A Comparative Study on Instantaneous and Mean Pulse Arrival Time for Cuffless Blood Pressure Estimation

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Abstract. Pulse arrival time (PAT) is the delay time between the peak of the R-wave Electrocardiogram (ECG) signal and the peak of Photoplethysmogram (PPG) signals. This method is widely exploited for continuous cuffless blood pressure measurement. In the literature, the PAT was determined based on the mean at a certain number or certain period of heartbeats, but none of them deployed a single pulse wave for PAT calculation. Therefore, in this paper, a relationship between mean PAT (15 pulses ± Standard Deviation (SD)) and instantaneous PAT (a pulse) with blood pressure (BP) was investigated on thirteen healthy male volunteers (aged between 17 to 42 years) through a pedal exercise. The PAT is grouped into three (3) categories which depend on the spatial position of the PPG signal measured; finger (PATf), wrist (PATw), and underfoot (PATt). The ECG and the PPG signals were synchronized using a Nexus-10 MK II data acquisition device and Matlab software (R 2014b) for subsequent analysis. An oscillometric cuff-based blood pressure instrument (Ostar, P2) was used as a BP reference during the experiment. Statistical analysis showed no significant difference in the |r| value between mean (15 pulses ± SD) and instantaneous PAT-BP; hence both methods are applicable for BP estimation using the PAT-BP calibration technique.

1. Introduction

Continuous blood pressure (BP) measurement provides highly important information on the individual’s cardiovascular disease, especially during surgery and hypertensive treatment. In practice, ambulatory BP measurement (AMBP) is deployed for monitoring BP measurement in diagnosing hypertension [1]. Unfortunately, these devices provide a measurement of systolic and diastolic at separate time intervals, thus limiting BP variability. Also, the cuff-based AMBP may result in discomfort and inconvenience for patients wearing the device for a long period [2]. Therefore, the cuff-less continuous BP measurement is a more desirable option as it can potentially provide deeper insight and understanding of BP variability to help identify serious cardiovascular events and allow anti-hypertensive therapy decisions.

The gold standard for the beat-to-beat BP measurement is based on an intra-arterial catheter. However, this technique is usually applied for patients in serious medical conditions only [3]. Besides, this technique introduces the risk of arterial injury and skin infection to the patient and requires a complex setup procedure [4]. Thus it is not suitable for out-of-hospital hypertension monitoring [5]. In general, the intra-arterial BP and cuff-based BP are not based on the same physiological observation,
and measurement with different devices may not produce the same results [6]. A cuff-based system measures systolic blood pressure (SBP) at one cardiac cycle, and the diastolic blood pressure (DBP) is measured at several cardiac cycles later. This problem is compounded by the pulse arrival time (PAT) technique that gets a single PAT measurement, but usually means it is over several cardiac cycles. Hence PAT (SBP and DBP) is measured over an averaging window of, say, 15 seconds, while the cuff measures SBP at one instance and then roughly 15 seconds later, it measures DBP. In other words, there is a considerable delay between Electrocardiogram (ECG) at SBP and ECG at DBP of at least 15 ECG beats. In literature, the variation of 15 beats BP measured by Finapres BP was 6 mmHg for SBP and 3 mmHg for DBP [7]. Hence this variation results in a variation in PAT over several ECGs. Then using several PATs at the SBP and DBP moment could potentially result in a wide spreading of the PAT error.

A review by Van Velzen et al. reported that the averaging periods in determining PAT ranged from 8 seconds to 6 minutes, with an averaging period of 1 minute being the most common [8]. Poon et al. showed that beat-to-beat PAT and SBP were highly correlated within a few beats [9]. They reported that the correlation coefficient (r) decreased from -0.73 to -0.63 when the number of beats increased from 15 to 360 beats. The PAT value obtained from long averaging periods may be affected by unsuitable pulse waves due to movement and associated noise [10].

Therefore, instantaneous PAT was introduced through this research to minimize errors during the calibration of PAT and BP. In these studies, the instantaneous PAT refers to a delay time on a single pulse that was manually determined according to the value of SBP and DBP recorded from the oscillometric BP device. This method was compared with a mean of 15 beats PAT during the calibration process on volunteers.

2. Methods

In this research, the PAT is determined based on the delay time between the R-peak of ECG signals and the peak of Photoplethysmogram (PPG) signals. All the signals were acquired by the data acquisition device (NeXus-10 Mark II, Mindmedia) through the input Ch A, Ch B, Ch E, Ch F, Ch G and Ch H with the Ch represent the Channel. Ch A and Ch B are the bipolar channels for ECG measurement using conductive fabric electrodes and surface electrodes, respectively. The PPG on the fingertip was monitored using Ch E using a Blood Volume Pulse (BVP) sensor (Nexus, NX-BVP1A). The plastic optical fibre (POF) was deployed for the PPG measurement on the wrist (Ch F) and the PPG measurement under the foot (Ch G). Ch H is used to monitor the pressure inside the BP cuff using a pressure sensor (MPX 4250). This device is attached on the volunteer’s body, and all the sensors connection is shown in Figure 1.

