Team 19

University of Pennsylvania
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ESE Senior Design

PulseTEAM

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Clinical Instrument for Detecting Pulse Wave Velocity

Abstract

One in four deaths every year within the United States is due to cardiovascular disease. Arterial stiffness is a crucial component in determining cardiovascular risk. Techniques for measuring arterial stiffness have been around for the past century; however noninvasive techniques to quantify arterial stiffness have only recently developed. Pulse wave velocity (PWV) is one such technique that determines the velocity at which an arterial pulse travels through arteries.

The main hindrance of PWV measurement devices to enter the clinical setting is the duration of time it takes for a physician to use such devices, often ranging anywhere from 15 - 60 minutes. Additionally, PWV devices are neither physician nor patient friendly. Physicians receive an unnecessary amount of data, requiring them to obtain training to use each device. Patients are sometimes required to wear multiple wires or uncomfortable neck clamps to obtain a reading. We hope to create a clinical instrument to detect PWV without these constraints.

In order to overcome these obstacles, our device will use a pressure sensor placed on a glove to provide tactile feedback to the user. Additionally the pressure sensor and ECG will send data wirelessly to a web application, easily accessible through any internet enabled device. The program will output several visualizations and a numerical output: PWV. Our goal is to create both the device and web application, and test our device on patients in a proof of concept study.

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 and the metric seems to be independent of age or gender. 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 is building a working prototype of a device to bridge that gap and 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 will resemble a glove to allow for a more natural interface between the physician and the device. The second component is the electrocardiogram (ECG) that monitors the electrical output of the heart. ECGs are well-designed and commonly used devices, and as such, we have no intentions of modifying existing ECG designs in any significant way for our project. Third is the software component, which will be a webapp designed to calculate and display the PWV data most relevant to the doctor. We intend to develop a wireless interface between the hardware components and the webapp.

In order to validate our device's functionality, we will test its accuracy and usability in two ways. First, we have completed an IRB application with the intention of testing our device on real patients in clinical trials. Once approved, our team, with the assistance of our advisor and a practicing cardiologist, will test our prototype on a random and diverse group of volunteers at HUP. We will use these trials to gather our own set of PWV data, and to determine the average amount of time physicians require to collect PWV samples using our device. These tests will primarily be used to prove the concept that our device can determine PWV. Gathering PWV

data from a diverse group of patients will allow us to quantify the consistency of our device by ensuring that we collect data within a reasonable range of PWV values without any significant outliers. 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. The second way to validate our device will be to measure PWV on a smaller sample, such as our team and advisors, with both the existing technology and our prototype, and calculate how our device compares. We aim to meet a maximum of +/- 5% error relative to the golden standard [3]. To further test ease of use, we will conduct physician surveys that will gauge the overall success of our project design.

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 and medical devices in general 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 minutes. Because our device should be available for widespread use, we want to choose the most appropriate platform for displaying processed PWV and ECG data. This widespread accessibility, however, leads to a reliance on wireless network access and computers or mobile devices.

Finally, our project has several financial constraints. We intend to limit our bill of materials to roughly $500 so that future products, if realized, could be commercially sold for less than the industry standard of $25,000. 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 competitors are AtCor,

Vicorder, and Complior, which share some similar important aspects that we intend to improve upon with our device. All three products have been validated as comparable with the gold standard and 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 encased within a stylus, which the doctor uses to probe around the patient's carotid and femoral arteries until he finds a strong pulse that produces a high-quality graph on the software program. This stylus is very difficult to use because it places a large physical boundary between the doctor and the patient that eliminates any 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 his neck for a significant period of time.

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, 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 efficacy 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 artery. 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 months of training and practice to perfect the art of measuring patient's pulse waveforms.

This new device's functional operation can be broken down into four distinct parts, which include 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 patients body for PWV calculations. For detecting pulse wave signals from the carotid and femoral arteries, a tonometer is constructed using a force-sensitive pressure sensor. Similarly, an electrocardiogram is used to collect the electrical activity of the heart. To counter the lack of feedback and discomfort of existing technologies, our tonometer will be worn like a thin glove such that the physician can still rely on feedback from the patient's arteries and actually feel for a

pulse. The actual pressure sensor will lie flat against the doctor's index finger pad and the fabric will be very thin, allowing the doctor to feel through the device to the pulse waves detectable at the surface of the patient's skin. The glove design will be familiar to general physicians, who have already been trained to feel for patients' pulses, and will therefore save physicians time and frustration. The ECG in our device will very closely resemble existing ECG devices.

