Development of a Novel Cardiovascular Health Monitor

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Daryl K. Brown II

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Technical Project Team Members

Brendan Kenefick

Justin Yao

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

John Hossack, Department of Biomedical Engineering

Sula Mazimba, Division of Cardiovascular Medicine

Nishaki Mehta, Division of Cardiovascular Medicine

Development of a Novel Cardiovascular Vessel Health Monitor

Daryl K. Brown II[a], Brendan P. Kenefick[a], Justin Z. Yao[a], Sula Mazimba[b], Nishaki K. Mehta[b], John A. Hossack[c,1]

[a] Undergraduate Student, University of Virginia Department of Biomedical Engineering
[b] Doctor of Medicine, University of Virginia Division of Cardiovascular Medicine
[c] Professor, University of Virginia Department of Biomedical Engineering
[1] Correspondence: jh7fj@virginia.edu, MR5 Rm 2121 415 Lane Rd., (434) 243-5866

Abstract

Cardiovascular disease (CVD) is the leading cause of death in the United States, causing one in every five deaths annually. Prevalence and medical costs of CVD are expected to continue to rise each year. Arterial stiffness increases with age and is related to the onset of CVD. Pulse wave velocity (PWV) is the speed at which waves generated by the heart propagate through the vasculature, and has a direct relationship with arterial stiffness. The main goal of this research was to design and perform IRB-approved clinical trials with a device that uses a novel method of calculating PWV (UVA IRB #21612). An Arduino-based device was prototyped, consisting of a finger pulse oximeter, an ear-clip pulse monitor, and an electrocardiogram (ECG). Due to COVID-19, clinical trials were suspended early, and validation of the novel device standard clinical devices was unable to be performed. Fourteen subjects of a 60-subject clinical trial were tested, consisting of five heart failure patients and nine healthy volunteers. The device was able to measure PWV both before and after exercise to a precision within ±0.5 m/s. Finger and ear PWV measurements using photoplethysmography and ECG yielded the lowest average standard deviations. Almost all p-values associated with the difference in PWV pre-exercise and post-exercise were found not to be statistically significant ($p < 0.05$). Finger and ear measurements were found to have statistically significant differences in average ($p < 0.0001$ in 7 of 8 tests; $p = 0.002$ in 1 of 8 tests). Weak negative correlations between pre-exercise finger PWV, body mass index (average $r = -0.62$, average $p = 0.03$) and diabetes mellitus (average $r = -0.64$, average $p = 0.023$) were calculated. Future work is required to complete clinical trials and validate the efficacy of the device against current clinical standards.

Keywords: Arterial Stiffness, Pulse Wave Velocity, Metabolic Equivalent of Task, Photoplethysmography, Pulse Transit Time

Introduction

Cardiovascular disease (CVD) is a class of diseases that affect the heart and blood vessels that include conditions such as heart failure and coronary artery disease.[1] CVD is the leading cause of death in the United States for both men and women, accounting for one in four deaths.[1] While middle-aged people are more at risk for heart conditions than young people, current research shows that the age group most at risk for CVD has decreased from ages 60 and above to those aged 35 and older.[2,3] Cardiovascular disease costs the US more than $318 billion annually, with an additional $237 billion resulting from indirect costs, including lack of productivity due to morbidity and premature mortality. As of 2015, 41.5% of Americans had some form of CVD, and by 2035, this number is projected to rise to 45.1%.[1]

Risk factors for CVD, including age, ethnicity, and genetics, are classified as either modifiable or non-modifiable.[2,4] Modifiable risk factors can be controlled or eliminated in order to improve cardiovascular health. The three key risk factors for CVD are smoking, high blood pressure (hypertension), and high cholesterol, and are shared by 47% of Americans.[2,4] An estimated 41% of Americans have hypertension. By incorporating physical exercise and a change to a diet low in trans fats, saturated fats, and salts, one can reduce the risk of developing CVD. Reducing alcohol intake has also been shown to decrease blood pressure.[4]

Atherosclerosis and Arterial Stiffness

Atherosclerosis is a disease in which plaques accumulate in the arteries, causing the wall of the artery to thicken and leave a narrower channel through which the blood can flow. Reduced blood flow results in less oxygen and nutrients delivered to body tissues.[5] Other cardiovascular diseases can arise due to plaque buildup, including coronary artery disease, angina, and chronic kidney disease. Atherosclerosis is slow and progressive, and symptoms occur with normal aging.[5] Arterial stiffness, in general, is strongly associated with the onset of other cardiovascular events and mortality especially in patients with hypertension.[6,7] Stiffness is associated with the relative amount of collagen in the wall. Because proximal arteries have greater amounts of elastin than collagen, they are normally less stiff than distal arteries, in which the protein relationship is the reverse.[8]

Pulse Wave Velocity

Pulse wave velocity (PWV) refers to the velocity of the blood pressure wave generated by systolic contraction of the heart traveling through the vasculature. Regional PWV is measured between two different arteries of the aortic tree,

while local PWV is measured in a short segment of an artery.[9] PWV has a direct relationship with arterial stiffness and, therefore, can be used to predict the onset of cardiovascular disease. PWV is increased in peripheral vessels as a result of the higher collagen content. The normal range (in a population of normotensive patients with a median age of 39) is defined as: 4-6 m/s in the aorta, and 8-9 m/s in the iliac and femoral arteries.[10]

