and presses the “Find PWV” button. Pulse Wave Velocity is then calculated and displayed to the user in the bottom part of figure 4-6.

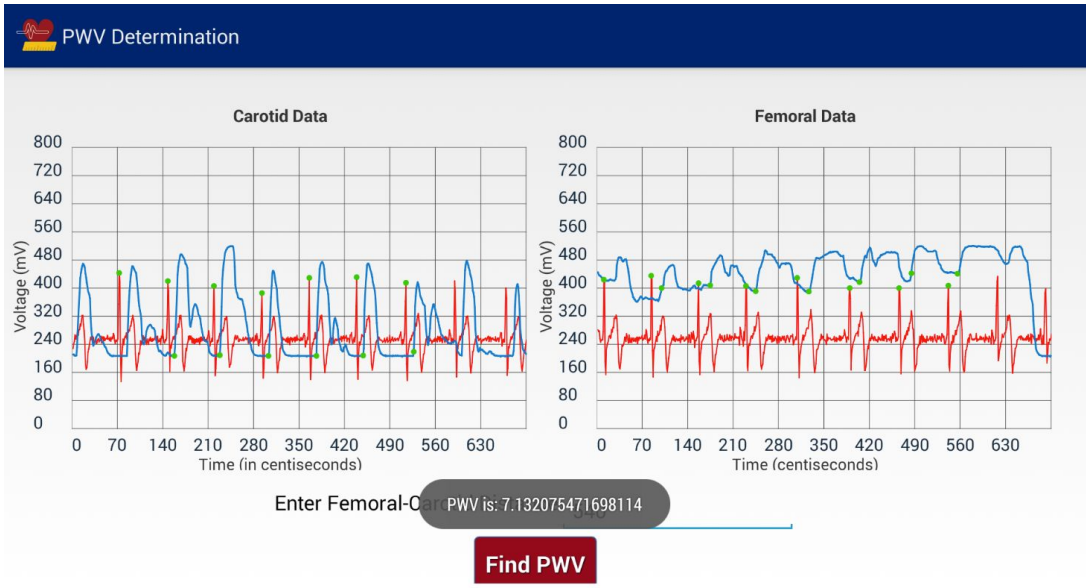


Figure 4-6 PWV Calculation Screen Capture

A PWV calculation of 7.13m/s is certainly in the expected range of health pulse wave velocities.

4.4 COMPARISONS WITH INDUSTRY STANDARD AND PREVIOUS RESEARCH

Two important components in the design of our system are ease of use and the accuracy of PWV measurements. We address the performance of our device across both of these components separately.

4.4.1 Ease of Use Comparisons with Sphygmocor

The Atcor Sphygmocor is notoriously difficult to use. Specialists who use the Sphygmocor on a daily basis claim it takes between 30-40 minutes to collect a full set of pulse wave data. We provided our device to a number of trained and untrained individuals. The data collected is provided in Table 4.4-1. The average amount of time an untrained medical professional requires to collect data using our device prototype was 17 minutes. Many professionals were able to collect data faster than the average, resulting in a median data collection period of 11 minutes. One specialist, a cardiologist we were in consultation with, was able to collect data in under 8 minutes. These results indicate our device is significantly easier to use than the industry standard.

Table 4.4-1 Average Duration of Procedure (Sample Size: 10)

Metric	**Duration**
Average	17 Minutes
Median	11 Minutes*

*Some specialists, such as the cardiologists we worked with, were able to collect data under 11 minutes.

4.4.2 Accuracy Comparisons

Figure 4-6 above is representative of the expected quality of data taken from our prototype device. Below, in Figure 4-7, we provide a sample of data which was taken using the industry standard. Qualitatively, the industry standard produces pressure waves that are cleaner and smoother than those collected by our prototype. However, the important components of each wave (the foot), are easily identifiable in both sets of data.