Next, 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 will be acquired at very low voltages and contain a relatively high signal-to-noise ratio. Moreover, the resulting signal will also contain Mains hum noise at 60hz which will also need to be removed. To isolate the desired signals, filtering and amplifying circuits will be 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 web application through a microcontroller. Because the user interface contains a live graph of the collected signals, the ECG and pulse wave data need to be aggregated and transmitted concurrently with each other. A microcontroller is used to digitize and collect the analog signals, package them, and deliver them wirelessly to the final output stage.

Lastly, the web application receives the raw signals, generates a visualized output, and performs data analysis. During signal collection, the web application generates a live graphical output of the ECG and tonometer data. After all the data has been collected, an algorithm calculates PWV with the numerical data from the signal plots, which will be in the form of pairs of voltage and time. The algorithm will detect the feet of the pulse waves and compare their times relative to a common point on the ECG wave. The "foot" of each wave will be identified as the lowest points on the pulse wave graphs, which are subsequently the lowest values in the numerical data. Any consistently recognizable point on the ECG will be adequate for the relative timing point. By analyzing the graphical and numerical outputs and comparing them over time, a physician will be able to track a patient's cardiovascular health.

3.2 SYSTEM SPECIFICATIONS

Table 3.2-1 Old vs New System Specifications

Characteristic	AtCor Sphygmocor	New Device
Cost	$25,000	<$500
Accuracy	+/- 5%	+/- 5% of SphygmoCor

Time of measurement	15-30 min	< 10 min

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 device and required several trials until a specific list characteristic requirements could be compiled. For one, the sensor must be small, thin, and flexible enough to fit comfortably in the finger of a glove without significantly impairing sense of touch. A force sensing resistor is most effective because the sensor will inevitably experience 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 requires 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.

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 a minimum viable product, 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 webapp, the signals from the ECG and the pressure sensor must be filtered to remove undesirable frequencies. Due to the nature of the human body and the signals we aim to collect, a robust Butterworth lowpass filter should work to preserve the desired low frequency signals and eliminate the higher and undesired frequencies. The lowpass also serves to remove the Mains hum noise at 60Hz, which is why we require a third order filter with a steeper response slope that more effectively cuts out frequencies above 30Hz.

A microcontroller was needed for signal digitization and transmission to the webapp. For this purpose, the mbed 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.

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 Instrumentation Amplifier Subsystem Requirements

Characteristic	**Requirement**
Number of Inputs	2
Signal to Noise Ratio	~17dB
Input Voltage Range	0-100mV
Gain G = 1 + 49.4kOhm/Rg	1-1000V/V
Supply Voltage	<=12V
High CMRR	>100dB

Table 3.3-3 Filter Subsystem Requirements

Characteristic	**Requirement**
Type	Lowpass
Design Method	Butterworth
Order	3rd
Cutoff Frequency	30Hz
Number of Inputs	1

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

Characteristic	**Requirement**
Number of inputs	2
Input Voltage Range	0-3V
Supply Voltage	6V
Sampling Frequency	500 Hz
Signal to Noise Ratio	~21dB
Analog to Digital Conversion	12-bit
Wireless Capability	Compatible with WiFly

3.3.2 Software Requirements

Producing a successful final prototype requires several software-related components. First, our hardware device must integrate seamlessly with our web 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, we will program our embed microcontroller to interface with our web application via websockets. Websockets are the most secure and lowest-latency options for our project.

Second, our device must be accessible from any mobile device and laptop computer, to provide physicians with the flexibility to collect data in the field. This flexibility requires that our software application be hosted on the internet, at a domain name accessible from any device. We have used Amazon Web Services to set up a server to deploy our web application.

Third, because we are deploying our application on the web, our prototype must be fully compliant with any hospital data transfer protocols. We expect that robust, well-known encryption protocols such as SSL can be used to suit our needs.