The gold standard for measuring PWV is threaded catheterization, however it is highly invasive and time-consuming and is usually reserved for cardiovascular diagnostic tests.[10] Other non-invasive methods include echocardiography (using the Doppler ultrasound technique), magnetic resonance imaging (MRI), sphygmomanometry, and photoplethysmography (PPG), the method used in this study.[9] Echocardiography involves recording the propagation of electrical signals in the heart, and MRI measures vessel lengths and calculates pulse wave transit times.[11] While these methods provide accurate readings, they are time-consuming and expensive and not commonly used in clinics. Oscillometric measurement via sphygmomanometry is a novel method that has been shown to be accurate within acceptable range given by catheter measurements (standard deviation < 1.5 m/s).[12] The PPG technique measuring two pulse pressure waves by shining red (660 nm) and infrared light (990 nm) into a tissue and using a photodetector to record the absorbance of each wavelength.[9] For the developed cardiovascular device, the PPG method was chosen as it non-invasively and quickly produces a regional PWV measurement and could be integrated with other clinical measurement devices.

For this method, two PPG probes were used, one attached to the index finger and one attached to the ipsilateral earlobe. The time difference between the two waves, known as the pulse transit time (PTT), was calculated and the vessel length was estimated based on distance measurements made over the body surface. The change in distance (in meters) between the finger and ear is then divided by the PTT (in seconds) to obtain a regional PWV. Figure 1 illustrates an example of a similar method for calculating pulse wave velocity. However, the figure demonstrates the calculation of the carotid-femoral PWV, the difference being the locations of the measured pulse waves (carotid-femoral vs. finger/ear).[13]

In addition to the two pulse oximeter probes, a Lead I electrocardiogram (ECG) was incorporated in the device in order to provide an avenue for obtaining two additional PWV measurements. For these measurements, the PTT is determined as the time difference between the ECG (electrical stimulus) and the onset of the pulse pressure waveform at either the fingertip or earlobe. Additional information regarding the PWV calculations is provided in the Materials and Methods section.

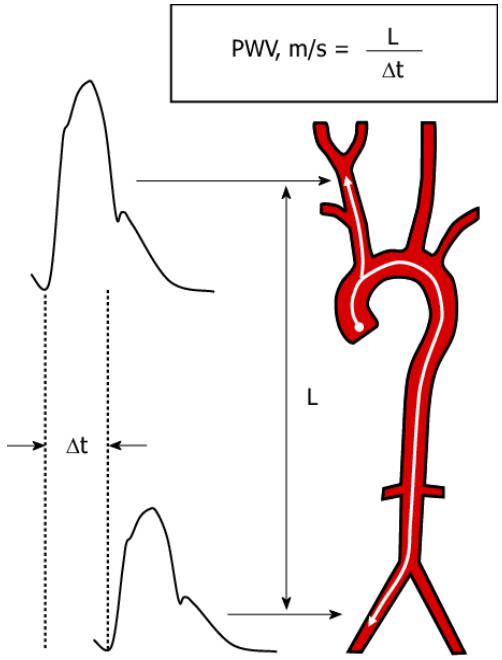

Fig. 1. Visualization of Pulse Wave Velocity Calculation by Zanoli et al. (2015). While this illustrates the carotid-femoral PWV, the method is the same; the difference in our method is the use of the fingertip and earlobe as the two locations for measuring the pressure waves. The vessel distance is divided by the PTT (Δt in the figure), which is calculated by measuring the time difference between the two pulse waveforms.

Metabolic Equivalents of Task

In addition to measuring pulse wave velocity, the measurement of metabolic equivalents of task (METs) using PPG was explored. METs is a measure of energy expenditure of a patient relative to their body mass.[14,15] By convention, one MET is defined as 3.5 ml of O_2 per kilogram of body mass per minute. METs is often used when determining a patient's functional capacity prior to surgery (pre-op clearance).[16] Healthcare professionals do not have a quick and objective method of measuring METs, and they often ask questions about the patient's relative athletic ability, such as being able to climb two flights of stairs.[17] This is a highly subjective method to measure a patient's condition for pre-op clearance, as patients sometimes overestimate the extent of their abilities. This device incorporates a METs computation formula derived using a correlation with index heart rate.[18] This method allows for a more objective determination of a patient's fitness for surgery without the need for a physically taxing

cardiopulmonary exercise test (CPET), the standard method of METs calculation.

Materials and Methods

Body Surface Measurements

In order to calculate pulse wave velocity, physical measurements must be made over the surface of the subject's body. For the calculations, the midline of the sternal angle was used as a reference point for each subject. The distance from this point to the index fingertip and directly to the ipsilateral earlobe (the measurement did not follow the curvature of the body – neck, head, etc.) were measured using a sewing tape measure.

In addition, the orthogonal distance from the earlobe and the subject's wingspan were measured and recorded. These distances were not used in the PWV calculation. However, they were recorded for future analysis and potential use as alternatives to the direct distances, described in the paragraph above. All distances were recorded in centimeters.

