An Investigation of Pulse Transit Time as a Non-Invasive Blood Pressure Measurement Method

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Abstract. The objective of this paper is to examine the Pulse Transit Method (PTT) as a non-invasive means to track Blood Pressure over a short period of time. PTT was measured as the time it takes for an ECG R-wave to propagate to the finger, where it is detected by a photoplethysmograph sensor. The PTT method is ideal for continuous 24-hour Blood Pressure Measurement (BPM) since it is both cuff-less and non-invasive and therefore comfortable and unobtrusive for the patient. Other techniques, such as the oscillometric method, have shown to be accurate and reliable but require a cuff for operation, making them unsuitable for long term monitoring. Although a relatively new technique, the PTT method has shown to be able to accurately track blood pressure changes over short periods of time, after which re-calibration is necessary. The purpose of this study is to determine the accuracy of the method.

1. Introduction
Blood pressure is a major indicator of the health of a person and is one of the five vital signs. However, unlike other vital signs, abnormal blood pressure can be a sign of a long term illness rather than an immediate one and can be used as a predictor of Cardiovascular Disease (CVD). CVD is the leading cause of death worldwide and accounted for 33.54% of all deaths in Ireland in 2009[1]. Blood Pressure is typically measured in a clinical setting using a sphygmomanometer, a stethoscope and a clinician. Although this is considered the golden standard for blood pressure measurement, it has been recognized that there are numerous problems with this method [2], [3],[4]. It is commonly acknowledged that a non-invasive and continuous blood pressure measurement device is preferable to the sphygmomanometer.

Up until recently, there has only been two major non-invasive, continuous blood pressure measurement techniques that have been researched extensively i.e. the oscillometric method and the Penaz method. Both of these methods, however, still use a cuff, which can lead to patient comfort impact and the occlusion of the artery increases the workload of the heart and causes circulatory interference at the measurement site [5].

The Pulse Transit Time (PTT) method is an alternative for blood pressure measurement. The PTT is the time it takes for a blood pressure pulse to travel from one arterial site to another [6]. Typically, the PTT is initiated by the R-wave of the ECG and the finger is used as the second arterial location. The arrival of the pulse at this location is usually detected by the use of a photoplethysmograph sensor. By monitoring the change of the PTT it is possible to track the changes in blood pressure.
The PTT has a number of advantages over the oscillometric and Penaz methods but the most significant advantage is the PTT method does not require an inflatable cuff, making it ideal for a wearable and continuous non-invasive blood pressure measurement device.

2. Background

The relationship between blood pressure and PTT as it is used in this method was first proposed by Chen in 2000 [7]. Chen related blood pressure to a third parameter known as Pulse Wave Velocity (PWV). The following is a summary of this derivation.

PWV is defined as the speed of propagation of a blood pressure pulse. The PWV is dependant of a number of arterial properties, namely the elasticity $E$, the arterial thickness $t$, the arterial diameter $d$ and the density of the blood $\rho$. This relationship is defined by the Moens-Kortweg equation:

$$\text{PWV} = \sqrt{\frac{gE}{\rho d}}$$  \hfill (1)

where $g$ is the gravitational constant. For the sake of simplicity, $g$ is usually omitted and the pressure is said to be hydrostatic, since $g$ is constant on earth. This equation is based on the assumption that, over a short period of time, neither the elasticity, the thickness of the walls nor the diameter of the walls changes significantly.

It has been noted that the elastic modulus of the vessel increases exponentially with increasing blood pressure such that:

$$E = E_0 e^{\gamma P}$$  \hfill (2)

Where $E_0$ is the elastic modulus at zero pressure, $P$ is the blood pressure (mmHg) and $\gamma$ is a coefficient ranging from 0.016 to 0.018 (mmHg$^{-1}$).

PTT is related to PWV by:

$$\text{PWV} = \frac{K}{\text{PTT}}$$  \hfill (3)

where $K$ is a proportional coefficient, indicating the distance that the pulse has to travel between the two arterial locations.

Using some manipulation [7], blood pressure can be related to PTT directly by:

$$P_e = P_b - \frac{2}{\gamma PTT_b} \Delta PTT$$  \hfill (4)

Where $P_b$ is the base blood pressure level, $PTT_b$ is the value of the PTT corresponding to the pressure $P_b$, while $\Delta PTT$ is the change in the PTT.

3. Methodology

Data was collected from six volunteers: four male and two female volunteers aged between 24 and 28 years. Each volunteer was tested three times, with half an hour’s worth of data being recorded at each sitting i.e. 90 minutes of data was recorded per volunteer.

Blood pressure was simultaneously recorded using an Omron M6 oscillometric blood pressure monitor. This device is recommended by Dabl Educational and was also recommended by a cardiologist. The Omron M6 was worn on the upper left arm and was used to recalibrate the estimated blood pressure at five minute intervals i.e. was used to provide $P_b$ from Equation (4).
Using this method, 540 minutes of data was recorded and 126 blood pressure measurements were recorded.