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

Table 3.3-5 Software Requirements

Characteristic	**Requirement**
Real-time data stream from hardware device	Hardware/software websocket integration
Accessibility from mobile device and from personal computer	Amazon Web Services instance setup
Flexible multiplatform software, deployable on multiple servers and networks, accessible from different internet browsers	Executable python script, which runs on Javascript and HTML/CSS frontend
Three-step click-and-go process, mapping out which measurements physicians should take during the PWV-measurement process	Well-designed HTML/CSS front end with hardware button controls on device
Hospital-compliant data transfer protocols	Using well-documented data encryption/decryption algorithms such as SSL

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 device in two distinct ways. To determine the accuracy of the tonometer and ECG we will need to test the device as a whole against one of the existing technologies with the golden standard rating. We will most likely use the AtCor SphygmoCor, which is available in our advisor's hospital and nicely displays both the pulse wave and ECG graphs and records their data as pairs of voltages and times.

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

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.

3.4.2 Demonstration

Our project is composed of several distinct steps that would best be 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 should accurately and clearly represent the process behind our project to even the least technical audience. If we are also able to produce a live PWV reading by the end of the demonstration, we will have successfully exhibited the point and purpose of the device. We will most likely use one team member as the “patient” and another as the “doctor” while the other two support the demonstration with further verbal explanations and poster exhibition.

3.5 PROJECT SCHEDULE

3.5.1 Schedule

The schedule can be found on the following page.

3.5.2 Schedule Discussion

The project is mostly on schedule, with some subtasks behind schedule. The Institutional Review Board Application is complete. We still must obtain information and make contact with the proper faculty members in order to pursue a patent. The user interface design is behind schedule and we plan on catching up by using the winter break period. This task can easily be done without school facilities. The initial "PUT" request onto web application server task has also been extended. In order to fulfill this task, Franklin will be helping Xinran with this assigned task at the beginning of the new semester. We have also extended the timeframe for testing our device with a doctor and testing it in a lab setting due to other tasks that have been delayed. If the previous tasks mentioned beforehand are addressed, this task will also be completed. We ambitiously posted this task to be completed before winter break; however, we well expected it to be completed at the end of January. Now that Vignesh has completed the IRB application, he will be able to assist with various tasks over break in order to meet the goal of having a working prototype ready by the end of January.

4 RESULTS

A rough prototype of the tonometer glove was developed and functions well enough, such that the material does not interfere with the pressure sensor readings or the comfort of the user or patient. Pulse wave data was successfully collected using this tonometer glove prototype from the carotid artery. 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. From the original data and its spectral frequency graph we were able to see that the signal was not quite clean enough yet. The spectral graph specifically showed what frequency of noise was still most prevalent, which allowed us to determine the need for a higher order filter and an instrumentation amp better suited for low frequency signals.