Device Hardware

The study team built the novel device to measure cardiovascular indicators using one ECG and two pulse oximeter (or PPG) probes. A digital finger pulse oximeter (ProtoCentral AFE4490 Pulse Oximeter Shield), analog ear pulse oximeter (Grove Ear-clip Heart Rate Sensor), and single lead (Lead I configuration) ECG (SparkFun AD8232 Single Lead Heart Rate Monitor) were acquired. The hardware was implemented using an Arduino Uno microcontroller, breadboard, wires, and USB A/B connector.

Device Software

Data Acquisition

The open-source Arduino integrated development environment (IDE), which uses a set of C/C++ functions, was used to configure the data acquisition of the hardware. Algorithms were written to sample the ECG and pulse oximeter (ear and finger) data.

Data Analysis

Algorithms were created in MATLAB in order to extract and analyze acquired data. The "MATLAB Support Package for Arduino Hardware" allowed for easy integration with the Arduino software. In addition, a graphical user interface (GUI) was created using the MATLAB App Designer IDE. The GUI incorporated the data acquisition and analysis algorithms in a single, user-friendly interface, removing the need to manually run the various software algorithms. In addition, the interface provided immediate user feedback through the visualization of calculated values and graphed ECG and pulse pressure waveforms.

Calculation of Pulse Wave Velocity

As briefly described in the Introduction, PWV using PPG is generically calculated using an estimation of vessel length and the PTT (Equation 1).[7,9,12] To estimate the vessel length, distance measurements were made over the surface of the body from the midline of the subject's sternal angle to their index fingertip and from the midline of the sternal angle directly to the earlobe. In this novel device, four unique pulse wave velocity calculations were developed. The first method, PWV 1, uses the time difference (PTT_V) between the peaks of the first derivative (ascent of the pulse waveforms) of the two pulse pressure waveforms (Equation 2). The second, PWV 2, uses the time difference (PTT_A) between the peaks of the second derivative (onset/foot of the pulse waveforms) of the two pulse waveforms (Equation 3). The third and fourth PTTs are calculated by measuring the time from the ECG (electrical heart beat signal) to the onset/foot of the finger and ear pulse waveforms, respectively (Equations 4 and 5). Previous groups have used similar methods for measuring PWV using an ECG, however, the PTT is measured from the peak of the R-wave to the onset of the pressure waveform.[19,20] While the R-wave peak is easiest to obtain algorithmically, physiologically it is indicative of the beginning of isovolumetric contraction and not left ventricular ejection.[21,22] The aortic valve does not open until the electrical signal returns to baseline, as shown in Figure 2, and, therefore, is a more accurate estimation of PTT.[23] An algorithm was created to find this point for each heartbeat, in the ECG waveform, and use it as the initial critical point for PTT and subsequent PWV calculations.

$$PWV = \frac{Vessel\ Length\ (meters)}{Pulse\ Transit\ Time\ (seconds)} \quad [1]$$

$$PWV\ 1 = \frac{Finger\ Distance - Ear\ Distance}{PTT_V} \quad [2]$$

$$PWV\ 2 = \frac{Finger\ Distance - Ear\ Distance}{PTT_A} \quad [3]$$

$$Finger\ PWV = \frac{Finger\ Distance}{t_{Finger} - t_{ECG}} \quad [4]$$

$$Ear\ PWV = \frac{Ear\ Distance}{t_{Ear} - t_{ECG}} \quad [5]$$

$$METs = \left(3.2 * \frac{Heart\ Rate_{Current}}{Heart\ Rate_{Rest}}\right) - 0.7 \quad [6]$$

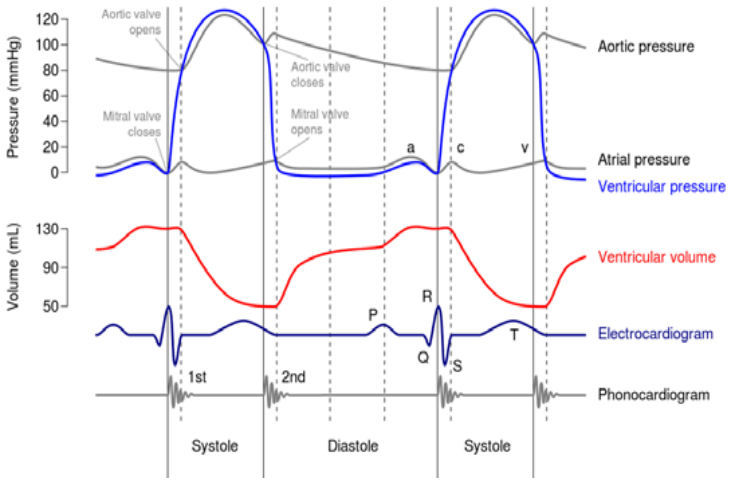

Fig. 2. Wiggers Diagram by Gokhale (2016). This figure shows Wiggers Diagram, a widely accepted teaching diagram used in cardiology. The figure shows that the aortic valve does not open until the first dashed line, which corresponds with the S-wave of the ECG returning to baseline. After the valve opens, left ventricular ejection occurs and the volume of blood in the left ventricle (shown by the red line) decreases, until diastole. Therefore, this point is a more accurate critical point for calculating the PTT using the ECG.