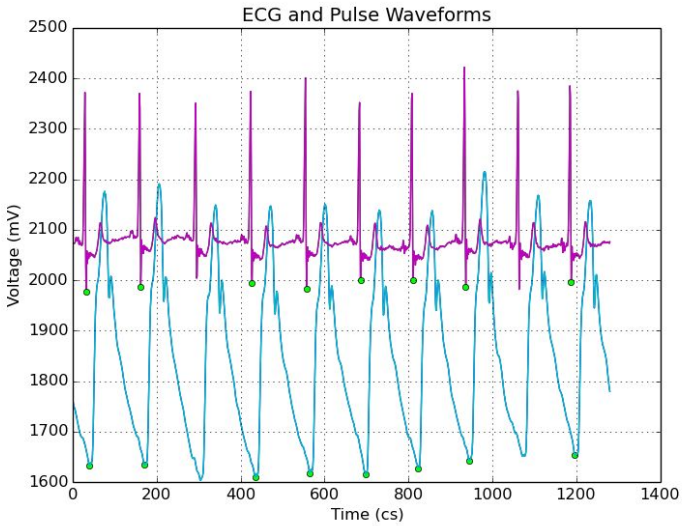


Figure 4-4 Processed ECG and Pulse Waveform Data

Although additional testing is needed, initial findings suggest that our device may have the potential to be as accurate as the Sphygmocor in measuring PWV. A recent study performed by the European Society of Cardiology indicate that average PWV values obtained using our device are roughly correct. The findings of the European Society of Cardiology are produced below, in Table 4.4-2, while our initial findings are displayed in Table 4.4-3.

We tested our device on 10 human subjects under 30 years of age and found that males on average have a pulse wave velocity of 6.3m/s. Females under 30 years of age were found to have

an average pulse wave velocity of 6.1m/s. These are both roughly in line with the findings by the

Table 4.4-2 Findings of the European Society of Cardiology [6]

Gender (individuals under 30 years of age)	**PWV +/- 1 Standard Deviation**
Male	6.1 +/- 0.40m/s
Female	6.2 +/- 0.80m/s

Table 4.4-3 Average PWV Measurements using our Device

Gender (individuals under 30 years of age)	**PWV +/- 1 Standard Deviation**
Male	6.3 +/- 1.0m/s
Female	6.2 +/- 0.9m/s

European Society of Cardiology, which state males have an average PWV of 6.1m/s, and females have an average PWV of 6.2m/s.

It is also important to note that the algorithm used in PulseTEAM's android application is identical to the algorithm used by the Atcor Sphygmocor. The Sphygmocor is documented to use the intersecting tangent foot-to-foot method for determining the foot of the wave, which was recreated exactly in the algorithm utilized by the android application.

4.5 SUMMARY OF RESULTS

We cannot yet definitively say that our device is as accurate as the industry standard. The device needs to be further tested on a greater patient population. However, preliminary findings suggest that our device has the potential to be competitive with the Sphygmocor, and is certainly easier to use. Average procedure times are reduced by over 50%, and many specialized medical professionals do not have any difficulty using our device.

5 LESSONS LEARNED

The members of this team had the pleasure of working with team members from diverse backgrounds. The composition of PulseTEAM was completely interdisciplinary; the team was comprised of one mechanical engineer, one bioengineer, one electrical engineer, and one computer scientist.

The main lessons learned were three-fold. First, working on an impactful device frequently requires a broad skill set, because members will be continuously pushed and faced with difficult engineering tasks. An important element which contributed to our ability to successfully prototype our device relied on trust between team members. In order to establish trust, team members must understand communication is key, and it is important to inform the team of possible engineering roadblocks early on in development. Thinking ahead and identifying difficulties requires a schedule to follow and abide by.

Second, it is important to build flex-time into the Gantt chart and project schedule. Particularly in a team as diverse as ours, it can be difficult to successfully coordinate on completing different deliverables and components of the device. In the beginning, we had anticipated that the electrocardiogram and pressure sensor filters would be completed by the beginning of February. In actuality, these components were not completed until early March. However, we had planned for the delay of at least some components of our device at the beginning of October, so we had the flexibility to push off the completion of these filtering circuits.

