Diagnosing Atherosclerosis

Kailash Subramanian
Plano Senior High School

Purpose

This study aims to develop a cost-effective, accessible method of diagnosing atherosclerosis to prevent the onset of heart attack and stroke via novel PPG signal analyses

Table of Contents

Abstract

Atherosclerosis is the buildup of plaque on arterial walls that reduces blood flow through arteries in the body. Limited transport of oxygen and nutrients can lead to life-threatening cardiovascular diseases, such as heart attack and stroke. Since doctors typically use electrocardiogram and exercise stress tests, which can rise up to thousands of dollars, many patients are steered away to ignore diagnosis.

This study intends to develop a cost-effective yet reliable form of diagnosis through optical photoplethysmographic (PPG) techniques based on the variances of the color in the blood. Traditional PPG techniques have only discussed obtaining heart rate or oxygen saturation by placing a finger on a single camera. The proposed solution involved the unique usage of the front and rear cameras to obtain a detailed PPG waveform for also estimating heart rate variability, blood pressure, QT interval, and other vital cardiovascular measurements. This novel prototype was able to accurately determine heart rate, with accuracy over 97%, and blood pressure, with accuracy over 93%. Adapting the American Heart Association guidelines for hypertension, it was possible to justify atherosclerotic severity in a patient.

Further research in the extrapolation of characteristic features in the ECG through a PPG signal is planned to supplement the diagnostic system used by the prototype. By developing a form of diagnosis that is cost-effective and reliable, the experiment has a profound social impact in opening the doors for accessible medical technology, while also serving as an impetus for future research in diagnosing diseases in a more cost-effective manner.

Introduction

Purpose

The study aims to develop an inexpensive, non-invasive, and reliable form of diagnosing atherosclerosis that is much more accessible than the traditional electrocardiogram test. Atherosclerosis can be diagnosed through an analysis of blood pressure, heart rate, and patterns in the electrocardiogram waveform, as well as the patient's past medical history. However, studies have discussed the extreme dangers of hypertension and its relation to the onset of atherosclerosis because "it is a disease that shows no early symptoms, and simultaneously, is the most significant risk factor for heart disease" (Sawicka et al., 2011).

The leading cause of death is cardiovascular disease, especially atherosclerosis, the accumulation of fats and cholesterol on the linings of artery walls. The narrowing of the artery can limit the flow of oxygen-rich blood to vital organs in the body, such as the heart. If not diagnosed beforehand, blood flow can gradually decrease to the point where the victim may have a heart attack or stroke. Typically, doctors use a combination of expensive electrocardiogram, echocardiogram, and exercise stress tests to diagnose atherosclerosis. As a result, the cost of diagnosis, let alone treatment, makes patients more willing to ignore the problem.

The purposes of this project are to develop an application capable of producing photoplethysmogram (PPG) waveforms from two points of the body to determine blood pressure, heart rate, heart rate variability, and the maximum QT interval in order to diagnose atherosclerosis using a scoring system. This method also provides doctors a way for determining characteristic data of the ECG using a more cost-effective, optically obtained PPG signal. The project also aims to determine the optimum illuminance level for data collection and developing multiple algorithms that allow it to perform well for phones of varying processing powers and hardware features.

Source of Idea

My mother had to undergo several ECG and exercise stress tests to examine potential abnormalities in her organs, and these tests had risen up to thousands of dollars, and consumed uncountable hours of time. ECGs are currently the only accurate form of examining the intricate properties of the heartbeat. In recent years, the drive towards inexpensive, yet reliable medical technology up to par with technology used in clinical settings has led to advancements in the

field of photoplethysmography. To reduce the cost of the traditional ECG, some researchers have investigated optical analysis of blood flow, rather than through electrical impulses.

However, recent methods of determining heart rate and blood pressure through the optical properties of the human skin have yet to completely discuss their relation to atherosclerosis, nor have they explored the influence of blood pressure. The photoplethysmogram (PPG) is an optically obtained waveform from the capture of light absorption by the blood. This method has the potential to non-invasively make measurements of heart rate, blood volume changes per heartbeat, and oxygen saturation.

The major problem associated with the PPG is its low resolution, which provides little information regarding cardiovascular activity, other than the heart rate. Recent PPG studies have also been limited towards machines with high processing powers. Practical applications into a smartphone are frequently inaccurate and difficult due to the variety of hardware and software features for different models.

Goals/Hypothesis

This study involves the development of a novel method utilizing the front and rear cameras of a smartphone to generate two PPG signals, and the creation of more efficient algorithms to provide accurate information to accommodate for lower-end smartphones.

By creating an inexpensive, reliable, and accessible method of determining physiological measurements acceptable in clinical settings for accurately diagnosing atherosclerosis, the project also aims to expand the current knowledge in the field of photoplethysmography and open doors to accessible yet reliable medical technology.

Review of Literature

Previous studies have discussed the methods of obtaining heart rate and hinted at correlations between light intensity, heart rate, the PPG signal, and the ECG signal.

Photoplethysmography

Electrocardiograms have been the traditional tool used by doctors to analyze heart irregularity and heart rate. The recent years have proposed an alternative method in diagnosing atherosclerosis via optically obtained data describing light absorption by the blood based on variations in light intensity when a finger is held up to a smartphone camera. Al-Qazzaz et al. suggests that "[the] ECG is a quasi-periodic, rhythmically repeating signal synchronized by the function of the heart," which is very similar to the PPG signal (2014, 1). Optically obtained signals are "convenient, simple, and economically efficient" compared to many other methods (Elgendi, 2012, 1). It has been demonstrated that it is possible to develop an application "[employing] a reliable pulse peak detection" to generate a "photoplethysmogram… signal" (Park et al., 2014, 1).

A photoplethysmogram (PPG) is a waveform derived from changes in light absorption by the blood. On mobile phones, Peng et al. (2014) describes how "a finger on the camera lens… [illuminated with] a built-in LED flash" can be used to identify "intensity changes of video frames… associated with variations of light absorption by the blood" (2). This method is able to circumvent the potential low-lighting situations induced by the impractical applications of the PPG method in smartphones. The PPG signal can be used to determine useful information regarding heart activity. Elgendi (2012) outlines the general method used to process a PPG signal: "preprocessing to emphasize desired waves," "feature extraction," and "classification or diagnosis" (3).

Obtaining the Raw Signal.

Recent studies have researched various methods of obtaining the raw PPG signal, with similar degrees of success. Most methods gravitate towards obtaining the average RGB values of a frame and converting it into the HSV color model. The HSV color model is described Elvers as three dimensions: The hue (the traditional "color"), saturation (the amount of white light added), and value (the brightness). Peng et al. uses the value parameter to describe "intensity changes of video frames" (2014, 2), while Altini uses the hue parameter of the HSV model. Neither study

explains the elimination of potential noisy data as both used higher-end equipment to test their models.

Kurylyak et al. developed a unique approach towards noisy data removal as they integrate the PPG method into a smartphone. As different smartphones have different cameras, their model requires calibration to discover the optimal region of interest (ROI) where the average RGB value may be obtained from. Kurylyak et al. demonstrate an analysis of the red, green, and blue channels for an adaptive algorithm based on the system's camera configuration, and they demonstrated calibration for the HTC HD2, with and without the LED flash, and the Samsung Galaxy S, with the LED flash. To obtain a circle outlining the ROI, they opted for an "approach [that does not require] significant computational resources and also [works well] in the case of non-smooth boundaries" (2012, 20). As a result, they proposed a system where a circular ROI is defined by the contained mean distance to the boundary of the frame from the centroid at every 45° angle. It was also noted that the devices produced low video resolutions of about 640 × 480 pixels, to achieve an impressive 30 frames per second of processing. Kurylyak et al. also proposed a method for determining whether an entire frame is to be recognized by the camera, based on "pressure of the finger… position on the camera… [and] missing contact between finger and camera" (2012, 25).

Preprocessing.

One must first preprocess the signal to eliminate noise and other extraneous data. Peng et al. (2014) supplements Elgendi's ideas by suggesting a "zero-phase Butterworth low-pass… [and] high-pass filter," and temporal resolution was increased through a "cubic-spline interpolation" (2). Removing noise is especially important because of the wide range of error while obtaining the PPG signal. For instance, subtle movements of the finger and excess light captured by the camera can alter the data significantly. Cubic-spline interpolation suggests a method for which one can estimate any unknown points, especially in cases where a smartphone may have a poor camera and a low frame rate. This might prove useful when women are being tested since Holubkov et al. suggests that "noninvasive [procedures tend to be] less accurate in women than in men" (2002, 1).

The Butterworth filter strives for the ideal electric filter that has "uniform sensitivity for unwanted frequencies" while not completely rejecting "the unwanted frequencies" (Butterworth, 1930, 1). Another mentioned algorithm is a spline interpolation, which holds a lot of importance

in this study due to its accuracy in correcting outliers and making up for low frame rates. Given the obtained data points, known as value pairs, or *knots*, a spline is a special piecewise polynomial that is "continuous in both the first and second derivatives" while passing through the given knots (Liu, 2015). If an outlier is detected based on Chauvenet's outlier test, the cubic spline will be used to approximate the value at the point. If the frame rate drops considerably while intensity measurements are taken, the cubic spline can be used to approximate values at those unrecorded times.