Calculation of Metabolic Equivalents of Task

Equation 6 correlated METs with the ratio of active heart rate over the heart rate at rest. This equation was found by Yamamoto et al. to fit a sample of 243 cardiovascular disease patients with the mean age of 58.7 and R_2 value of 0.548.[18] This equation was implemented in MATLAB to allow for smoother analysis of both PWV and METs. Future work may be needed to create a novel correlation between METs and heart rate, once validation, by CPET, is completed in clinical trials.

Clinical Trial Data Collection

As previously mentioned, the study team received approval from the University of Virginia Institutional Review Board for Health Sciences Research (IRB-HSR) for a 60-subject clinical trial (IRB #21612). Due to the ongoing restrictions on research due to COVID-19, only five heart failure patients from the University of Virginia Cardiovascular Medicine Division and nine healthy subjects have been enrolled and tested, as of writing this report.

At the beginning of each test, each subject was introduced to the study and had any and all questions answered before signing the consent form. Then, the subject's body measurements were recorded with a tape measure and the three ECG electrodes and pads were attached in the Lead I configuration (one electrode attached to each wrist and one attached on the subject's right-side below the level of the navel). The finger and ear pulse oximeters were attached to the subject's right index finger and right earlobe, respectively. With the subject in an upright seated position, three fifteen-second captures of data were recorded using the device. Before moving the probes to the next position, the subject's vitals were recorded on the right-side; vitals recorded included: heart rate, oxygen saturation, blood pressure, and body temperature. This process was repeated three more times: once on the pulse oximeter probes on the left finger and ear with the patient in the seated position and once on each side with the patient lying supine (for a total of 12 measurements). After the measurements were recorded, each subject was asked to perform a six-minute walk test, as per the standard guidelines outlined by the American Thoracic Society.[24] The distance the subject traveled during the walk was recorded and the subject then connected again to the device and the complete set of 12 measurements (three on both sides, both sitting and supine) was repeated.

Finally, as part of the study, each of the subjects consented access to the subject's medical history, for purposes of record keeping and data analysis. Only team members with approved clearance from the University of Virginia Health System will receive access to the records.

Results

The study team received initial approval from the University of Virginia Institutional Review Board for Health Sciences Research (IRB-HSR) for a 60-subject clinical trial on June 14, 2019. Study enrollment began on February 14th, 2020. The goal of the clinical trials was to test 40 heart failure outpatients and 20 heart failure inpatients from the University of Virginia Cardiovascular Medicine Division. However, only five heart failure outpatients had been enrolled prior to the restrictions on human contact clinical trials being instituted, due to COVID-19. In order to supplement this data, the study team enrolled an additional nine healthy volunteer subjects.

Device validation against the current clinical standard for pulse wave velocity measurement (echocardiography) has yet to be completed due to a delay in the arrival of necessary software, prior to the restrictions caused by COVID-19. Therefore, the conclusions that can be drawn from the following results are limited, due to the small sample size and lack of clinical validation.

Internal Device Validation

Without the ability to validate the PWV measurements with echocardiography, increased emphasis was placed on

Table 1. Internal Device Validation. Green cells represent PWV calculations that met the target goal for internal error (< 0.5 m/s). Yellow cells represent the PWV calculations that nearly met the target goal (0.5-1.0 m/s). Red cells represent those that did not meet the target goal (> 1.0 m/s).

PWV Data Summary		Pre-Exercise				Post-Exercise			
		PWV	PWV 2	PWV Finger	PWV Ear	PWV	PWV 2	PWV Finger	PWV Ear
Right Sit	Average PWV	9.05384237	7.84933494	4.191127613	1.914012273	10.61811958	8.095639204	4.496358077	2.560894443
	Average St. Dev.	1.15942986	0.541513212	0.173982399	0.098386086	0.782818198	0.425115902	0.279610555	0.263455006
Left Sit	Average PWV	9.851356613	7.696997889	4.211703073	1.976698055	12.5233353	8.806250172	4.434457747	1.918007715
	Average St. Dev.	0.929512677	0.39118038	0.252253812	0.153680447	0.563210635	0.363186445	0.156494314	0.08457206
Right Supine	Average PWV	8.100864797	6.653770697	4.307690512	2.362958553	8.469886185	7.171958109	4.372181964	2.449288352
	Average St. Dev.	0.623522233	0.488351881	0.107711527	0.142669209	0.522852158	0.365977337	0.174090613	0.175272081
Left Supine	Average PWV	8.29441509	6.794725492	4.320180566	2.524220665	11.25261076	8.026981347	4.491708648	2.367791872
	Average St. Dev.	0.678490688	0.317162952	0.228510391	0.277408108	1.692106451	0.532433115	0.116489942	0.15973151

analyzing the device's internal error with the data gathered from clinical trials. Primarily, this included analysis of the standard deviations of the four PWV calculation methods across all scenarios and subjects. Prior to clinical trials, the study team set an aim to measure PWV within ±0.5 m/s consistently. Table 1 displays the average PWV and average standard deviation for each PWV method across all 14 subjects and positions. From this data, we were able to determine that the PWV calculated using the first derivative of the pulse waveforms did not meet the ±0.5 m/s goal for any position. Using the second derivative of the pulse waveforms, the PWV calculation nearly met this goal for the right sitting position pre-exercise and left supine position post-exercise. The calculation met the goal for the other three positions both pre- and post-exercise. Finally, the PWVs calculated using the ECG and onset of the finger and ear waves individually easily met the criteria for all positions, pre- and post-exercise. This result was expected, as there is often variation in pulse waveforms when measuring using PPG. Since the first two calculations rely on using two pulse waveforms, it was expected that the error would be higher in these measurements, compared to the two that use only one PPG waveform and an ECG that is generally more consistent and has less variation in shape.