Finally, we reflect on the progression of our prototype from design to development. At the beginning of this project, we had anticipated our device would interface with a web application. Most of the components of the web application were completed by the end of January, and integration with hardware was planned to occur mid-February. However, several lag and latency issues with data communication led to the decision that a web application would be infeasible for this medical device. Instead, towards the end of February, we pivoted and decided we would build an application compatible with Android devices.

It is essential that engineers stay flexible in the design and development of a prototype. Above all, it's important to consider all of the advice given by mentors, advisors, and peers. Frequently, third parties present recommendations that engineers are uncomfortable admitting to themselves. Humility and receptiveness to criticisms are just as important as engineering competence.

6 EQUIPMENT/FABRICATION/SOFTWARE NEEDS

Our circuit requires several components which were not available at Penn. We took initiative and reached out to several device manufacturers to obtain these pieces of equipment. Examples include the pressure sensor and the microcontroller we are using in our final prototype for the tonometer. The remainder of our equipment and software is available from Penn.

7 CONCLUSIONS AND RECOMMENDATIONS

PulseTEAM was able to successfully identify a problem and then design, prototype, and test a device for measuring pulse wave velocity. The device includes several key innovations. The first is the pressure sensor, or tonometer, which is designed to be a wearable glove. The glove prototype provides physicians with direct tactile feedback and significantly enhances the ease of use of our device. Initial findings suggest that physicians prefer using the glove design to the design of current devices in industry, which utilize a stylus tonometer. The second innovation is the software application, built to be wireless and compatible with all Android devices. The Android device frees clinicians from the typically fixed workstation and provides a full range of mobility about an exam room. Lastly, our device is cheap and portable enough to be accessible in a clinical care setting. The total bill of materials of PulseTEAM's device is under $100 and the device itself fits inside a shoebox.

Moving forward, we envision creating future versions of the device with several improvements as well as taking advantage of our IRB approval at HUP to obtain clinical data. We have been in consultations with a couple cardiologists who had the chance to try our current device and they offered similar recommendations. For one, they suggested using a smaller pressure sensor. The pressure sensor currently has a 0.5" diameter, which covers up nearly the entire fingertip; however, it could be helpful to have a smaller sensing area to make it easier to feel for arteries that are in hollows or that are not perfectly located at the skin's surface. Another recommendation was to use a better tuned pressure sensor, such that pressure changes from the pulse wave are not detected until the physician has applied some external pressure to the artery to hold it in place. This modification would allow the physician to capture better waveforms because the pressure wave upstroke would not be lost to the side of the artery the physician cannot feel.

In addition, we have some ideas of our own on how to further improve the device as well as validate it. In future iterations we would like to implement full wireless communication, such that the glove and the ECG are wireless as well. We also envision an overall downsized version of the system; the device would incorporate printed circuit boards, minimal wiring, rechargeable batteries, and an enclosure that fits on a belt clip. Our software will hopefully become platform agnostic, such that PWV measurements may be collected, recorded, and calculated on anything from Android to IOS devices. Lastly, there is only initial data which supports the conjecture that our device is as accurate existing technology. Additional human subject trials data will be required to reliably prove competitive accuracy.

8 NOMENCLATURE

PCB	-	Printed Circuit Board
PWV	-	Pulse Wave Velocity
Tonometer	-	a device that measures pressure in parts of the body
ECG	-	Electrocardiogram
Webapp	-	Web application
HUP	-	Hospital of the University of Pennsylvania
IRB	-	Institutional Review Board
PulseTEAM	-	Pulse Tonometer and ECG for Arterial stiffness Measurements
SSL	-	Secure Sockets Layer
HIPAA	-	Health Insurance Portability and Accountability Act

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11 FINANCIAL INFORMATION

11.1 FINAL BILL OF MATERIALS

Include below is a table indicating our final bill of materials for the prototype presented during Demo Days. The table appeared in system specifications, but has been repeated here for convenience.