Electrocardiogram (ECG) data was recorded from a self developed electrocardiogram, the Tyndall Physiological Health Board. This Physiological Health Board uses a three electrode ECG monitor to record the data from each of the patients. A three electrode system was developed since it provided the accuracy that was required for ECG monitoring while not being obtrusive for the patient. The electrodes were placed in a manner which satisfied Einthoven’s Triangle [8]. The Physiological Health Board uses a 12-bit ADC (AD7490, Analog Devices) to transmit data to the on-board micro-controller (Atmel Mega 1281) for transmission.

The photoplethysmograph (PPG) data was recorded from another device that was developed within Tyndall. This PPG sensor uses a finger cuff and is placed on the middle finger of the right hand. Both the ECG and PPG the signals were recorded at a sampling rate of 400Hz using a personal computer based signal acquisition system through LabView and stored in an spreadsheet for post processing.

Pulse Transit Time was defined as the time interval between the R-wave of the ECG and the peak of the PPG signal at the finger site, within the same cardiac cycle. Measurements were taken from 2.00 PM to 4.30PM in a quiet environment at 20°C. The volunteers were asked to refrain from smoking and ingesting caffeine or any other blood pressure altering drugs in the hours prior to the test, as per the recommendations for all blood pressure measurements [4].

All post-processing of the recorded data was performed using Matlab (MathWorks, Natick, MA, USA) using a self derived algorithm. This algorithm initially filtered all the data to remove excess noise. The filtered data was then analyzed to detect the peaks of the ECG and the peaks of the PPG. From this it is possible to calculate the PTT and ΔPTT. The algorithm then used the data recorded from the Omron M6 blood pressure monitor (Pb) and the ΔPTT to calculate the estimated blood pressure Pe, using Equation (4).

4. Results

The results from this test described in section 3 can be seen in Table 1. The data is presented in the form of the mean and standard deviation of the error of the estimated Blood Pressure. These results show a good correlation between the blood pressure measured using the clinically validated Omron M6 and the PTT method.

The largest standard deviation is seen from Volunteer 3’s results. This can be explained by the fact that this volunteer is both hypotensive and a diabetic. It was noted during testing that this volunteer had poor circulation which adversely affected the signals being recorded from the PPG sensor which was placed on the finger.
Table 1. Summary showing the mean error of the estimated and the standard deviation for each volunteer.

| Volunteer | Estimated Error of Systolic BP |
|-----------|-------------------------------|
| 1         | 1.81 ± 4.39                  |
| 2         | -0.82 ± 3.69                 |
| 3         | -1.34 ± 7.93                 |
| 4         | -1.44 ± 5.71                 |
| 5         | -2.57 ± 6.23                 |
| 6         | -0.53 ± 3.70                 |

5. Discussions and Conclusions

This study intended to evaluate the PTT method that has been used as an alternative to the use of a sphygmomanometer and other cuff based methods of blood pressure measurement. The results, shown in Table 1, demonstrate a high degree of accuracy between the two methods. The mean difference between all the results for each of the volunteers is less than 3mmHg. However, there is a quite large standard deviation between the PTT and traditional methods. Even though this group also contained a hypotensive volunteer, the PTT method was able to track this person's blood pressure with reasonable accuracy.

Although volunteer 3 was known to be diabetic and hypotensive, this was not the case for volunteers 4 and 5, which also show a large standard deviation. Analysis of the results of all patients have revealed that some of the peaks of the PPG sensor were not correctly identified. It had been previously established, while testing volunteer 3, that poor circulation adversely affects the results but analysis of volunteers 4 and 5 showed a particularly noisy signal. This noisy signal can be attributed to movement of the finger during the recording of the data. Although the filtering that was applied using Matlab was able to eliminate some of this noise, it has become apparent that more filtering of the signals will be required to eliminate noise due to movement.

Overall, this test has shown that it is possible to track blood pressure with reasonable accuracy using the Pulse Transit time. However, this tracking of blood pressure was done using constant re-calibration at 5 minute intervals. It is predicted that extending this calibration interval would mean a deterioration of the results but a further study will be required to establish this level of deterioration.

6. Future Work

Further work will be required to complete the evaluation of the PTT as an alternative to the traditional methods of blood pressure monitoring. The algorithm that have been used to filter the data, to determine the peak detections and to calculate the PTT, will have to be extended to account for motion artefact reduction. This will help to increase the accuracy of the results.

A larger study group will need be tested in the subsequent rounds of testing. It would be preferable that this group will contain a larger amount of patients, both with normal and abnormal blood pressures, to examine the usefulness of the technology for both healthy and ill patients.

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