In addition, to the improved internal error compared to using two pulse oximeters, using the ECG and finger pulse oximeter method for PWV calculation may also prove to be superior when validating with echocardiography. While there is no way to know how the values will compare to the echocardiography data, theoretically the method is less prone to human error in the body distance measurements. The measurement used for this method (distance from the midline of the sternal angle to the index fingertip) is a longer distance than that from the sternal angle to the ear, as well as the distance used for the PWVs with two pulse waveforms (the subtracted distance of the two measures, above; finger distance - ear distance). For the 14 subjects already tested, the average distance from the sternal angle to the fingertip was found to be 85.96 cm. The average direct distance from the sternal angle to the earlobe was found to be 21 cm. The distance for the PWVs using both the finger and ear pulse waves is 64.96 cm (85.96 cm - 21 cm). Therefore, every centimeter in measurement error with the tape measure results in 1.16%, 4.76%, and 1.54% error in the final PWV values, respectively.

Statistical Differences in Measurement

The relationship between all pre-exercise and post-exercise PWVs was analyzed, using a paired t-test, to determine whether there existed a statistically significant difference in

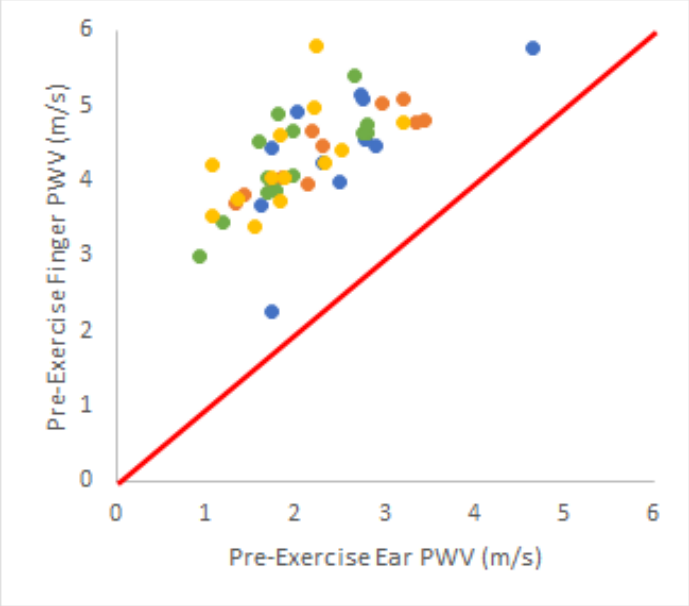

Fig. 3. Comparison of Finger and Ear PWVs. This graph shows the comparison of the Finger and Ear PWVs for each subject in each position. The right-sitting position is represented by green markers, the left-sitting position is represented by yellow markers, right-supine position is represented by orange markers, and the left-supine position is represented by blue markers. The red line represents where the Finger PWV equals the Ear. All points fall above this line, demonstrating that the Finger values were found to be greater than the respective Ear values.

Table 2. Statistical Analysis of Finger & Ear PWV: P-values

Run Type	Pre-Exercise	Post-Exercise
Right-side Sitting	<0.0001	0.0002
Left-side Sitting	<0.0001	<0.0001
Right-side Supine	<0.0001	<0.0001
Left-side Supine	<0.0001	<0.0001

the averages in each set of measurements. As shown in Supplemental Table 1, almost all p-values were above the threshold for a 95% confidence interval ($p < 0.05$), so we conclude that there is no statistically significant difference in means across all four positions for any given measurement. The second derivative pre-exercise and post-exercise PWV differences did trend towards significance across all four positions, with p-values of 0.077, 0.08, and 0.04, the latter of which is indicative of statistical significance.

In addition to the aforementioned t-test analysis, paired t-tests were run on the pre-exercise finger measurements versus those of the ear, as well as the post-exercise measurements of each. We hypothesized that, because the ear is the more proximal of the two extremities, its PWV should be of a lower magnitude. This is because more proximal blood vessels are known to be less stiff and, therefore, have a lower PWV than distal, peripheral vessels.[8] Figure 3 illustrates that finger PWVs were always greater than those of the ear, and Table 2 displays the p-values associated with the t-tests across each position. From this, we are able to conclude that there is a significant difference in the means of each measurement, and by inspection we conclude that the ear PWVs are slower than those of the finger; which was predicted in the initial hypothesis.

Correlation with Body Mass Index and Diabetes Mellitus

For each subject variable, the correlation, if any, with each PWV measurement was calculated. A negative correlation between finger PWV measurements both before and after exercise with increasing body mass index (BMI) and the presence of diabetes mellitus was identified. Figures 4 and 5 display linear regression and point-biserial correlation p-values for each variable and PWV method, respectively. In three of the four positions, a correlation coefficient $r < -0.5$ is associated with a p value < 0.05, allowing the conclusion that these results would be produced if there were no correlation ($r = 0$, the null hypothesis).