Feature extraction.

After extraneous data has been removed, the PPG signal can be utilized to extract the desired features. The signal is composed of multiple smaller waveforms. A typical PPG waveform consists of three characteristic parameters: The systolic peak, the dicrotic notch, and the diastolic peak. The systolic peak is the highest value of the waveform, while the dicrotic notch identifies the concave location as the waveform declines in a cubic curve. The frequency of the systolic peaks can be used to determine the patient's heart rate in beats per minute. In Elgendi's study, it was noted that there was a "short time of measurement (20 seconds)" (3), allowing for potential light disturbances due to fidgeting or slight movements of the patient.

Elgendi supplies a table representing thorough research on the effects of the systolic peak amplitude towards blood volume and vasoconstriction. It can be generalized that a "low systolic peak amplitude" is linked to a "decreased blood volume pulsation and a decreased venous blood volume" (3).

Elliot examines the relationship between average blood pressure and heart rate variability. In his study, he defines average blood pressure, p, as $^{systolic + diastolic}/_{2}$ and heart rate variability, v, as the difference between the maximum and minimum heart rate over the time interval. The described power trend was calculated to be $p = 116.525v^{-0.119197}$.

Although the power trend could be used for algorithms where time is of the essence, it is clearly prone to producing inaccurate results for different types of humans. The American Heart Association (AHA) emphasizes that "heart rate and blood pressure do not necessarily increase at the same rate" because healthy blood vessels expand and grow to accommodate the increase in heart rate. This segues into the discussion in regards to the relationship between exercise and blood pressure.

Fagard's study discusses that a fit individual's stroke volume, the amount of oxygen delivered to the body per heartbeat, increases in athletes due to exercise training, causing the heart rate to decrease for more fit individuals. If that were the case, then the power trend would falsely predict a falsely large mean blood pressure (as the heart rate variability increases with longer durations of time between heartbeat).

Diagnosis.

The severity of atherosclerosis can be described by the severity of hypertension in the patient. LiveFitLean cites the American Heart Association in the following guidelines for blood pressure category.

Blood Pressure Category	Systolic (mmHg)	Diastolic (mmHg)
Normal	Less than 120	Less than 80
Prehypertension	120 – 139	80 – 89
Hypertension Stage I	140 – 159	90 – 99
Hypertension Stage II	160 – 180	100 – 110
Hypertensive Crisis	Over 180	Over 110

Along with the heart rate pattern regularity, age, and past medical history, it is possible to diagnose atherosclerosis and prevent disease. In a study conducted by Younessi et al., "blood pressure was measured [multiple] times" (2014, 2). This suggests that blood pressure is varying and taking it more than once can help to improve the accuracy of the results. Elgendi also compiled research from other studies to describe various indices.

Let the processed PPG signal be $p = p(t)$ over t seconds. The peaks of p may be determined by analyzing the roots of $p'(t)$ such that the derivative at the point changes signs from positive to negative. The frequency of the peaks can be converted into peaks per minute for determining the average heart rate over the selected interval. Jang et al. suggests a "mean absolute difference [method]" at "pulse peak intervals" (2014, 3).

Elgendi investigates the topic even further by discussing the acceleration PPG (APG), $p''(t)$. A selected frame of the APG was then examined such that a is the first peak, b is the first valley, c is the second peak, d is the second valley, and e is the third peak. Elgendi notes that the ideal APG would notice good circulation of the blood if $b < c$. He also discusses Baek's aging

index $(b-e)/a$, Sano et al.'s aging index $(c+d-b)/a$, Takazawak's arterial stiffness index b/a, c/a or d/a, and Aiba et al.'s blood lead concentration index $-b/a$.

Compiling these values for average blood pressure, heart rate, and various indices of age and arterial characteristics based on the processed PPG signal, the severity of atherosclerosis in a patient may be determined by a modified Sponder et al. scoring system that "investigates the connection between [atherosclerotic diseases] and laboratory parameters" (2014, 1) in correlation with the American Heart Association criteria for hypertensive crisis for the diagnosis of arterial atherosclerosis.

Blood Pressure

Blood pressure is formally described as the "force of blood pushing against blood vessel walls," measured in millimeters of mercury (mmHg), according to the American Heart Association (2017, 1). The pressure against the blood vessel walls depends on the thickness of the fluid, which varies based on one's diet.

Blood pressure is categorized into *systolic* and *diastolic* features. For each beat of the heart, the blood vessels encounter two distinct phases. Pressure against blood vessel walls is highest when the pulse passes through, known as the systolic phase. The diastolic pressure is measured when the heart is resting between each beat, where blood pressure against the blood vessel walls is lowest.

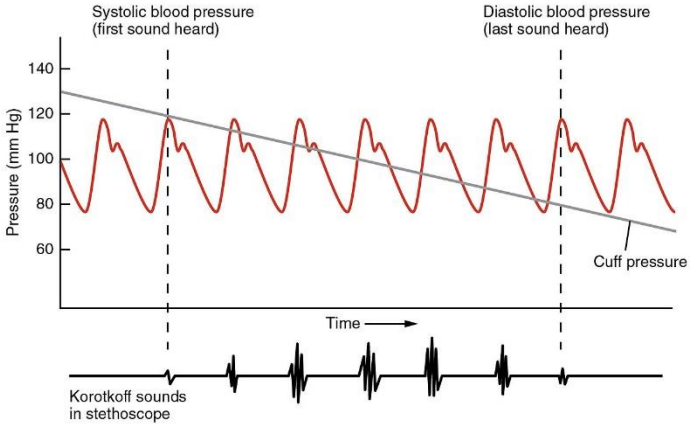
Pathology to Atherosclerosis.

Typically, blood pressure changes can be safe as the "elastic fibers embedded in [arterial] walls make them resilient" (Manzano). High blood pressure, also known as hypertension, is caused due to extremely large blood pressure, over 140/90 mmHg. Elastic fibers experience extra strain, inevitably causing small tears. The tissue can swell up, and it attracts plaque, which "is made up of fat, cholesterol, calcium, and other substances found in the blood" (National Heart,

Lung, and Blood Institute, 2009, 1). In his discussion, Punwani affirms that the buildup of plaque is a condition known as atherosclerosis.

On its own, atherosclerosis holds no major problems. However, the continuous buildup and severity of atherosclerosis can lead to the clogging up of major arteries. Different diseases can develop "based on which arteries are affected" (National Heart, Lung, and Blood Institute, 2009, 1). When the artery is clogged, oxygen and other nutrients can't make it to vital organs of the body. When the blood flow reaches a critical level, it can lead to coronary artery disease, such as angina, and more life-threatening conditions such as heart attack or stroke. An advisory by Go et al. warns that "[it is imperative to] improve hypertension awareness, treatment, and the proportion of patients treated and controlled" (2013, 9).

Oscillometric Measurement.



Blood pressure is frequently measured through devices with inflatable cuffs. Berger explains that the cuff's pressure decreases, the reducing pressure on the artery "allows blood to flow through it and sets up a detectable vibration in the arterial wall." The systolic pressure pushes blood through the artery. When the cuff pressure falls below the patient's diastolic pressure, the fading vibration allows the monitor to record the pressure. A doctor may also listen to the Korotkoff sounds via a stethoscope as the blood pressure cuff is deflating, in order to obtain a diastolic and systolic pressure measurement.

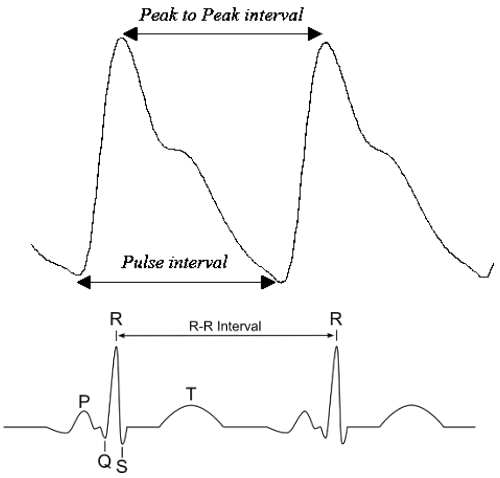
Electrocardiographic Measurement.

The electrocardiogram (ECG) provides a method for doctors to measure several features of the heart, including the heart rate variability through responses to electrical signals. The ECG waveform is made up of smaller waveforms, each with 5 peaks and termed PQRST complexes. The figure on the following page depicts the close relationship of the ECG's PQRST complex to the PPG, albeit with the latter at a lower resolution. The QRS complex gives a representation of ventricular contraction and its hypopolarization (caused by electrical impulses), and an analysis of the RR interval provides heart rate and heart rate variability.

ECG-PPG Correlation.