Item	Cost
1 Arduino Microcontroller	$30.00
1 Bluetooth Module	$20.00
1 Force Sensitive Resistor	$6.95
1 Cotton Glove	$1.13
Assorted Electrical Components	$10.00
1 Sheet ¼ Acrylic	$7.32
2 9V Batteries	$5.99
Total:	**$81.39**

12 ETHICAL ISSUES

Our system fits clearly into the medical world; its use is intended for general physicians in the clinical setting and for cardiologists and other doctorates in the research field. Between these two sectors, our system will impact four distinct groups: the patients, the users, the people benefitting from the researchers' findings, and the institutions purchasing the system. Each group is significantly affected by the safety and success of the device in overlapping, but still different ways.

The patient is directly affected by the quality of the system in that all of the components and readings must be up to practical medical standards and levels of accuracy. We could not morally allow use of the system without ensuring that we are not endangering the public. In particular, we had to establish an isolated ECG system, such that electrical activity is only received by the system and never sent. Similarly, the physician must be protected from any potential hazards that arise with coming into contact with a system, but he also must not be held responsible for a faulty or inaccurate device. According to the IEEE Code of Ethics, our system must "avoid injuring others, their...reputation, or employment by false or malicious action," which could include providing them with a dud device [7]. The institutions purchasing the system would be affected similarly in that they must provide quality care and a bad device could put their reputation at risk. Finally, the beneficiaries of the research done on PWV are affected when the data collected is inaccurate or otherwise unusable. Our system must provide reliable data in order for it to prove its efficacy and usefulness.

In order to address the above concerns, our system must include a specific protocol for the proper manufacturing, maintenance, and use of the device. Much of these ideas could be accomplished through the FDA approval process, which should ensure that only a device that is on par with medical standards will make it into industry. On our end, however, we can establish a preliminary set of guidelines based on human subject trials, clinical trials, and constant technical testing. If we properly follow through with the testing procedures for accuracy, consistency, and ease of use explained above, we could confidently state that our prototype is ready for streamlined or potentially mass production. We can also detail a protocol for training and procedure methods, such that physicians will collect the highest quality data achievable with our device. Luckily, the safety hazards associated with the hardware end of our device are few and minimal; however, the proper use of the information gathered are left to the discretion of HIPAA compliance rules. Our software application is currently flexible enough to limit the amount of data actually recorded on the mobile device, such that nothing is stored as of now. In future iterations, the amount of personal data collected will have to be decided, but currently that is not a concern.