Discussion

Cardiovascular disease affects a significant portion of the world's population. The early detection of risk factors and other diseases that cause cardiovascular complications aids healthcare professionals in treatment and can help patients identify healthy lifestyle choices. A widely used metric for assessing cardiovascular health is the determination of how stiff one's arteries are through PWV measurement. The standard method of catheterization to measure PWV is costly, invasive, and time-consuming, and requires a period of recovery after the operation. Our novel method for determining PWV is non-invasive and can produce measurements in minutes to a precision of ±0.5 m/s. The

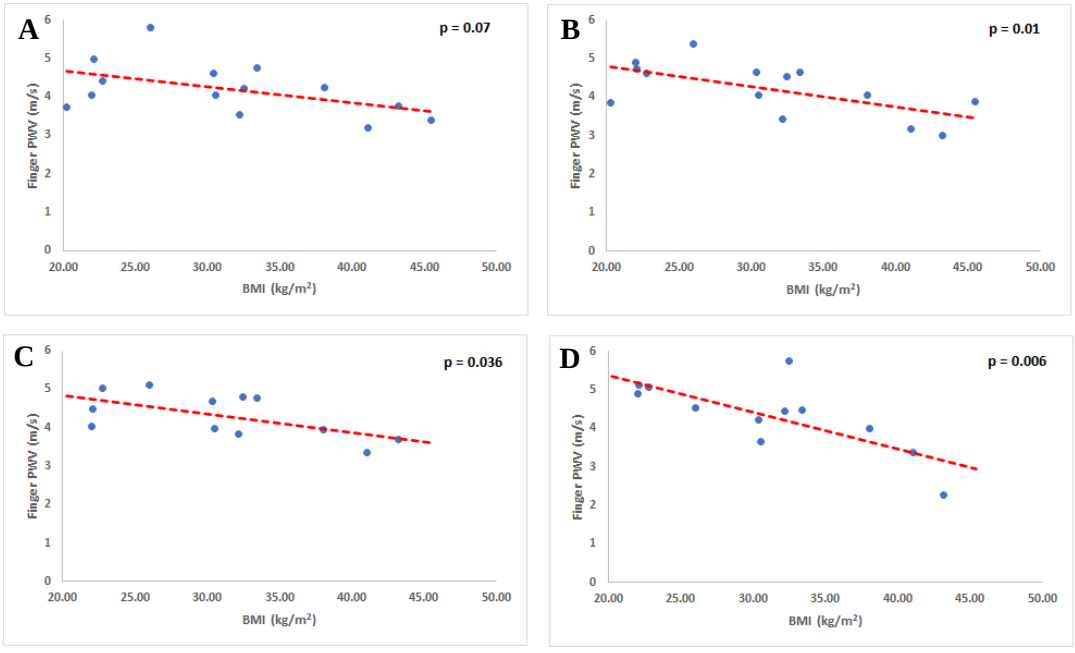

Fig. 4. Correlation Between Pulse Wave Velocity and Body Mass Index, Pre-Exercise. The four graphs show the negative correlations between PWV and BMI for each of the four measurement positions, prior to the subject exercising. A) Left Sit position. B) Right Sit position. C) Left Supine position. D) Right Supine position. The blue markers represent each of the 14 subjects. The red dashed lines represent the negative trend lines of the correlations. P-values for each are shown at the top right of each graph.