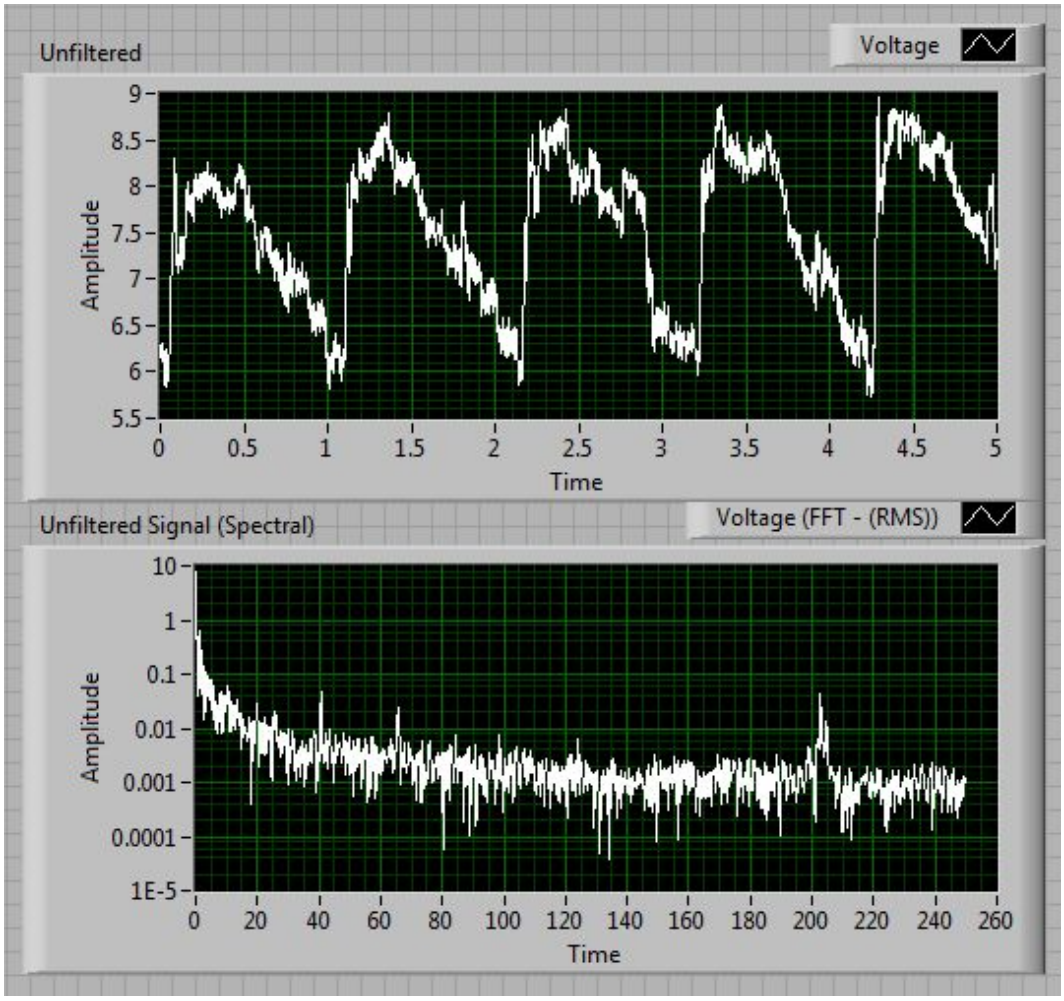

Figure 4-1 Tonometer Data in LabView

Rough ECG data was also collected using a Biopac three-lead set. The signal was also displayed on labview after passing through a nearly identical instrumentation amp and

lowpass filter circuit. The data, as shown in Figure 4-2, resembled the desired form of an ECG signal with its distinctive peaks, but still needs further filtering and most likely a more sensitive instrumentation amp as well.