APPENDICES

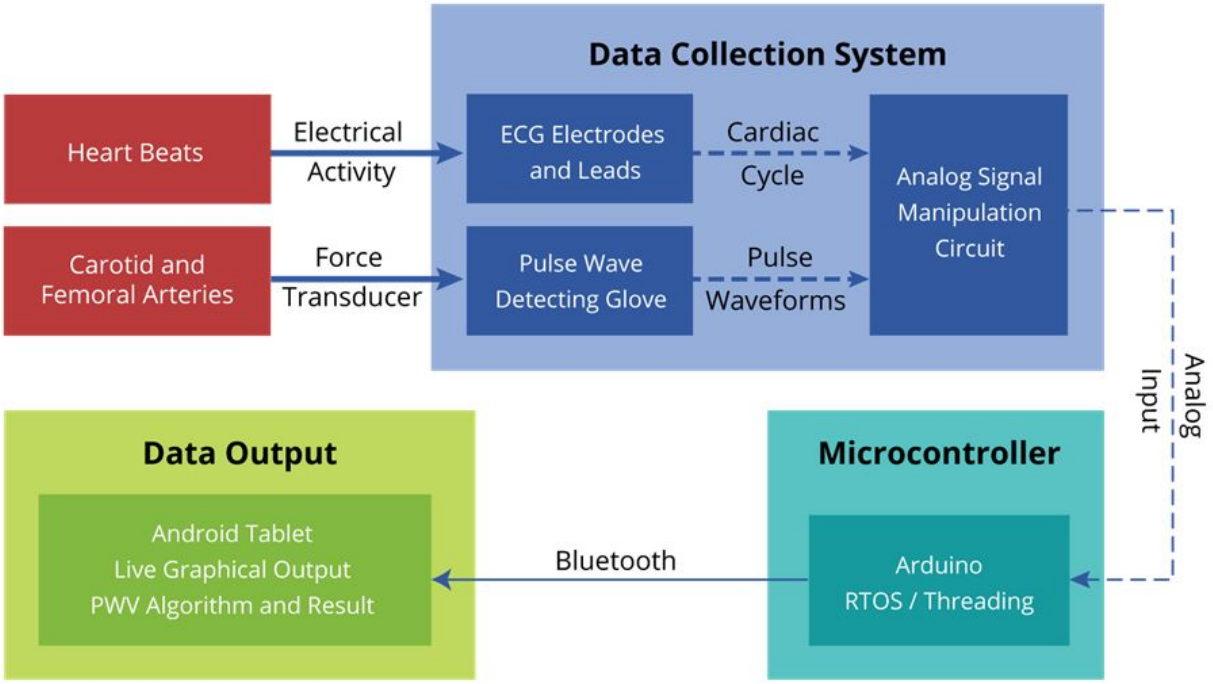

Fig A-1 System Block Diagram

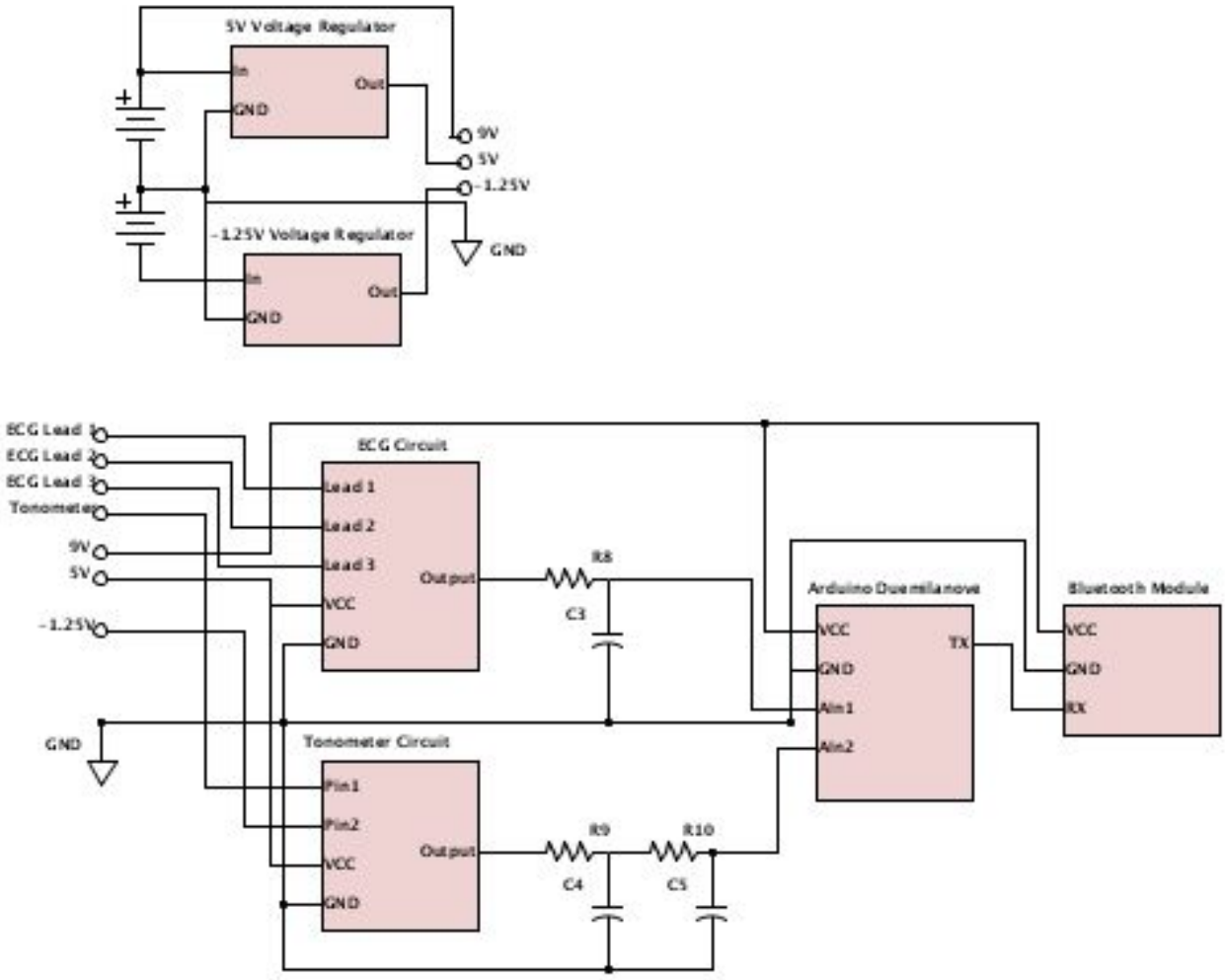

Fig A-2 Top-level Circuit Diagram