According to the lead II measurement, the ECG signals were measured on the chest because the QRS axis normally aligns with these leads [11]. The surface electrode and the fabric electrode were placed side by side, as shown in Figure 1. The chest strap was used on top of the fabric electrode to secure it to the body and ensure good contact between the electrode and skin for ECG measurement. The PPG was measured at three locations; index finger (PATf), wrist (PATw), and under the foot (PATf). The PPG on the index finger was measured using a Blood Volume Pulse (BVP) sensor based on transmission mode. Reflection mode POF was used to measure the PPG measurement on the wrist (Ch F) and the PPG measurement under the foot (Ch G). Ch H is used to monitor the pressure inside the BP cuff using a pressure sensor (MPX 4250). This device is attached on the volunteer’s body, and all the sensors connection is shown in Figure 1.

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Figure 1. Sensor placement on the volunteer. ECG surface electrodes and ECG fabric electrodes on the chest, POF on the wrist (right arm) and underfoot (right leg), Blood Volume Pulse (BVP) sensor on the index finger (right arm) and Ostar BP on the left arm.

The Nexus data acquisition device synchronized the PPG and ECG signals. The “pairs” between them were determined with the ECG as a “reference” signal. The PAT is determined by subtracting the peak location of PPG with the peak location of the R-wave ECG in the same cardiac cycle, as shown in Figure 2. A manual check on these data was performed to ensure the peak is correctly located on each ECG and PPG signal. Some of the peaks (less than 10%) were not properly detected, especially on a corrupted signal due to motion artefact will be replaced by the interpolation data. A linear interpolation method was applied to determine the missing peak by finding a mean between the peak values before and after the missing data [13]. Next, a mean value of 15 “pair” of pulses (mean PAT) is taken to represent a PAT corresponding to a BP reading during the cuff deflation (dash circle), as shown in Figure 3. The oscillation of the BP cuff waveform is used to synchronise between the BP and the PAT reading. A Y-tube connection was deployed to connect the pressure sensor (MPX4250), BP cuff, and Ostar BP Monitor.

Figure 2. A graphical representative of PAT (the delay time is calculated from the peak of R-wave ECG signal to the peak of PPG signal in one cardiac cycle as indicated by the arrow signed).

Figure 3. A BP cuff pressure waveform for volunteer 1.
Meanwhile, a single pulse representing instantaneous PAT was selected according to where the oscillometric BP device was recording the SBP and DBP via an external pressure sensor (MPX 4250). As shown in Figure 4, for example, the SBP measured by the Ostar BP device is 120 mmHg (as shown by the device’s monitor), and this value was marked manually on the cuff oscillation curve (recorded by the MPX4250). An ECG pulse wave that occurred at that point was identified, and the delay time between the ECG and PPG was computed, resulting in an instantaneous PATsys measurement (Figure 4). The same procedure was applied to identify instantaneous PAT for DBP (80 mmHg) as indicated by PATdia (Figure 4).

Figure 4. Instantaneous PAT measurement for SBP (PATsys) and DBP (PATdia). The black trace represents the deflation of the BP curve (BP Cuff), the blue trace represents the ECG measured using surface electrode (ECG Nex), and the red trace represents the PPG on the fingertip measured by the BVP sensor (PPG Nex).

Initially, 15 volunteers were employed, but only 13 volunteer’s data were utilised for further analysis. The other two volunteer’s data has been excluded because of the illegible or missing response of some PPG signals under the foot and the BP measurement device repeatedly reporting an error during the experiment. The pressure exerted on the skin during the pedal exercise experiment may influence the missing PPG signals. An irregular heart rate during or after the exercise may produce errors in the BP measurement. All volunteers are healthy, and the age ranges from 17 to 42 years. This research is limited to male participants because it involves male researchers attaching electrodes to the chest of volunteers.

In this experiment, the PAT and the BP of volunteers were monitored before, during, and after pedal exercise on an Exercise Bike (Domyos VM740). The volunteers were asked to stay in the same position during BP and PAT measurements. The time required for each volunteer to finish the experiment is approximately 32 minutes. The ECG and PPG were recorded continuously at 256 samples/second during the experiment, allowing continuous PAT calculation. Simultaneously, 9 BP measurements were recorded using a cuff-based OSTAR BP monitor (6 BP readings were taken during the rest section (before and post-exercise), and 3 BP readings were taken during the exercise section). A method for recording the PAT and BP before and after exercise has been implemented by other researchers to assess the relation between PAT and BP [10][14].