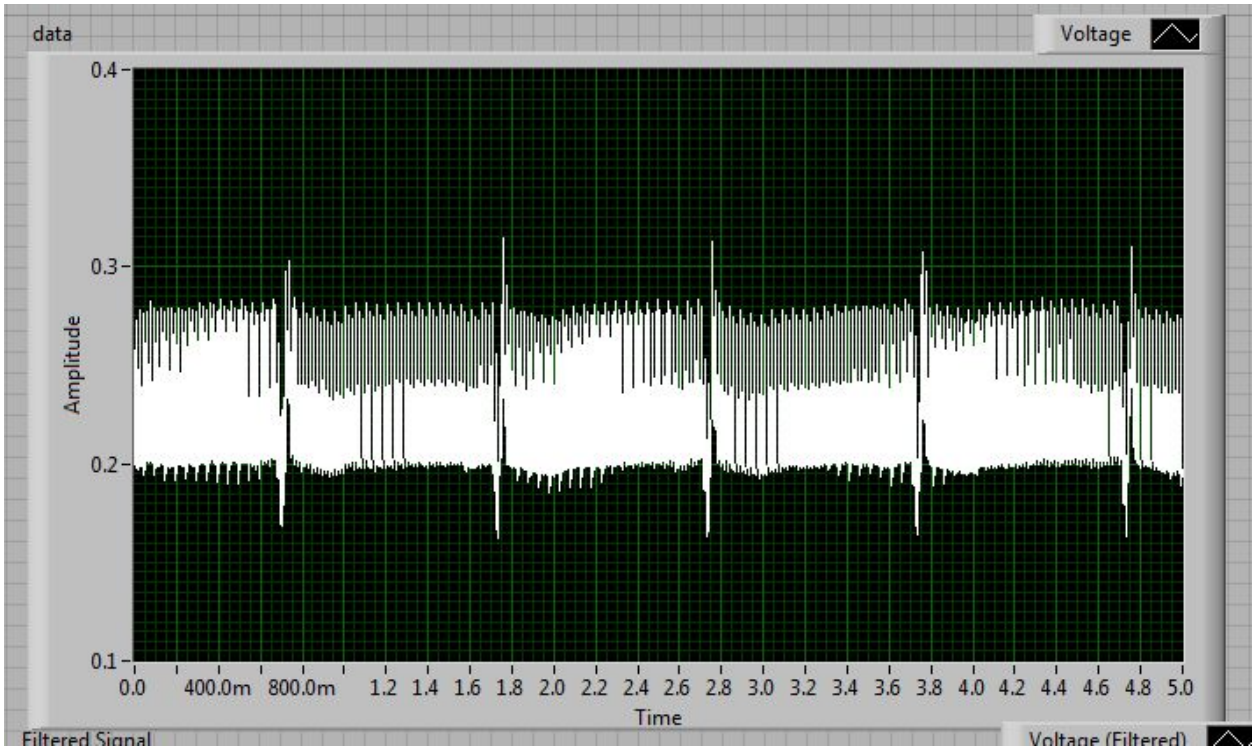

Figure 4-2 ECG Data in LabView

There was also progress on the software side of our application. Over the past few weeks, the embed microcontroller was programmed to connect to local wireless networks, and a server was set up using Amazon Web Services. This server serves as the foundation for our Python/Javascript web application, which is accessible from the embed via websockets.

The web application itself is capable of processing PWV data from a .txt application, and produces an output graph identifying the foot of each wave (Figure 4-3). Figure 4-3 displays the transposed ECG and PWV waveforms, clearly marking the foot of each wave with the light green dots.

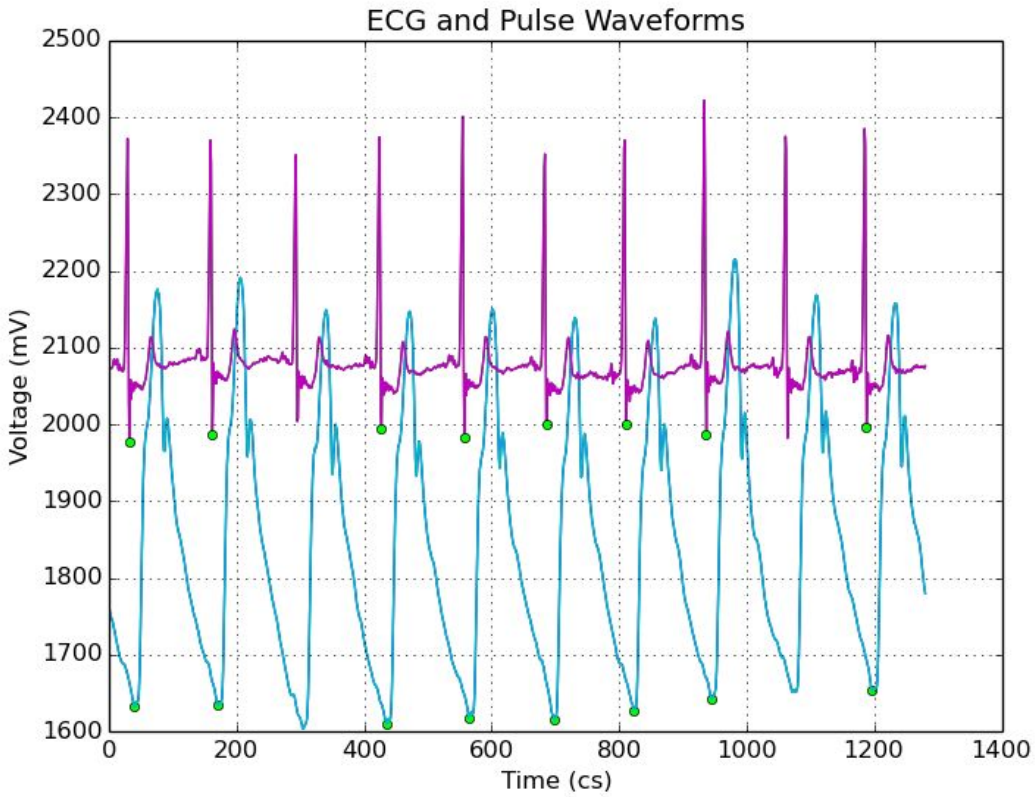

Figure 4-3 Processed ECG and Pulse Waveform Data

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.