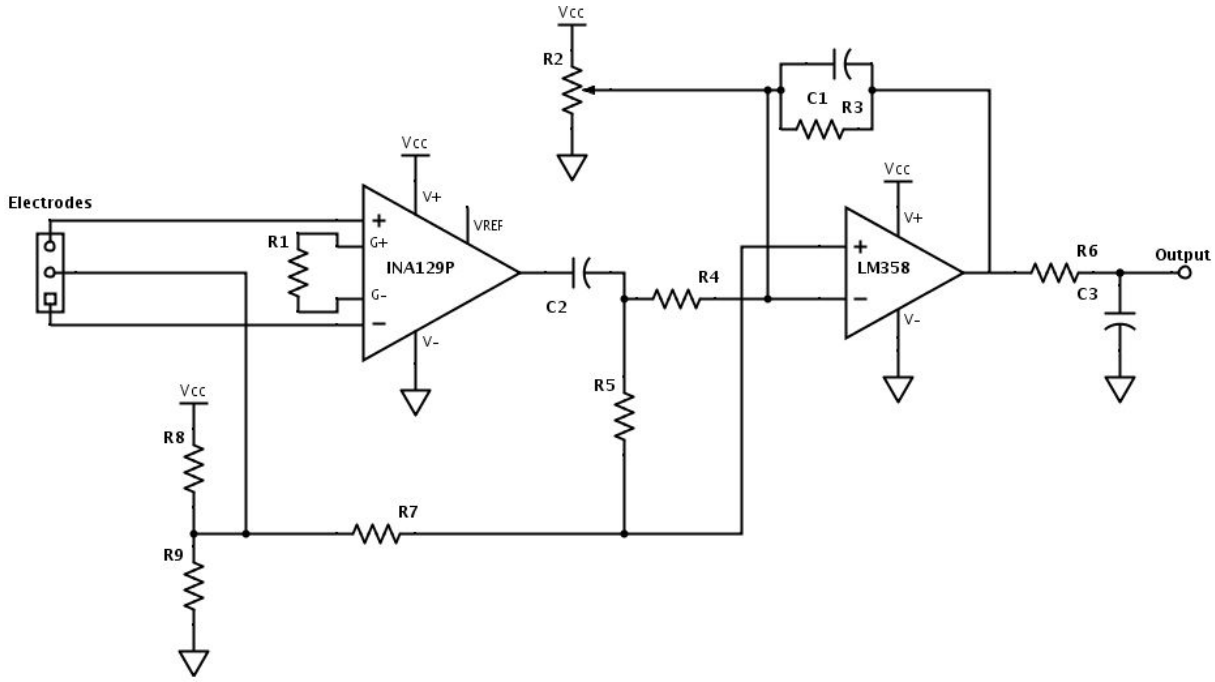

Fig A-3 Subsystem Schematic: Analog ECG Signal Processing Circuit

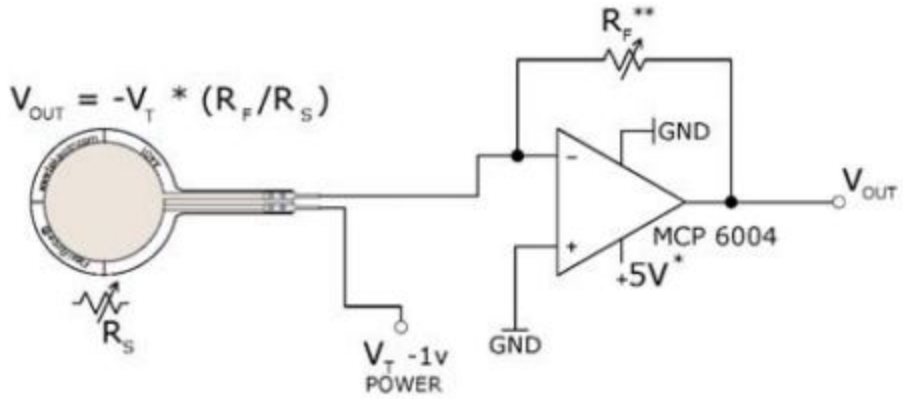