As PPG study is a relatively new field in the integration of optical sciences and technological hardware, very little research has been done on its relationship to the traditional ECG. A few studies have explored the signature PQRST complex of the ECG, caused by the movements of the heart per different pulses.

It can be clearly seen that the PPG signal's maximum peak is directly linked to the ECG's so-called *R* value, in the PQRST complex. Linking the PPG pulse peak (PP) and the ECG R value aligns the PPG and ECG signals, demonstrating the potential in obtaining ECG data using a raw PPG signal. The diagram on the right represents the PPG signal (top) and the aligned ECG signal (bottom) to demonstrate the equivalence of the RR interval and the peak to peak intervals.



Elgendi, M. (2012). On the Analysis of Fingertip Photoplethysmogram Signals. Current Cardiology *Reviews*, *8*(1), 14–25.

In a different study, Wang et al. utilized a PPG and ECG signal measured at two different points on the body and discovered a phase difference between the two. Using the Moens-Korteweg equation, $PWV = \frac{L}{PTT} = \sqrt{\frac{E*h}{2r\rho}}$, relating the pulse wave velocity (PWV) with L, the vessel length; PTT, the phase difference in seconds; ρ, the blood density; r, the inner radius of the vessel; h, the vessel's thickness, and E, the elasticity (a parameter mentioned as a pathological factor towards atherosclerotic conditions), Wang et al. developed the blood pressure formula under the assumption of equal, unvarying arterial vessel characteristics:

$$BP_n = a * \ln(PTT) + b * (HR) + c * BP_{n-1} + d$$

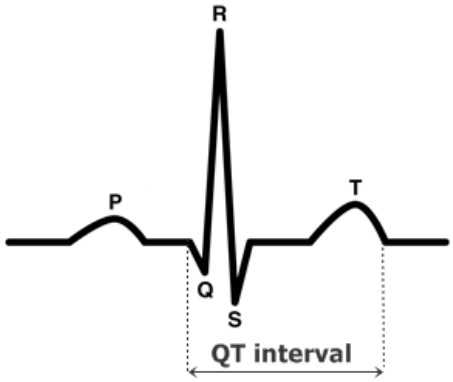
where BP_{n-1} was a previous blood pressure measurement, and HR was the current average heart rate.

The study demonstrated the possibility of utilizing PPG signals for obtaining volumetric measurements of the heart; however, it still underscores the drawbacks of the low-resolution PPG signal, and the fact that an expensive ECG is still required for accurate BP readings, rendering the solution impractical for the average user. Currently, the only practical reading for

the average user is that of the heart rate calculated by the simple frequency of the PPG signal's pulse peaks.

QTc_{max}

The QT interval of the traditional ECG has *not* been researched in PPG studies. However, past studies have explored the relationship between QT and heart rate values. The QT interval should be analyzed as prolonged QT intervals have been associated with conditions such as Torsades de Pointes (TdP) and degeneration into ventricular fibrillation. Rossing et al. discussed the influence of the QT interval towards mortality due to diabetes. Determining the maximum possible value of the QT interval helps to eliminate any false negatives regarding atherosclerotic diagnosis, but may also result in potential false positives.



Stefanek, Jiri, and Martin Fajmon. QT Interval. 2015, www.health-tutor.com/prolongation-of-qt-interval ecg.html.

Modern QT calculations use an ECG, but the standard clinical correction utilizes Bazette's formula:

$$QTcB = \frac{QT}{\sqrt{RR}}$$

The determination of the maximum QTc value has been suggested by Yanowitz through a linear regression analysis between Bazette's and Fridericia's formulas, $QT = 0.44 - 0.02(RR)$.

Method

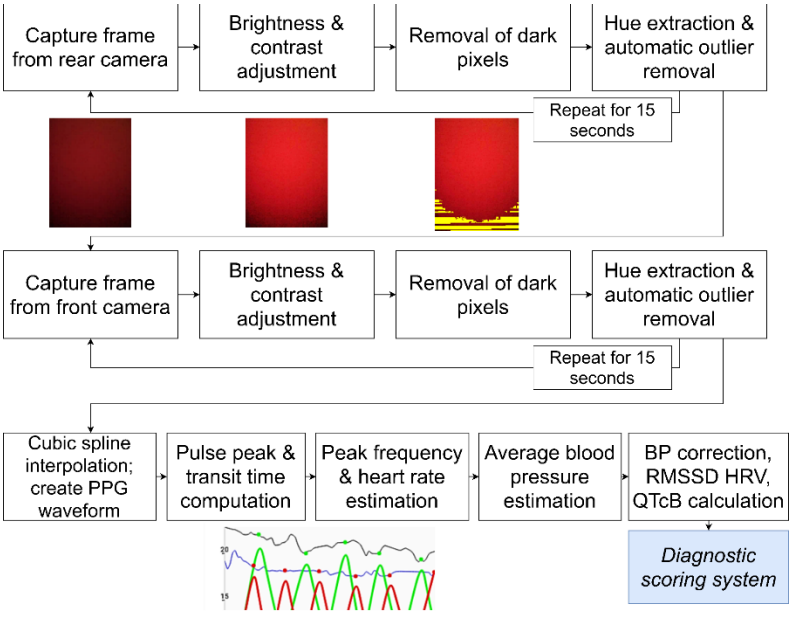
This study focused on the development of an Android application that can use the rear camera to determine changes in light absorption by the finger and the arm. Two algorithms were created in this study to be applied in practical usages, for lower-end and standard smartphones.

Participants

Participants from a variety of age ranges were selected for participation in the study. Four adolescents (age range: 12 – 17 years) and two adults (age range: 45 – 54 years) were chosen to determine the accuracy of the program in determining heart rate, systolic, and diastolic blood pressure.

Design

The goals of the project were to develop algorithms that could run efficiently on lower-end devices, such as an Amazon Fire e-reader. On the algorithm designed to be efficient, the software uses the rear camera of an Android tablet to identify changes in light intensity. Raw data is first obtained, then processed for the necessary features to be extracted. Raw data should be obtained by asking the user to place an arm in contact with the camera of the tablet. The user should use the same arm that they used while obtaining data from an FDA approved blood pressure monitor. All processing and feature extraction tasks must be taken place in a separate thread so that the user interface does not freeze or hang up. Multithreading keeps the user's general user interface (GUI) active while intensive background processing takes place. A general overview of the method is shown on below in the form of a flowchart.



Raw data.

This project explores a unique method of determining heart rate and blood pressure through the usage of two cameras. Once the user has placed their finger on the front camera and arm on the rear camera, the program will obtain data for 15 seconds from each point on the body. The total data collection time is 30 seconds. The RGB value will be converted into an HSV color model and the value parameter will be stored for later use.

The RGB value will be optimized to focus solely on the area of the finger covered by the camera. For example, notice in the image below the darkened areas on the fringes of the frame after the contrast was adjusted towards the optimal amount. The accentuated darkened areas allows the program to efficiently remove dark pixels; in this study dark pixels had a brightness, *V*, parameter of less than 0.2 in the HSV parameterized color model.

Lag caused by intensive calculations will replace the repeated data points by a constant value, such as -1, to be handled in interpolation methods. For lower-end devices, the algorithm was optimized to avoid real-time results and calculations regarding HR and BP; rather, obtaining the data and analyzing it in a separate stage.

Processing.

Indeed, the hardware limitations on the device do not allow for simultaneous capturing of the front and rear cameras. The program will overcome the limitations by obtaining data from the front and rear cameras in back-to-back sets, and any lag between will be removed by using a background timer on a separate thread.

Both sets of raw data will be run through a modified Chauvenet's criterion implementation for outlier identification. If the product of the probability density at a point and data set length is less than 0.6, then the point is an outlier, and it will be replaced with the same constant value used in the raw data module, such as -1. The process is repeated for every point.

After all outliers are taken care of, the program will loop through the data set and remove all outliers marked with a constant value from the data set. When this happens, time values are

naturally lost, so two data sets must be created: one representing the *time* domain while the other representing the *value* domain. Skips in time due to outlier removal and data loss will be replaced with the cubic spline interpolation. The cubic spline interpolation was used to determine the predicted values for unknown time values with an accuracy of 0.25 seconds. Outlier removal and interpolation methods are shown in the diagram on the next page. The method is repeated for the front-facing PPG data as well, and the pulse transit time (PTT) between the two peaks will be calculated in the next phase.