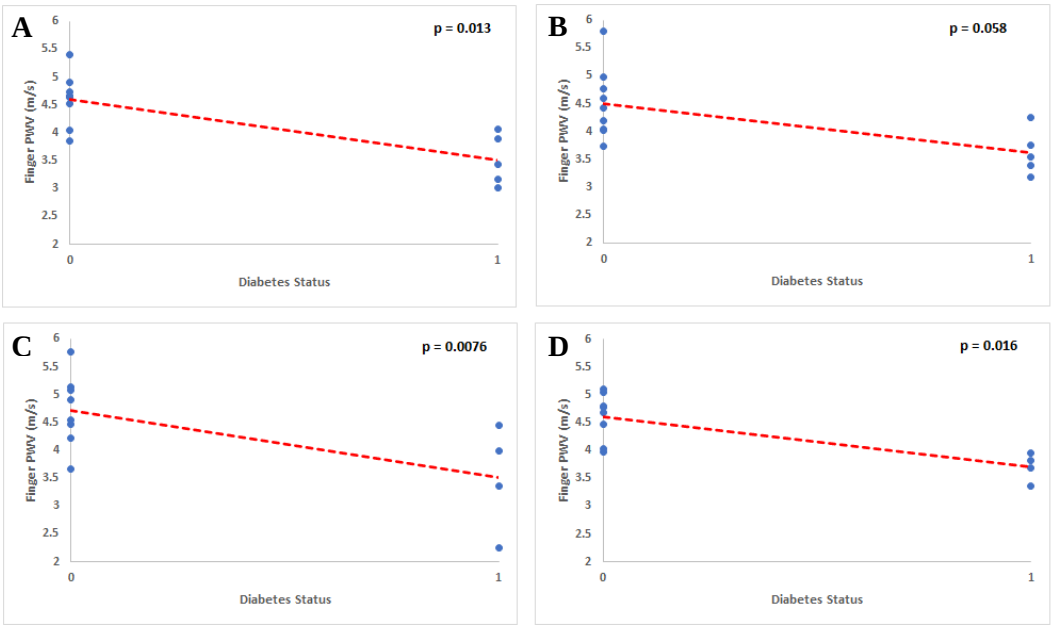

Fig. 5. Correlation Between Pulse Wave Velocity and Diabetes Mellitus, Pre-Exercise. The four graphs show the negative correlations between PWV and diabetes for each of the four measurement positions, prior to the subject exercising. A "1" represents subjects with diabetes. A "0" represents subjects without diabetes. Of the 14 subjects, four had diabetes, while the other nine did not. A) Left Sit position. B) Right Sit position. C) Left Supine position. D) Right Supine position. The blue markers represent each of the subjects. The red dashed lines represent the negative trend lines of the correlations. P-values for each are shown at the top right of each graph.

accuracy of these measurements is yet to be validated with a larger sample size and echocardiography, so future research is necessary to verify the measurements on a new set of patients. Previous studies have shown the need for an 80% correction factor to account for vessel length.[25] The applicability of this correction factor should be determined based on the data validated by echocardiography measurements. Measurement of the sternal angle was performed over clothing. imprecision could impact distance measurements, and ultimately PWV measurements.

The novel method of PWV measurement used in conjunction with the calculation of METs makes the device a viable method of assessing overall cardiovascular health. Reducing the amount of time necessary for these measurements will allow for them to be performed during a routine clinical visit. Knowledge of arterial stiffness and functional capacity for a patient allows for physicians to determine a patient's fitness for surgery and risk for cardiovascular disease.

End Matter

Author Contributions and Notes

D.K.B., B.P.K., J.Z.Y., S.M., N.K.M. and J.A.H. designed research; D.K.B., B.P.K., and J.Z.Y. performed research; D.K.B., B.P.K., and J.Z.Y. developed hardware and software; D.K.B., B.P.K., J.Z.Y., S.M., N.K.M., and J.A.H. analyzed data; and D.K.B., B.P.K., and J.Z.Y. wrote the paper.

The authors declare no conflict of interest.