3. Result and Discussion

In this study, PAT is grouped into three (3) categories that depend on the PPG signal's spatial position measured; finger, wrist, and underfoot. A typical waveform of the ECG and PPG is shown in Figure 5, with ECGnex refers to ECG measured by the surface electrode and ECGfab refers to the ECG measured by the conductive fabrics electrode. For the PPG measurement, PPGf refers to PPG measured by the BVP sensor on the right finger and the PPGw, and the PPGt refers to the PPG measured by the plastic optical fibre sensor on the right wrist and under the right foot, respectively.
A mean of 15 beats was deployed, and the accuracy of this method was compared with a single pulse wave PAT or instantaneous PAT. Figure 6 shows the instantaneous and mean PAT with BP at three different sites of PPG measurement; finger, wrist, and underfoot on volunteer 1 (volunteer code: 1001). The mean PAT was plotted based on a mean ± SD of 15 pulses corresponding to SBP and DBP recorded by the BP monitor. By referring to the linear equation and the R-squared valued (as shown in Figure 6), there appears to be not much difference in the regression line between instantaneous PAT and mean PAT versus BP.

SPSS software was used to perform statistical analysis on the mean and instantaneous PAT. There were six pairs compared; mean PATf SBP and Ins. PATf SBP, mean PATf DBP and Ins. PATf DBP, mean PATw SBP and Ins. PATw SBP, mean PATw DBP and Ins. PATw DBP, mean PATt SBP and Ins. PATt SBP, mean PATt DBP and Ins. PATt DBP. All the data were normally distributed according to the Shapiro-Wilk test (p > 0.05). A student t-test was performed to determine the statistical difference.
between the mean and instantaneous PAT. The results showed no statistically significant difference between the mean and instantaneous PAT for all the data pairs (p > 0.05).

A linear regression model was applied to mean/instantaneous PAT-BP data, and the Pearson correlation coefficient, r, was determined on each volunteer. Statistical analysis using the two proportion Z-test was performed to compare the proportions of data distribution for |r|>0. The results showed that 85 % of SBP correlates with PAT (|r| > 0.5), compared to 44 % recorded by DBP. Next, a Shapiro-Wilk test was performed to test the normality of the data distribution. This test showed that p > 0.05 for each data on all categories PATf, PATw, and PATt (mean and instantaneous PAT) indicated that the data were normally distributed. Therefore, the student t-test was performed to check the statistically significant difference between the mean and instantaneous (Ins.) PAT-BP in 6 pairs; mean PATf-SBP with Ins. PATf-SBP, mean PATw-SBP with Ins. PATw-SBP, mean PATt-SBP with Ins. PATt-SBP, mean PATf-DBP with Ins. PATf-DBP, mean PATw-DBP with Ins. PATw-DBP and mean PATt-DBP with Ins. PATt-DBP.

The results showed that the p-value was greater than 0.05 (p > 0.05) for all pairs except for mean PATf-DBP with Ins. PATf-DBP. The p-value > 0.05 suggested that the null hypothesis (H₀) was accepted and statistically showed no difference in the |r| value between mean and instantaneous PAT-BP. The p-value for mean PATf-DBP with Ins. PATf-DBP is less than 0.05 (p = 0.039, < 0.05), indicated that the null hypothesis (H₀) was rejected and that there is a statistically significant difference between mean PATf and instantaneous PATf with DBP. The variation in BP over several beats gets in the way of a mean value calculation of PAT compared to an instantaneous PAT resulting in a difference in |r| value obtained in three volunteers. The outlier points on the oscillation waveform may cause by the movement artefact [15]. In general, a single outlier that appeared on the PAT-BP plotted line may dramatically alter the correlation coefficient, r, and reduce the accuracy of the equation in estimating BP [16].

4. Conclusion
In the literature, the PAT was determined based on a mean at a certain number of heartbeats or a certain period, but none of them deployed a single pulse wave for PAT calculation. Hence one of the contributions of this work is comparing the instantaneous PAT and the mean PAT with BP measurement. A linear regression model was applied to mean/instantaneous PAT-BP data, and the absolute correlation coefficient, |r|, was determined on each volunteer. The results show that the PAT is well correlated with systolic BP but shows a weak correlation between PAT and diastolic BP. The statistical analysis shows no significant difference between a mean ± SD of 15 pulses and instantaneous PAT with BP. Thus, there will be insignificant changes of the calibration equation using a mean of 15 pulses or instantaneous PAT in BP estimation for each volunteer.

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