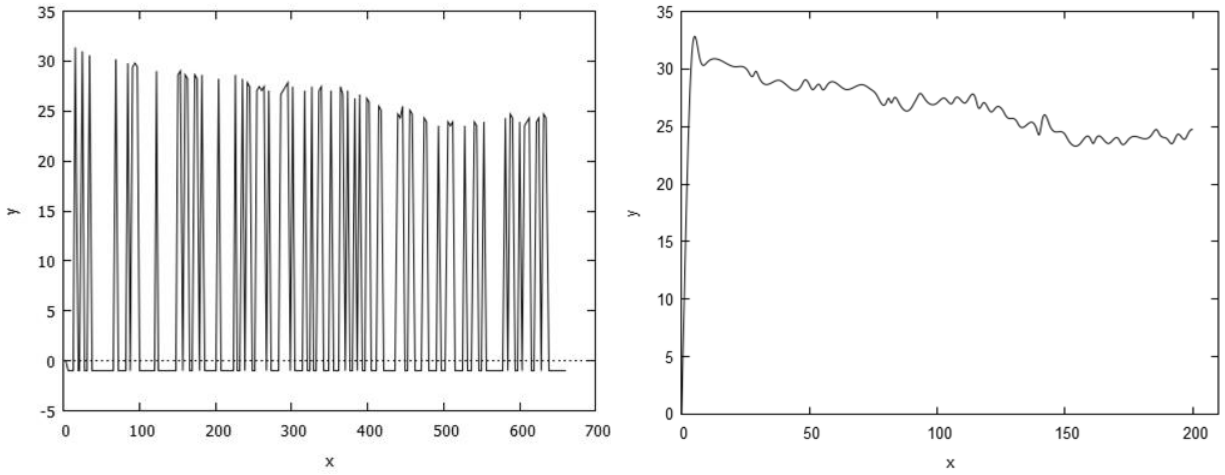


Figure 1. Left: Raw data obtained from rear PPG signal (frame number vs value). A value of -1 denotes an unknown value. Right: Processed data after outlier removal and cubic spline interpolation (fourth of a second vs value).

Feature extraction.

Now that data for 30 seconds with an accuracy to the fourth of a second has been collected, the necessary step is to determine the heart rate and blood pressure. The first derivative of the processed PPG signal will be calculated. Although we were initially dealing with two domains (time and value), it can be collapsed after the cubic spline interpolation, so a single data set, $p(t)$ such that t is measured in seconds, may be used for peak detection. This means that the data point for the first derivative at time t and index i is $\left(\frac{i+1}{4}, p'(i)\right)$.

A peak is found when the derivative changes from positive to negative. Every peak's time value is stored in a separate data set that will be used to identify average frequency of the peaks. The mean absolute difference of the time between each peak will be converted into peaks (beats) per minute, representing the average heart rate, h. The maximum and minimum heart rates can be obtained by a similar procedure. Using the heart rate variability, $v = h_{max} - h_{min}$, an approximation of the average blood pressure, p, could be determined using Elliot's power trend $p = 116.525v^{-0.119197}$. The average blood pressure was defined as the average of the systolic

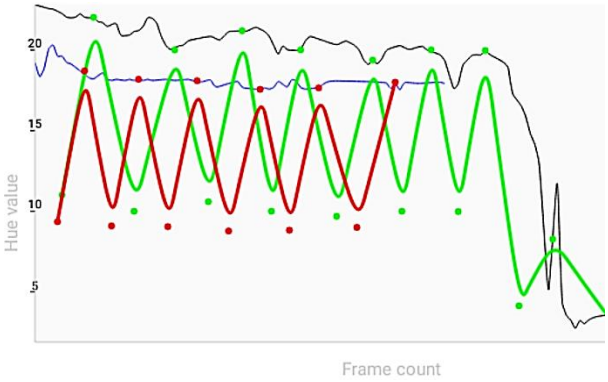
and diastolic values, and if needed, possible values of systolic and diastolic values can be determined to reasonable accuracy. These values can then be used for diagnosis of atherosclerosis based on a scoring system.

Customized Blood Pressure Algorithm.

The algorithm for calculating the blood pressure has been altered to provide more accurate results while running on other devices that may support heavy calculations. Initially, the algorithm was intended to support current flagship phones, but testing the application on a weaker Samsung J7 phone with just a 5 MP front-facing camera and an 8 MP rear-facing camera provided impressive results.

Determination of PTT.

The PTT, pulse transit time, is the time taken between any two correlating peaks on the two PPG signals. The transit time is caused by a small time offset as the blood is pumped through the artery. A measurement of this time can give an indication of how fast the blood is moving, influenced most directly by the diameter of the artery. The arterial diameter is dependent on the amount of fat that accumulated on the arterial wall, directly linked to atherosclerosis.



Given the two PPG signals, the peaks found when the derivative changes from positive to negative have a change in frames, $PTT = \Delta x$. This is compared to the PTT of the peak on the second PPG signal that is closest to the peak that is being analyzed. In the event that any one of the signals "runs out" of peaks to compare with, further PTT calculations will be disregarded as errors. For instance, in the plot shown on the right, the green (rear) PPG has a noticeable phase difference compared to the red (front) PPG. The PTT is calculated from the available data: noisy data that was removed from the front PPG for several frames is disregarded in the PTT calculation due to a lack of available data.

Optimized BP Measurement.

Using Fung et al.'s method for BP determination, $\Delta BP = \frac{1}{2}\left(\frac{\rho d^2}{PTT^2}\right) + \rho g h$, the pressure drop of 70% results in $BP = 0.7 * \Delta BP = \frac{A}{PTT^2} + B$, where $A = (0.6h)^2 + \frac{\rho}{1.4}$, and ρ was suggested to be a blood density of 1035 kg/m^3.

The formula was changed to consider the distance variance between the arm and the fingertip, and on average, $d = 0.11h$. As a result, the percentage drop also had to change. A correction was added to the blood pressure in regard to the heart rate calculation. Optimizing ΔBP allows us to determine:

$$\Delta BP = \frac{1}{2}\rho\left(\frac{0.0121h^2}{PTT^2}\right) + \rho gh$$

The complete formula, considering $\overline{BP} = \Delta BP * c$, where $c = 0.33\%$ as a correction factor:

$$\overline{BP} = \left[\frac{1}{2}\rho\left(\frac{0.11h}{PTT}\right)^2 + \rho gh\right] * (0.0033) + [HR] * (0.1)$$

The 10% correction from the heart rate was added due to the lack of knowledge of CVP (central venous pressure). Fung et al.'s study had assumed the negligence of CVP, but it could make a determining factor if the blood pressure was extremely high or low. The percent correction factor was also adjusted from Fung et al.'s original correction of 0.7.

The definition of BP average was *not* the traditional Mean Arterial Pressure (MAP), but rather the literal average of the systolic and diastolic pressures, as expressed:

$$\overline{BP} = {systolic + diastolic}/{2}$$

Using this definition of the average blood pressure, it is possible to approximate the systolic and diastolic blood pressure. However, to obtain more accurate results, calibration is recommended, and the user will be provided an option to calibrate a PPG reading based on an FDA approved monitor. Otherwise, the program will default to centering the systolic and diastolic values, based on the discovered average blood pressure, towards the ideal blood pressure of 120/80.

Heart Rate Variability Estimations.

Now that we have a plethora of information regarding volumetric measurements of the human heart, the heart rate variability may be calculated using the root mean squared of successive differences method (RMSSD).

Heart rate variability helps give an indication of how consistent each heart beat lies on the discovered PPG waveform. An inconsistent heart rate suggests a cardiovascular disorder, since the heart is pushed to work much harder when there is an accumulation of plaque along the arterial wall. The traditional method of HRV calculation is the RMSSD method, which is also frequently used with ECG data.

Given the available data from each PPG waveform, we can allow *n* peaks where each consecutive peak has a time (expressed in frames) t_i, t_{i+1}, and so on, to calculate the heart rate variability as:

$$HRV_{RMSSD} = \sqrt{\frac{\sum_{i=1}^{n-1}(t_i - t_{i+1})^2}{n-1}}$$

Maximum QTc Value.

By improving the resolution of the linear regression suggested by the literature review, the upper limit of the QT interval can be calculated as $QTc_{\max} = 440 - 2R$, where R is the heart rate and QTc is the length of the QT interval, in milliseconds.

The linear model is most accurate for average resting heart rates, about 60 – 70 beats per minute, but it might overshoot QT length approximations for higher or lower resting rates. The upper limit of the QT interval was used in the diagnosis scoring system to ensure that false negatives are limited. Although this gives rise to an increase in the amount of false positives, it might be better than ignoring a potential problem.

Diagnosis for Efficient Results.

Sponder et al.'s study suggested a diagnostic method that was modified in this study to be applicable to atherosclerosis in general. For lower end devices where HR and BP values had to be optimized through a more efficient algorithm (see Method: Pages 15-17), the system was used in correlation with the table of hypertensive severity provided by the American Heart Association to create a scoring system as described below:

Medical History	Score
Gender	
Male	1
Female	0.5
Physical activity	
No	2
Often	1
Frequent	0.5
Average blood pressure	
Over 115 mmHg	3
Over 130 mmHg	4
Over 145 mmHg	5
Smoking	
Yes	3
Ex-smoking	2
Never smoked	0.5

The program uses the designations to generate a total score, which is then compared to the following table for diagnosing atherosclerosis.

Score	Diagnosis
$s > 4$	Extreme risk, consult doctor
$3 < s \leq 4$	High risk, consult doctor
$2 < s \leq 3$	Potential risk
$s \leq 2$	Low risk

Diagnosis for Precise Results.