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Supplemental Material

Right Side Sitting		Left Side Sitting		Right Side Supine		Left Side Supine	
Paired T-test		**Paired T-test**		**Paired T-test**		**Paired T-test**	
Pre/Post PWV	0.23	Pre/Post PWV	0.08	Pre/Post PWV	0.45	Pre/Post PWV	0.18
Pre/Post PWV2	0.81	Pre/Post PWV2	0.077	Pre/Post PWV2	0.08	Pre/Post PWV2	0.04
Pre/Post PWVFinger	0.28	Pre/Post PWVFinger	0.3	Pre/Post PWVFinger	0.38	Pre/Post PWVFinger	0.16
Pre/Post PWVEar	0.13	Pre/Post PWVEar	0.37	Pre/Post PWVEar	0.32	Pre/Post PWVEar	0.61
Pre PWVFinger, PrePWVEar	<0.0001	Pre PWVFinger, PrePWVEar	<0.0001	Pre PWVFinger, PrePWVEar	<0.0001	Pre PWVFinger, PrePWVEar	<0.0001
Post PWVFinger, Post PWVEar	0.0002	Post PWVFinger, Post PWVEar	<0.0001	Post PWVFinger, Post PWVEar	<0.0001	Post PWVFinger, Post PWVEar	<0.0001
Pearson Correlation - PrePWV (r val, p val)		**Pearson Correlation - PrePWV**		**Pearson Correlation - PrePWV**		**Pearson Correlation - PrePWV**	
PrePWV, Age	0.18, 0.57	PrePWV, Age	0.31, 0.3	PrePWV, Age	0.28, 0.4	PrePWV, Age	0.21, 0.53
PrePWV, BMI	-0.19, 0.52	PrePWV, BMI	0.36, 0.23	PrePWV, BMI	0.58, 0.06	PrePWV, BMI	0.36, 0.28
PrePWV, Caucasian	-0.30, 0.32	PrePWV, Caucasian	0.04, 0.9	PrePWV, Caucasian	0.04, 0.91	PrePWV, Caucasian	0.23, 0.5
PrePWV, Diabetes	-0.44, 0.14	PrePWV, Diabetes	0.35, 0.24	PrePWV, Diabetes	0.58, 0.06	PrePWV, Diabetes	0.34, 0.31
Pearson Correlation - PostPWV		**Pearson Correlation - PostPWV**		**Pearson Correlation - PostPWV**		**Pearson Correlation - PostPWV**	
PostPWV, Age	0.43, 0.19	PostPWV, Age	0.62, 0.03	PostPWV, Age	0.11, 0.73	PostPWV, Age	0.2, 0.53
PostPWV, BMI	0.17, 0.63	PostPWV, BMI	0.5, 0.1	PostPWV, BMI	0.47, 0.13	PostPWV, BMI	0.13, 0.68
PostPWV, Caucasian	-0.59, 0.056	PostPWV, Caucasian	0.24, 0.45	PostPWV, Caucasian	-0.3, 0.34	PostPWV, Caucasian	-0.15, 0.63
PostPWV, Diabetes	-0.18, 0.59	PostPWV, Diabetes	0.37, 0.24	PostPWV, Diabetes	0.25, 0.43	PostPWV, Diabetes	-0.03, 0.94
Pearson Correlation - PrePWVFinger		**Pearson Correlation - PrePWVFinger**		**Pearson Correlation - PrePWVFinger**		**Pearson Correlation - PrePWVFinger**	
PrePWVFinger, Age	-0.3, 0.29	PrePWVFinger, Age	-0.48, 0.08	PrePWVFinger, Age	-0.24, 0.46	PrePWVFinger, Age	-0.32, 0.3
PrePWVFinger, BMI	-0.5, 0.07	PrePWVFinger, BMI	-0.63, 0.01	PrePWVFinger, BMI	-0.61, 0.036	PrePWVFinger, BMI	-0.74, 0.006
PrePWVFinger, Caucasian	-0.05, 0.88	PrePWVFinger, Caucasian	-0.2, 0.5	PrePWVFinger, Caucasian	-0.56, 0.06	PrePWVFinger, Caucasian	-0.46, 0.14
PrePWVFinger, Diabetes	-0.52, 0.06	PrePWVFinger, Diabetes	-0.64, 0.01	PrePWVFinger, Diabetes	-0.67, 0.016	PrePWVFinger, Diabetes	-0.73, 0.0076
Pearson Correlation - PostPWVFinger		**Pearson Correlation - PostPWVFinger**		**Pearson Correlation - PostPWVFinger**		**Pearson Correlation - PostPWVFinger**	
PostPWVFinger, Age	-0.5, 0.12	PostPWVFinger, Age	-0.41, 0.16	PostPWVFinger, Age	-0.09, 0.78	PostPWVFinger, Age	-0.20, 0.5
PostPWVFinger, BMI	-0.74, 0.0085	PostPWVFinger, BMI	-0.45, 0.13	PostPWVFinger, BMI	-0.16, 0.61	PostPWVFinger, BMI	-0.28, 0.35
PostPWVFinger, Caucasian	-0.3, 0.37	PostPWVFinger, Caucasian	0.21, 0.49	PostPWVFinger, Caucasian	-0.42, 0.15	PostPWVFinger, Caucasian	-0.12, 0.7
PostPWVFinger, Diabetes	-0.59, 0.057	PostPWVFinger, Diabetes	-0.33, 0.26	PostPWVFinger, Diabetes	-0.45, 0.12	PostPWVFinger, Diabetes	-0.41, 0.16
Pearson Correlation - PrePWVEar		**Pearson Correlation - PrePWVEar**		**Pearson Correlation - PrePWVEar**		**Pearson Correlation - PrePWVEar**	
PrePWVEar, Age	-0.35, 0.24	PrePWVEar, Age	-0.47, 0.1	PrePWVEar, Age	-0.6, 0.85	PrePWVEar, Age	0.09, 0.78
PrePWVEar, BMI	-0.28, 0.36	PrePWVEar, BMI	-0.46, 0.11	PrePWVEar, BMI	-0.29, 0.39	PrePWVEar, BMI	-0.12, 0.73
PrePWVEar, Caucasian	0.12, 0.71	PrePWVEar, Caucasian	-0.036, 0.91	PrePWVEar, Caucasian	-0.42, 0.19	PrePWVEar, Caucasian	-0.54, 0.08
PrePWVEar, Diabetes	-0.15, 0.62	PrePWVEar, Diabetes	-0.38, 0.2	PrePWVEar, Diabetes	-0.4, 0.22	PrePWVEar, Diabetes	-0.24, 0.49
Pearson Correlation - PostPWVEar		**Pearson Correlation - PostPWVEar**		**Pearson Correlation - PostPWVEar**		**Pearson Correlation - PostPWVEar**	
PostPWVEar, Age	-0.4, 0.25	PostPWVEar, Age	-0.44, 0.16	PostPWVEar, Age	-0.15, 0.64	PostPWVEar, Age	-0.12, 0.72
PostPWVEar, BMI	-0.42, 0.22	PostPWVEar, BMI	-0.38, 0.22	PostPWVEar, BMI	-0.26, 0.41	PostPWVEar, BMI	-0.19, 0.54
PostPWVEar, Caucasian	0.03, 0.94	PostPWVEar, Caucasian	0.14, 0.66	PostPWVEar, Caucasian	-0.2, 0.53	PostPWVEar, Caucasian	-0.25, 0.43
PostPWVEar, Diabetes	-0.36, 0.31	PostPWVEar, Diabetes	-0.22, 0.49	PostPWVEar, Diabetes	-0.42, 0.18	PostPWVEar, Diabetes	-0.37, 0.23

Supplemental Table 1. Statistical Analysis of All Pulse Wave Velocity Measurements. The table details statistical tests run on different combinations of variables. Paired t-tests were conducted on pre-exercise and post-exercise measurements as well as internally for ear and finger measurements. A Pearson's correlation was conducted for each PWV measurement with each subject variable. Green cells represent p-values which are statistically significant, while yellow cells represent p-values that trend to significance.