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

9 REFERENCES

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APPENDICES

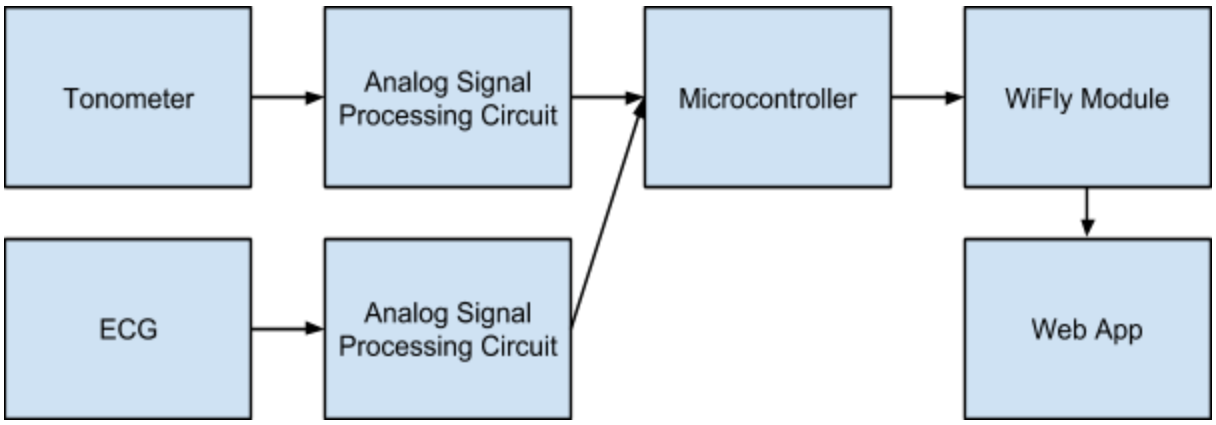

Fig A-1 System Block Diagram

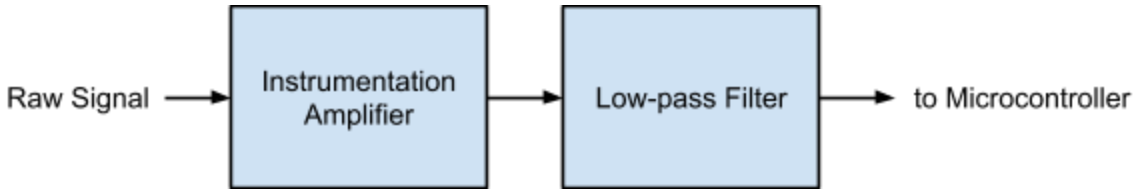

Fig A-2 Subsystem Block Diagram: Analog Signal Processing Circuit

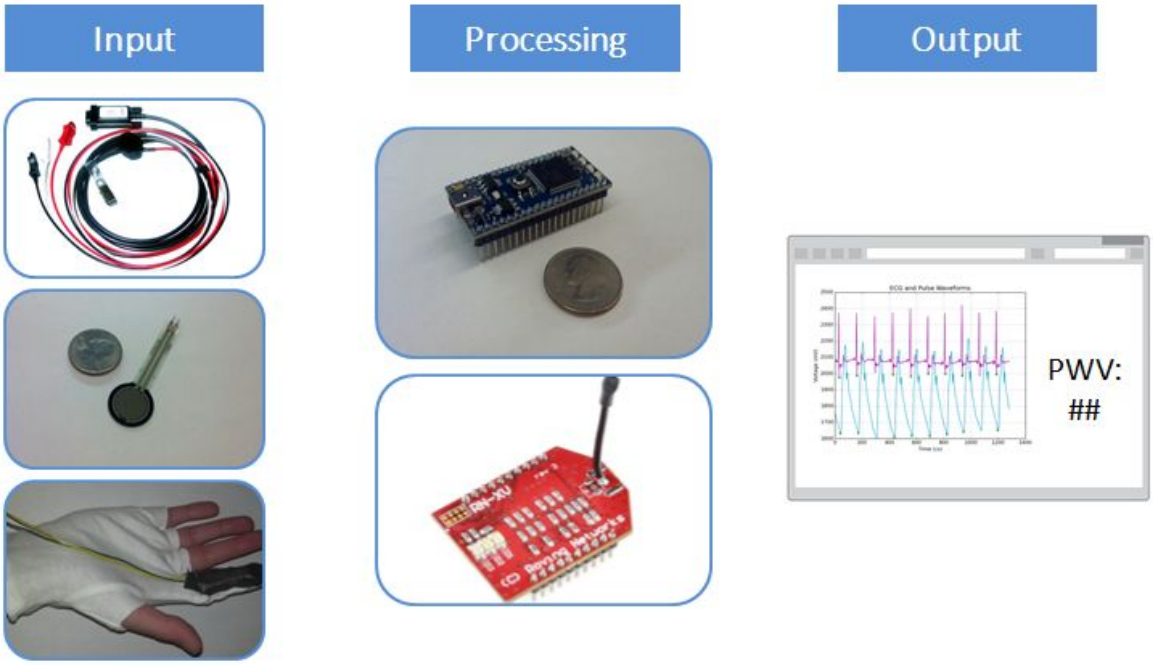

Fig A-3 Simplified Block Diagram with Visuals

5 Lessons Learned

A lot of the lessons learned from the first semester have less to do with the technical side of our project and more to do with management and execution of such tasks. At the beginning of our project we had difficulty even coming up with a project. We knew we wanted to do something healthcare related and found the proper faculty advisor to put us into contact with HUP physicans. They were able to identify a need that we thought we could address, which was creating and implementing a PWV device in a clinical setting. The lesson learned here is communication is key. It allowed us to find a problem that we could fix. Our faculty advisor also set goals for us throughout the school year to meet, which was useful for instilling a sense of urgency thoughout the school year.

Defining and dividing tasks beforehand are crucial. At the beginning of the year we were unorganized in our planning. Having no clear tasks defined for meetings lead to inefficentcies and

Franklin Yang:
Section 1 (Introduction): Clarity of background information - Subtotal
• Project justification, general background material, theory and description of what is to be accomplished are clearly articulated.
• Quantifiable and measurable goals are given as appropriate to the project.
• The particular approach chosen is shown to be appropriate for the identified stakeholders or clients or user community.
• Discussion of appropriate constraints (technical or non-technical) is included.
Franklin Yang:
Replaced:

Pulse wave velocity (PWV), however, is an indicator for arterial stiffness and risk of heart disease that is relatively simple to measure non-invasively. Existing technologies that measure PWV are primarily used in research and are expensive and difficult to use, which makes them unsuitable for clinical use. Our team intends to develop a working prototype of a new device that will allow physicians to easily determine PWV with the same accuracy as existing technologies, but without the drawbacks.
Franklin Yang:
Section 2 (Previous Work): Prior art/Current state of art - Subtotal
• Summarizes the results of each previous approach considered, and their pros and cons.
Franklin Yang:

Section 3 (40% - Subtotal Score)