Devices that have more processing capabilities than the regular e-Reader have the ability to take advantage of a more precise algorithm (see Method: Pages 17-18), which requires a different diagnostic system. When special volumetric features were able to be calculated without issues, the program will use a more efficient and reliable scoring system defined below:

Medical History	Score
Gender	
Male	2
Female	1
Physical activity	
No	2
Often	1
Frequent	0.5
Average blood pressure	
Over 115 mmHg	3
Over 130 mmHg	4
Over 145 mmHg	5
Smoking	
Yes	3
Ex-smoking	2
Never smoked	0.5
Upper limit of QTcB interval	
480 ms	3
460 ms	2
450 ms	1
RMSSD for heart rate variability (HRV)	
550 ms	1
450 ms	0.5

The program uses the designations to generate a total score, which is then compared to the following table for diagnosing atherosclerosis.

Score	Diagnosis
$s \geq 10$	Extreme risk, consult doctor
$7 \leq s < 10$	High risk, consult doctor
$4 \leq s < 7$	Potential risk
$s < 4$	Low risk

Data Export.

Once the diagnosis is complete, the user will have an option to export their data through a means of their choosing, such as email. The exported data will contain the date, time, average, maximum, and minimum heart rate, average blood pressure, systolic and diastolic blood pressure, the raw PPG signal data, and the processed PPG signal data.

Materials

The software was developed for a 5th generation Amazon Fire tablet running Android Lollipop. The tablet utilized a rear 2MP camera and a 1.3 GHz processor with 1 GB RAM. A laptop running Windows with at least 2 GB RAM and 1.5 GB available hard disk space capable of running Java IDE compatible with Android software, such as Eclipse or IntelliJ IDEA was used to develop the software. The program was tested based on an FDA approved Juning digital wrist blood pressure monitor.

Procedure Overview

1. Develop an Android application using IntelliJ Idea or Android Studio that can determine the likelihood of a patient having atherosclerosis. The application will obtain data from each frame from the front and rear cameras for 15 seconds each.
2. A voluntary human subject will place their finger touching the front camera of the Android device that the application will run on, and their arm in contact with the rear camera.
3. The application should use the center of each frame to record changes in the frame's average RGB value, which is then converted into the HSV model.
4. Next, the application should search for peaks of intensity in the PPG, and use the frequency to determine the heart rate. The HRV and mean BP will be calculated using the PTT (the lag between the two peaks due to pulses from different areas of the body).
5. The application should run an algorithm on the PPG that can identify common signs of atherosclerosis based on its close relationship to ECG waveforms.
6. The application should output the likelihood of the patient having atherosclerosis.
7. The result should be cross-checked with heart rate and blood pressure measurements obtained from a blood pressure monitor and whether they have had heart problems in the past. Repeat steps 2 – 7 for a total of 3 trials over 3 days, at the same time each day.

8. Repeat steps 2 – 7 for at least 5 other human subjects. Evaluate the data and make improvements for the next prototype based on the application's accuracy rate.

Data/Results

Lower-End Devices Utilizing the Efficient Algorithm.

The data generated by the PPG signal output the heart rate (HR) in beats per minute, blood pressure (BP) in mmHg, average blood pressure (BP_{ave}), and a diagnosis for atherosclerosis for each of the 6 subjects. Readings from an FDA approved blood pressure monitor were also collected to determine the accuracy of the results. Data points marked with an asterisk (*) were reported by the blood pressure monitor to be a possible inaccuracy.

Subject 1

Trial	PPG HR	PPG BP	PPG BP_{ave}	PPG diagnosis	Approved HR	Approved BP	Approved BP_{ave}
1	66	113/63	88	Low risk	70	119/80	99.5
2	66	119/65	92	Low risk	68	120/78	99
3	74	113/74	93.5	Potential	72	112/71	91.5
Average	68.7	115/67	91.17		70	117/76	96.67

Subject 2

Trial	PPG HR	PPG BP	PPG BP_{ave}	PPG diagnosis	Approved HR	Approved BP	Approved BP_{ave}
1	72	119/70	94.5	Low risk	72	120/75	97.5
2	71	125/68	96.5	Low risk	71	119/67	93
3	72	133/74	103.5	Low risk	68	114/65	89.5
Average	71.67	126/71	98.17		70.33	118/69	93.33

Subject 3

Trial	PPG HR	PPG BP	PPG BP_{ave}	PPG diagnosis	Approved HR	Approved BP	Approved BP_{ave}
1	60	119/65	92	Low risk	63	70/53*	61.5*
2	75	122/67	94.5	Low risk	66	120/78	99
3	77	124/68	96	Low risk	71	112/71	91.5
Average	70.67	122/67	94.17		66.67	116/74.5	95.25

Subject 4

Trial	PPG HR	PPG BP	PPG BP_{ave}	PPG diagnosis	Approved HR	Approved BP	Approved BP_{ave}
1	65	127/70	98.5	Low risk	65	146/91	118.5
2	66	132/68	100	Low risk	67	45/12*	28.5*
3	74	133/67	100	Potential	66	142/94	118
Average	68.3	131/68	99.5		66	144/93	118.25

Subject 5

Trial	PPG HR	PPG BP	PPG BP_{ave}	PPG diagnosis	Approved HR	Approved BP	Approved BP_{ave}
1	67	117/81	99	Low risk	87	141/100*	120.5*
2	74	124/79	101.5	Low risk	79	128/83	105.5
3	77	125/77	101	Low risk	85	129/84	106.5
Average	72.67	122/79	100.5		83.67	129/93	106

Subject 6

Trial	PPG HR	PPG BP	PPG BP_{ave}	PPG diagnosis	Approved HR	Approved BP	Approved BP_{ave}
1	82	112/81	96.5	Low risk	89	118/98	108
2	75	118/73	95.5	Low risk	73	112/81	96.5
3	78	119/78	98.5	Low risk	75	116/79	97.5
Average	78.33	116/77	96.83		79	115/93	100.67

Analysis described on following page.

Analysis for Percent Error.

The percent error that the PPG signal results had in comparison to the approved blood pressure monitor was calculated.

- Subject 1: 1.9% HR error, 1.7% systolic BP error, 11.8% diastolic BP error, and 5.68% BP_{ave} error
- Subject 2: 1.9% HR error, 6.8% systolic BP error, 2.9% diastolic BP error, and 5.19% BP_{ave} error
- Subject 3: 6% HR error, 5.17% systolic BP error, 10.1% diastolic BP error, and 1.13% BP_{ave} error
- Subject 4: 3.49% HR error, 9.03% systolic BP error, 26.88% diastolic BP error, and 15.86% BP_{ave} error
- Subject 5: 13.15% HR error, 5.43% systolic BP error, 15.05% diastolic BP error, and 5.19% BP_{ave} error
- Subject 6: 0.85% HR error, 0.87% systolic BP error, 17.2% diastolic BP error, and 3.81% BP_{ave} error

Further Analysis.

The results show that the algorithm on a lower-end device showed promising results, albeit using the novel, efficient algorithm which was expected to show much more variance than the precise algorithm. In fact, it was able to nearly meet the design criteria; when averaged, the average BP had an accuracy of just under 90%, while the average HR had an accuracy at about 95%. When the more precise algorithm, which was also developed for running on standard smartphones, is utilized, it is expected to see a larger percent accuracy regardless of the lighting illuminance.

Standard Android Devices Utilizing the Precise Algorithm.

Most standard smartphones can handle processing done through the novel, precise algorithm producing more accurate data. Further data analysis was conducted to analyze the effect of light illuminance on prototype accuracy. Determining optimal illuminance can be helpful for doctors and patients while checking their blood pressure and other vital signs.

For this experiment, 6 subjects went through 3 trials of 5 different lighting illuminances varying from 300 to 2300 lux, the parameters for which the study had created its design criteria. The complete data for the 90 trials is shown in the following page.