Fig A-4 Subsystem Schematic: Analog Tonometer Signal Transduction

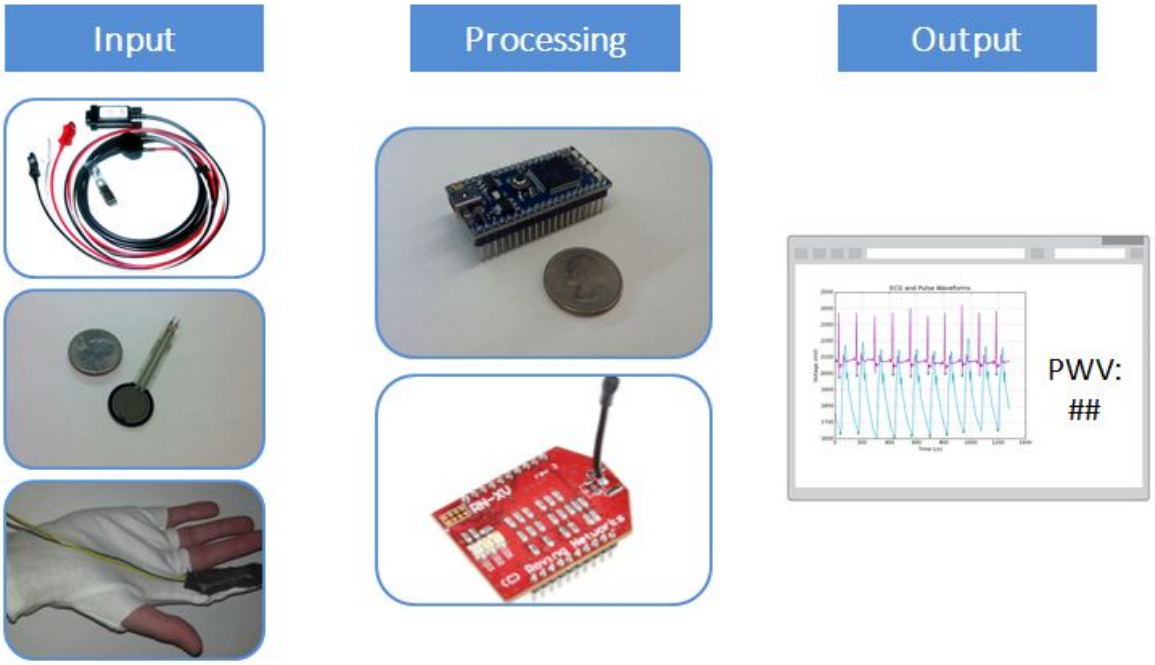

Fig A-5 Simplified Block Diagram with Visuals