Section 3.1 (System's Approach and Methodology): The approach should include - Subtotal
• Description of the methodology to be used.
1) signal collection -> 2) signal processing -> 3) data analysis -> 4) output
• Description of the supporting information & data to be collected.
• Discussion of alternative solutions to be developed and how they will be evaluated and compared.
• System block diagram(s) or system flow chart(s) or both with appropriate discussion.
• Preliminary theory of operation and description of what the expected benchmark performance will be. We expect to see the following:
• Description of what will be designed
• Description of the functional operation of the anticipated design.
• Preliminary theoretical, mathematical, or logical analysis of the anticipated design's operation.
• Description of expected performance (which ties into the previously stated project goals Section 1).
Franklin Yang:
Section 3.2 (System Specification): The system specification should include - Subtotal
• Table, with appropriate discussion, of quantitative and qualitative characteristics of the system being designed.
Section 3.3 Requirements: Each report is expected to have either Section 3.3.1 or 3.3.2 or both; as appropriate to the project - Subtotal
Section 3.3.1 (Hardware Requirements); if only hardware
Section 3.3.1 (Hardware Requirements); if hardware & software
• Quantitative tasks that the hardware must accomplish in order to meet the system specifications. Subsystem and subsystem block diagrams.
Section 3.3.2 (Software Requirements): if software alone
Section 3.3.2 (Software Requirements): if hardware & software
• Qualitative and quantitative requirements that the software is to fulfill in a generic sense & an approach that is planned for satisfying them.
Franklin Yang:
• Include detailed tasks that must be completed during the project year to successfully complete the project. An expected completion date & responsible team member are included for each task.
Franklin Yang:
• If all of the measurement equipment, computer equipment and/or software packages needed to execute your project are available for your use at Penn, then a simple declarative statement stating this fact is all that is needed in this section.
Franklin Yang:
• The following items need to be identified in this section: (1) special measurement equipment,

(2) computer equipment, (3) software packages that are not available for your use within Penn; and mechanical items that need to be fabricated or purchased.

Franklin Yang:

Section 10 (Prelim Bibliography)

• Alphabetical listing of literature used for research NOT cited in text.

Section 11 (Prelim Financial Information)

• Preliminary project budget