Heart rate for 5 different lighting illuminances

	Heart rate, 300 lux								
Subject	Trial 1	Trial 2	Trial 3	Average	Actual	Actual	Actual	Average	Percent accuracy
1	75	74	70	73	78	71	82	77	94.81
2	82	81	79	80.67	83	72	73	76	93.86
3	79	92	84	85	84	77	74	78.33	91.49
4	89	78	73	80	89	83	85	85.67	93.39
5	79	74	78	77	84	87	89	86.67	88.85
6	78	73	72	74.33	86	83	82	83.67	88.84
									91.87
	Heart rate, 800 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	79	81	83	81	78	71	82	77	94.81
2	82	78	85	81.67	83	72	73	76	92.54
3	84	83	83	83.33	84	77	74	78.33	93.62
4	83	85	82	83.33	89	83	85	85.67	97.28
5	82	96	102	93.33	84	87	89	86.67	92.31
6	79	80	82	80.33	86	83	82	83.67	96.02
									94.43
	Heart rate, 1300 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	75	79	78	77.33	78	71	82	77	99.57
2	81	78	83	80.67	83	72	73	76	93.86
3	79	77	72	76	84	77	74	78.33	97.02
4	82	81	85	82.67	89	83	85	85.67	96.5
5	87	91	78	85.33	84	87	89	86.67	98.46
6	78	80	79	79	86	83	82	83.67	94.42
									96.64
	Heart rate, 1800 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	75	79	82	78.67	78	71	82	77	97.84
2	75	77	73	75	83	72	73	76	98.68
3	79	78	73	76.67	84	77	74	78.33	97.87
4	72	81	85	79.33	89	83	85	85.67	92.61
5	79	77	79	78.33	84	87	89	86.67	90.38
6	72	79	78	76.33	86	83	82	83.67	91.24
									94.77

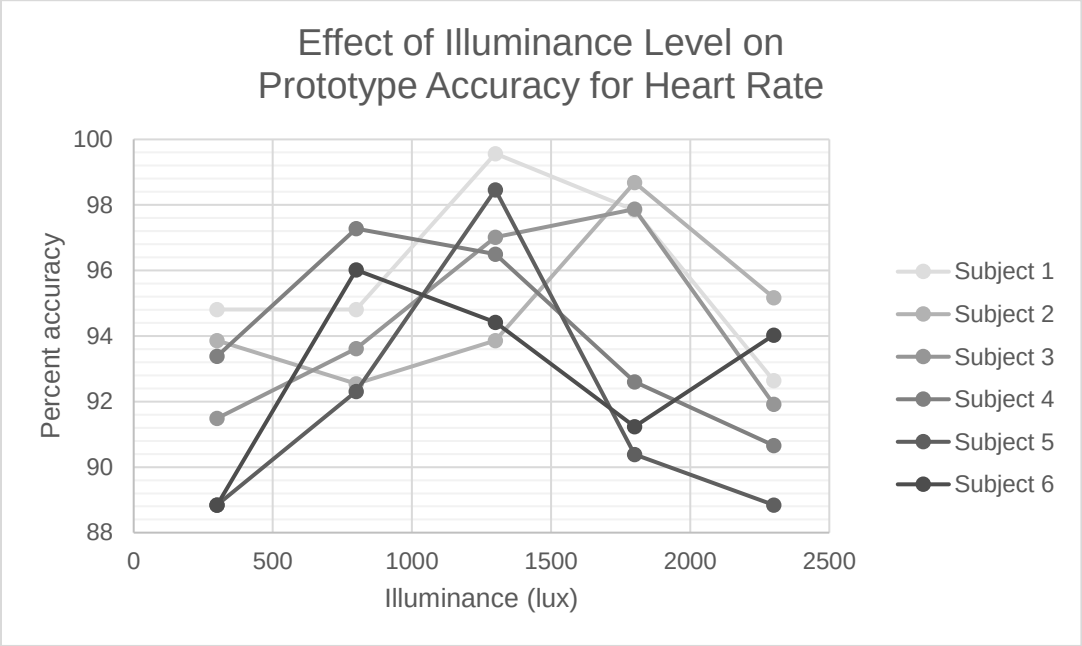
	Heart rate, 2300 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	56	79	79	71.33	78	71	82	77	92.64
2	79	79	81	79.67	83	72	73	76	95.18
3	77	69	70	72	84	77	74	78.33	91.91
4	79	77	77	77.67	89	83	85	85.67	90.66
5	83	73	75	77	84	87	89	86.67	88.85
6	92	89	85	88.67	86	83	82	83.67	94.02
									92.21

Blood Pressure for 5 different lighting illuminances

	BP, 300 lux								
Subject	Trial 1	Trial 2	Trial 3	Average	Actual	Actual	Actual	Average	Percent accuracy
1	78	73	68	73	78	84	82	81.33	89.75
2	72	89	87	82.67	98	102	90	96.67	85.52
3	103	98	104	101.7	96	98	94	96	94.1
4	59	113	108	93.33	120	114	118	117.3	79.55
5	103	105	104	104	116	110	114	113.3	91.76
6	89	93	78	86.67	92	94	102	96	90.28
									88.49
	BP, 800 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	79	82	89	83.33	78	84	82	81.33	97.54
2	91	89	87	89	98	102	90	96.67	92.07
3	89	84	83	85.33	96	98	94	96	88.89
4	93	98	103	98	120	114	118	117.3	83.52
5	139	104	104	115.7	116	110	114	113.3	97.94
6	94	96	102	97.33	92	94	102	96	98.61
									93.1
	BP, 1300 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	82	84	79	81.67	78	84	82	81.33	99.59
2	78	95	93	88.67	98	102	90	96.67	91.72
3	101	95	73	89.67	96	98	94	96	93.4
4	104	112	103	106.3	120	114	118	117.3	90.63
5	120	99	105	108	116	110	114	113.3	95.29
6	98	99	92	96.33	92	94	102	96	99.65
									95.05

	BP, 1800 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	84	89	79	**84**	78	84	82	**81.33**	96.72
2	95	98	92	**95**	98	102	90	**96.67**	98.28
3	89	105	104	**99.33**	96	98	94	**96**	96.53
4	117	122	115	**118**	120	114	118	**117.3**	99.43
5	120	110	105	**111.7**	116	110	114	**113.3**	98.53
6	93	110	95	**99.33**	92	94	102	**96**	96.53
									97.67
	BP, 2300 lux								
Subject	Trial 1	Trial 2	Trial 3						
1	79	85	83	**82.33**	78	84	82	**81.33**	98.77
2	78	77	91	**82**	98	102	90	**96.67**	84.83
3	109	89	84	**94**	96	98	94	**96**	97.92
4	140	114	120	**124.7**	120	114	118	**117.3**	93.75
5	174	74	78	**108.7**	116	110	114	**113.3**	95.88
6	89	94	98	**93.67**	92	94	102	**96**	97.57
									94.79

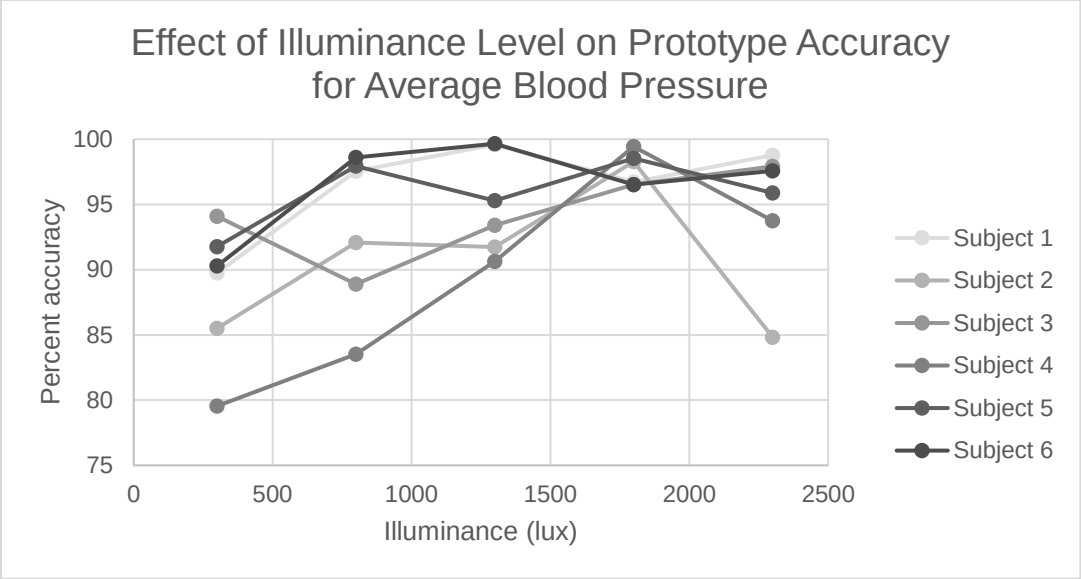
Analysis of Light Illuminances.



The chart depicts that largest accuracy occurred at about 1300 lux and 1000 lux, but was varied throughout. This may be due to the fact that rear camera data obtaining methods involved the usage of a flashlight, so the outside illuminance did not matter as much as it did for the front facing camera. As a result, the chart suggests that heart rate finds relatively high accuracy regardless of the potential inaccuracies found by the front camera.

When analyzed further, it is clear that one of the hypotheses was confirmed; the precise algorithm did show improvements over the more efficient algorithm reserved for lower-end devices. However, both of the novel algorithms developed in this study have shown to provide promising results; the efficient algorithm approaches design criteria of 97% and 95% accuracy for HR and BP, while the precise algorithm has reached the design criteria while under optimal illuminance.

It is also visible that errors may impede data analysis. Different subjects have different cardiovascular systems, so it may be difficult to properly create the “silver bullet” algorithm that can produce accurate results under several variances in temperature and minute variances in biological processes.



The chart above reinforces the importance of illuminance through a transmission method to allow the front facing camera to make accurate readings of the frames. An interesting development, however, is the high accuracy at around 1800 lux, which was off by about 500 lux to the expected 1300 lux after reviewing results from the illuminance and heart rate correlation.

The purpose of obtaining optimal illuminance levels was to delve further into the extend that the two novel algorithms may succeed in, as well as showing doctors and patients the optimal lighting conditions necessary for creating these volumetric measurements. The above charts help to show the possibility of utilizing multiple PPG signals at the body for a practical, simple, affordable, yet still clinically accurate form of obtaining volumetric measurements of the heart to provide justifications for the diagnosis of major heart disease conditions, such as atherosclerotic behavior.

Furthermore, the results provided a way to improve the algorithm used to alter brightness and contrast based on the current brightness of the frame. Using the value parameter discovered by the HSV color model, an offset is calculated to match the desired illuminance of about 1475 lux (the average between 1150 lux desired for heart rate and 1800 lux desired for blood pressure). Another algorithm could be created for flagship devices that can support brightness adjustment for each frame and create an additional 2 PPGs representing alterations when corrected to match desired heart rate and blood pressure, while still maintaining a decent 30 frames per second.

Impacts on Frame Rate

The resolution of the input image differed for the lower-end Amazon Fire and a more standard smart device, such as the Samsung Galaxy J7. To determine its impact on the frame rate and the processing speed (a larger image can take a larger amount of time for average RGB calculation, brightness and contrast manipulation, and accentuated dark pixel removal). Since so many factors were affecting the speed of the device, it was necessary to determine which had the largest impact on frame rate. Frame rate was calculated through an internal clock in the system based on how long it took for the Android system to obtain a new video frame from the camera. The default settings used in the current prototype need to be analyzed to determine which scenario affects frame speed and accuracy of the data, to further improve the current prototype.

Each of the factors were held constant and conducted over a course of multiple scenarios on a single subject. The default setting for other scenarios was used as constants when a setting in selected scenario was changed. Although exact calculations were recorded, they are not necessary since only the relative speed differences would need to be considered.

Scenario	**Setting**	**Frame Rate (nearest frames per second)**
Image Resolution (percent of native resolution)	100%	17
	50% (default)	30
	25%	36
Brightness and Contrast Manipulation	Both enabled (default)	30
	Brightness manipulation only	32
	Both disabled	33
Dark Pixel Removal	Brightness less than 15% (default)	30
	Brightness less than 5%	31
	Disabled	44

A large jump in frame rate was observed as the image resolution was changed. The native resolution of 1280 x 960 produced by the Samsung Galaxy proved to take an extremely long time to process, so the frame rate was only 17 frames per second (fps). At half the resolution (640 x 480) there was nearly double in frames processed, and this was already programmed as the default setting for the prototype. There was also a noticeable change when the resolution

further decreased to 25% the native resolution of the input image, but it might be detrimental to the PPG accuracy due to an extremely low number of pixels in average RGB calculation.

Brightness and contrast manipulation showed very little change in frame rate. This is potentially due to the pixels being manipulated as the RGB is being determined for each pixel; since brightness was a more important aspect towards RGB determination, as shown by an analysis of light illuminances, contrast manipulation was not analyzed. Future research may include a deeper analysis into how the contrast affects the frame rate, and where the line must be drawn between accuracy and speed.

Dark pixel removal based on the brightness was shown to be a similar frame rate when enabled. When it was disabled, however, the frame rate jumped to over 40 fps, at the default 50% resolution and enabled brightness manipulation. Further prototypes need to examine the improvement on the dark pixel removal algorithm, which at the current stage uses a simple linear scan of the pixels in the provided input image.

Since it is necessary to determine how each of these changes can influence the accuracy of the heart rate and the blood pressure on multiple subjects, in order to draw a line between accuracy and speed of the program, further research is planned for more data collection. Further research also involves improvement of the program to determine the individual systolic and diastolic pressures from a calculated mean blood pressure based on either a calibration method or the determination of the ideal blood pressure from the QTcB, HRV, and HR, further enhancing the propositions of the diagnostic scoring system.

Discussion and Analysis

The results of the PPG data are very promising. The program was accurate in determining average heart rate to a reasonable degree. In the efficient algorithm, systolic blood pressure had had a noticeable, but not drastic, amount of error. However, the program frequently reported diastolic blood pressure values lower than the theoretical value. Due to this inaccuracy, the average blood pressure was slightly affected as well.

It was also discovered that Subject 4 displayed unusually large errors, as the heart rate, blood pressure, and average blood pressure errors were some of the largest out of all the tested subjects. Since data for Subjects 4 and 5 were captured in bright settings, it was theorized that the program had difficulties discovering changes in intensity values since so much light was being passed through. This error seems to be natural because it is also reminiscent of common errors arising in spectrophotometric experiments involving the absorption of light to draw the absorbance-wavelength plot for certain solutions. Solutions that absorb and transmit light such that transmittance is outside the boundaries of 10% to 79% will not be able to perform well under spectrophotometric tests. A similar constraint could be applied to avoid large errors while the PPG is collecting raw data.

The results may have been slightly affected to report a higher blood pressure as some of the subjects reported that they have done some activity before the testing was conducted. For instance, Subject 5 reported that he/she had been eating before the test had taken place. As a result, the diagnosis of the PPG was inadvertently affected to suggest a potential risk for atherosclerosis.

Although the blood pressure calculations could be improved, it was noted that the program was able to determine heart rate very accurately, apart from Subjects 4 and 5. A more intelligent program that is able to ameliorate a suboptimal or poor environment in which the data collection is taking place could improve the heart rate and systolic blood pressure results.

In the more precise algorithm, these subtle variances were seen to be removed; the real time calculation of two PPG signals rather than utilizing a power trend and a single PPG signal showed about a 2-3% increase in the accuracy of the prototype. After over 100 trials of testing both algorithms, it was concluded that the precise algorithm supports most smartphones with optimal results at about 1300 lux; a more efficient algorithm also proves to reach design criteria.

Conclusions

Atherosclerosis is a condition that is caused by the buildup of fats and cholesterol along arterial walls. If left unnoticed, the blood flow through the arteries can reach a critical level, possibly cutting off the transport of nutrients and oxygen to vital organs altogether, leading to major cardiovascular diseases such as coronary artery disease, heart attack or stroke. The best way to prevent these diseases is diagnosing atherosclerosis and the buildup of plaque at its early stages. However, the cost of diagnosis, let alone treatment, steers patients away from the problem.

The purpose of the study is to develop a cost-effective, reliable, and accessible form of diagnosis to identify atherosclerosis early on. Traditional methods of diagnosis, such as the electrocardiogram, give doctors data in regards to heart regularity and the normalcy of blood pressure. This study attempts to obtain the same information through a simpler and more accessible fashion, via a technique known as photoplethysmography (PPG), which involves the observation of changes in light intensity based on the amount of light absorbed by a finger on the back of a camera. The proposed solution uses the PPG signal to derive blood pressure, heart rate, and a diagnosis for atherosclerosis that is accessible and cost-effective for millions worldwide. The prototype was tested on six subjects with three trials each (one trial each day), and the output data was compared with readings from an FDA approved digital blood pressure monitor.

The results showed that the prototype was generally able to accurately measure the heart rate and blood pressure. The program saw only about a 5% error in heart rate and a 10 – 15% error in blood pressure, but these values can be further improved by applying filters such as the Butterworth filter and processing the raw signal more to allow the program to determine the possibility of data inaccuracy, and change accordingly, due to poor environmental settings. The novel, more precise algorithm was able to discern heart rate and blood pressure values more readily, with about a 2-3% higher accuracy than that of the more efficient algorithm. From this it can be concluded that both algorithms have shown impressive accuracy, and PPG signal analysis from multiple points of the body holds more potential than once believed.

The experiment holds a lot of promise in accurately determining key factors contributing to atherosclerosis. With a power to prevent deaths caused by heart attack and stroke by providing a cost-effective yet reliable form of investigating the degree to which plaque has accumulated on

arterial walls, the study encourages patients to feel calmer about financial troubles and immediately take action to reverse the possible onset of atherosclerosis.

Future Research

Future research involves the improvement of systolic and diastolic blood pressure based on the average blood pressure calculations, investigation on aging and arterial stiffness indices mentioned by Elgendi's research, and the extrapolation of certain PQRST characteristics of the ECG from the PPG signal for further refining the diagnostic functions of the current prototype and increase the alignment to protocols followed in clinical settings based on the analysis of ECGs. It is also important to determine the impact on changing certain algorithms to run faster while still obtaining accurate results, and finding an ideal blood pressure using either calculated data or a calibration method for centering the systolic and diastolic values from a calculated mean blood pressure.

Applications

The study proposes a new cost-efficient and accessible method of extrapolating heart rate, blood pressure, and the severity of atherosclerosis (the buildup of plaque on arterial walls) based on a quick reading of light absorption changes by the blood using a smartphone or a tablet. The project opens doors to accessible and reliable medical technology for millions of people worldwide, and reducing the cost of diagnosing atherosclerosis can allow patients to feel more relaxed and stress-free from the financial troubles arising from traditional methods of diagnosis. By pushing research in the field of photoplethysmography to include more accurate blood pressure readings and extrapolation of ECG data from a PPG, the project will provide an impetus for more scientific investigations on cheaper, yet reliable, medical technology.

Literature Cited

Al-Qazzaz, N. K., Abdulazez, I. F., & Ridha, S. A. (2014). Simulation Recording of an ECG, PCG, and PPG for Feature Extractions. *Al-Khwarizmi Engineering Journal*, *10*(4), 81–91.

Atherosclerosis at a Glance. (n.d.). US Department of Health and Human Services. Retrieved from https://www.nhlbi.nih.gov/files/docs/public/heart/atherosclerosis_atglance.pdf

Blood Pressure and Hyptertension.pdf. (n.d.). American Heart Association.

Butterworth, S. (1930). *On the Theory of Filter Amplifiers* (p. 6). England: Admiralty Research Laboratory. Retrieved from http://www2.ee.ufpe.br/codec/paper%20BUTTERWORTH.pdf

Elgendi, M. (2012). On the analysis of fingertip photoplethysmogram signals. *Current Cardiology Reviews*, *8*(1), 14–25.

Elliott, S. (2010, April 24). Researchers Examine Correlation Between Blood Pressure And Heart Rate Variability. Retrieved November 26, 2017, from http://www.bmedreport.com/archives/11909

Elvers, G. (n.d.). Hue, Saturation and Brightness (HSV). Retrieved November 26, 2017, from http://elvers.us/perception/hsv/

Ginghina, C., Ungureanu, C., Vladaia, A., Popescu, B. A., & Jurcut, R. (2009). The electrocardiographic profile of patients with angina pectoris. *Journal of Medicine and Life*, *2*(1), 80.

Go, A., Bauman, M., & King, S. (2013). An Effective Approach to High Blood Pressure Control. *American Heart Association*, 27. https://doi.org/10.1161/HYP.0000000000000003

Holubkov, R., Pepine, C. J., Rickens, C. R., Reichek, N., Rogers, W. J., Sharaf, B. L., … Kelsey, S. F. (2002). Electrocardiogram abnormalities predict angiographic coronary artery disease in women with chest pain: results from the NHLBI WISE Study. *Clinical Cardiology*, *25*(12), 553–558.

Jang, D.-G., Park, S., Hahn, M., & Park, S.-H. (2014). A Real-Time Pulse Peak Detection Algorithm for the Photoplethysmogram. *International Journal of Electronics and Electrical Engineering*, 45–49. https://doi.org/10.12720/ijeee.2.1.45-49

Peng, R.-C., Zhou, X.-L., Lin, W.-H., & Zhang, Y.-T. (2015). Extraction of Heart Rate Variability from Smartphone Photoplethysmograms. *Computational and Mathematical Methods in Medicine*, *2015*, 1–11. https://doi.org/10.1155/2015/516826

Punwani, V. (n.d.). *Atherosclerosis: Circulatory System and Disease*. Retrieved from https://www.youtube.com/watch?v=g3kDdg8r6NY

Reisner, A., Shaltis, P. A., McCombie, D., & Asada, H. H. (2008). Utility of the photoplethysmogram in circulatory monitoring. *The Journal of the American Society of Anesthesiologists*, *108*(5), 950–958.

Sawicka, K., Szczyrek, M., Jastrzebska, I., Prasal, M., Zwolak, A., & Daniluk, J. (2011). Hypertension–The silent killer. *Journal of Pre-Clinical and Clinical Research*, *5*(2).

Sazani, N. (n.d.). *How Blood Pressure Works*. Retrieved from https://www.youtube.com/watch?v=Ab9OZsDECZw

Sponder, M., Fritzer-Szekeres, M., Marculescu, R., Litschauer, B., & Strametz-Juranek, J. (2014). A new coronary artery disease grading system correlates with numerous routine parameters that were associated with atherosclerosis: a grading system for coronary artery disease severity. *Vascular Health and Risk Management*, *10*, 641–647. https://doi.org/10.2147/VHRM.S68919

Sun, S., Bezemer, R., Long, X., Muehlsteff, J., & Aarts, R. M. (2016). Systolic blood pressure estimation using PPG and ECG during physical exercise. *Physiological Measurement*, *37*(12), 2154–2169. https://doi.org/10.1088/0967-3334/37/12/2154

What is High Blood Pressure? (2015, March 2). Retrieved November 26, 2017, from http://www.livefitlean.com/high-blood-pressure/

Bibliography

Al-Qazzaz, N. K., Abdulazez, I. F., & Ridha, S. A. (2014). Simulation Recording of an ECG, PCG, and PPG for Feature Extractions. *Al-Khwarizmi Engineering Journal*, *10*(4), 81–91.

Atherscleros at a Glance. (n.d.). US Department of Health and Human Services. Retrieved from https://www.nhlbi.nih.gov/files/docs/public/heart/atherosclerosis_atglance.pdf

Blood Pressure and Hyptertension. (n.d.). American Heart Association.

Butterworth, S. (1930). *On the Theory of Filter Amplifiers* (p. 6). England: Admiralty Research Laboratory. Retrieved from http://www2.ee.ufpe.br/codec/paper%20BUTTERWORTH.pdf

Elgendi, M. (2012). On the analysis of fingertip photoplethysmogram signals. *Current Cardiology Reviews*, *8*(1), 14–25.

Elliott, S. (2010, April 24). Researchers Examine Correlation Between Blood Pressure And Heart Rate Variability. Retrieved November 26, 2017, from http://www.bmedreport.com/archives/11909

Elvers, G. (n.d.). Hue, Saturation and Brightness (HSV). Retrieved November 26, 2017, from http://elvers.us/perception/hsv/

Ginghina, C., Ungureanu, C., Vladaia, A., Popescu, B. A., & Jurcut, R. (2009). The Electrocardiographic Profile of Patients With Angina Pectoris. *Journal of Medicine and Life*, *2*(1), 80.

Go, A., Bauman, M., & King, S. (2013). An Effective Approach to High Blood Pressure Control. *American Heart Association*, 27. https://doi.org/10.1161/HYP.0000000000000003

Heravi, Y., Amin, M., Keivan, M., & Sima, J. (2014). A New Approach for Blood Pressure Monitoring Based on ECG and PPG Signals by Using Artificial Neural Networks. *International Journal of Computer Applications*, *103*(12).

Holubkov, R., Pepine, C. J., Rickens, C. R., Reichek, N., Rogers, W. J., Sharaf, B. L., … Kelsey, S. F. (2002). Electrocardiogram abnormalities predict angiographic coronary artery disease in women with chest pain: results from the NHLBI WISE Study. *Clinical Cardiology*, *25*(12), 553–558.

Jang, D.-G., Park, S., Hahn, M., & Park, S.-H. (2014). A Real-Time Pulse Peak Detection Algorithm for the Photoplethysmogram. *International Journal of Electronics and Electrical Engineering*, 45–49. https://doi.org/10.12720/ijeee.2.1.45-49

Peng, R.-C., Zhou, X.-L., Lin, W.-H., & Zhang, Y.-T. (2015). Extraction of Heart Rate Variability from Smartphone Photoplethysmograms. *Computational and Mathematical Methods in Medicine*, *2015*, 1–11. https://doi.org/10.1155/2015/516826

Punwani, V. (n.d.). *Atherosclerosis: Circulatory System and Disease*. Retrieved from https://www.youtube.com/watch?v=g3kDdg8r6NY

Reisner, A., Shaltis, P. A., McCombie, D., & Asada, H. H. (2008). Utility of the photoplethysmogram in circulatory monitoring. *The Journal of the American Society of Anesthesiologists*, *108*(5), 950–958.

Sawicka, K., Szczyrek, M., Jastrzebska, I., Prasal, M., Zwolak, A., & Daniluk, J. (2011). Hypertension–The silent killer. *Journal of Pre-Clinical and Clinical Research*, *5*(2).

Sazani, N. (n.d.). *How Blood Pressure Works*. Retrieved from https://www.youtube.com/watch?v=Ab9OZsDECZw

Sponder, M., Fritzer-Szekeres, M., Marculescu, R., Litschauer, B., & Strametz-Juranek, J. (2014). A New Coronary Artery Disease Grading System Correlates with Numerous Routine Parameters that were Associated with Atherosclerosis: A Grading System For Coronary Artery Disease Severity. *Vascular Health and Risk Management*, *10*, 641–647. https://doi.org/10.2147/VHRM.S68919

Sun, S., Bezemer, R., Long, X., Muehlsteff, J., & Aarts, R. M. (2016). Systolic Blood Pressure Estimation Using PPG and ECG During Physical Exercise. *Physiological Measurement*, *37*(12), 2154–2169. https://doi.org/10.1088/0967-3334/37/12/2154

What is High Blood Pressure? (2015, March 2). Retrieved November 26, 2017, from http://www.livefitlean.com/high-blood-pressure/

Acknowledgements

I would like to thank my parents and friends for supporting me throughout the study.

Selected journal articles and research papers that were discussed in this study are reprinted on the following pages.