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A NOVEL WAVEFORM MIRRORING TECHNIQUE FOR SYSTOLIC BLOOD PRESSURE ESTIMATION FROM ANACROTIC PHOTOPLETHYSMOGRAM

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Abstract

Continuous cuffless Blood Pressure (BP) measurement is an important tool to monitor the health of individuals at risk. In this study, a new method is proposed for Systolic BP (SBP) estimation utilizing Photoplethysmograms (PPG). To this end, toe and carotid PPG were recorded from seventeen subjects aged 20-28 years, whereas their SBP were measured using a standard BP cuff monitor for validation purpose. The proposed method is based on a novel mirroring technique, which allows for an accurate estimation of the Pulse Transit Time (PTT) from the PPG's rising part (anacrotic) waveform using an ARX System Identification approach. Based on the modified Moens-Korteweg equation, SBP was then calculated based on the estimated PTT values obtained from the ARX model. The estimated PTT was found to be highly correlated to the measured SBP (R2 = 0.98). Comparison of calculated SBP to the measured SBP obtained using standard BP cuff monitor results in a mean error of 3.4%. Given that 95% of the estimated SBP values are accurate in the +/- 8 mmHg range, this method seems promising for non-invasive, continuous BP monitoring.

Keywords: ARX model, Blood pressure (BP), Linear systems, Morphological signal processing, Photoplethysmography (PPG), Pulse transit time (PTT), System identification, Systolic Blood Pressure (SBP).

1. Introduction

Blood Pressure (BP) is one of the markers for healthcare monitoring and clinical assessment of patients. In each heartbeat, the blood pressure varies continuously between Systolic Blood Pressure (SBP) and Diastolic Blood Pressure (DBP). SBP refers to the pressure during the heart's pumping and DBP refers to the pressure during the heart's resting between beats [1]. The unit of BP measurement is in millimetres of mercury (mmHg) with a normal range level of BP for healthy adults between 120 mmHg (SBP) to 80 mmHg (DPB) [2]. High BP is one of the major risk factors for cardiovascular disease, leading cause of death worldwide. According to Ding et al. [3], monitoring high BP, a condition medically a referred as hypertension, has led to significant investment in developing novel devices to measure and monitor the BP. As stated by Patzak et al. [4], one of the most widely used methods for measuring non-invasively the BP is the cuff-based method.

Invasive BP measurement is the primary calibration technique that is used for measuring blood pressure. This technique requires inserting a needle in the artery to establish a hydraulic connection between a pressure transducer and the brachial artery where BP is measured. The procedure also exposes the patient to the risk of infection and requires a person who has been well trained and specialized to conduct the measurement. It is also employed only in the operating room methods [5]. Because of the drawbacks of using the invasive method for measuring BP, many indirect non-invasive BP measurements have been developed. Non-invasive BP measurement techniques include Doppler, auscultation, oscillotonometry, liquid manometers, electronic systems and Pulse Transit Time (PTT) [5].

Pulse Transit Time (PTT) is the time that the blood needs to travel from one point to another in the peripheral system. These two points can be identified in different locations along the body such as ear, carotid, finger and toe. To calculate the PTT, two signals should be acquired from different locations on the body, such as ear and finger, where the PTT is the time difference between these two waveforms [6, 7]. Pulse Transit Time (PTT) received the attention of many researchers over other methods because it is a non-invasive, cuffless and continuous method for measuring and tracking the changes in Blood Pressure (BP) [3]. The main advantage of using the PTT over the traditional oscillometry methods is that PTT does not require an inflatable cuff [8]. This advantage makes the PTT method suitable for a non-invasive, continuous and wearable blood pressure measurement device.

The time difference between the *R* peak of the Electrocardiograph (ECG) and the maximum peak of Photoplethysmogram (PPG) waveforms acquired from the finger is the typical method of estimating the PTT in most researches [4, 8]. The limitation of this method is that it depends on two different signals that are collected using two different sensor types. Based on studies by Xu et al. [6], several improvements have been introduced to estimate the PTT. Two main reasons for wide use of PPG signal in the estimation of PTT is the fact due to that the PPG signal contains information regarding the heart's activities including the blood travelling through the arteries and is easy to record PPG from the body [9]. In the previous study, researchers found that PTT is highly correlated with SBP and it provides an accurate estimation of SBP, but not for DBP [10]. In addition, the relationship between the PTT and BP differs from posture to posture and from person to person [10]. In an earlier study, Zahedi et al. [11] and Sameen et al. [12]

demonstrated that PTT can be obtained from two synchronized PPG signals collected from two points on the body surface.

This paper describes the estimation of SBP from PTT taken from two PPG signals. The reason for selecting only the SBP is to show the ability of the proposed system to estimate the BP utilizing PTT from PPG signals. The paper is organized as follows: Section 2 describes PPG signals. Section 3 explains the System Identification (SI) definition and the use of system identification in this research. Section 4 details out the overall method that is used for estimating the SBP from PTT. Section 5 elaborates on the results and the discussion and finally, Section 6 presents the conclusion of the research.

2. Photoplethysmogram (PPG)

Photoplethysmography is able to capture information regarding blood volume changes in the microvascular tissues. The word photoplethysmography comes from (photo), which means optical origin, and (plethysmo), related to the volume changes of the blood. Low cost and simple optical techniques are used for detecting the PPG [13]. According to Al-Fahoum et al. [14], the PPG signal is detected by shining on the tissue using a light beam such as LED and collect the reflected light using a photodetector. The PPG waveform comprises two parts, which are AC and DC components. The AC is the pulsatile physiological waveform that represents the changes in blood pressure with each heartbeat. The AC part of the PPG waveform comprises two phases. The rising edge of the pulse, which is known as the anacrotic phase and the falling edge of the pulse, which is known as the catacrotic phase. The anacrotic phase is related to the systolic blood pressure and the catacrotic is related to the diastolic blood pressure [13]. The dicrotic notch is difficult to detect, which appears in the catacrotic phase, especially for subjects with a health condition. For that reason, most researches are focusing on the systole part of the waveform. The DC is a low varying baseline attributed to the respiration signal with a lower frequency compared to the AC signal.

As stated by Allen [13], despite its components not being fully understood, the PPG has been widely used in studies investing the cardiovascular systems because it provides valuable information. The signal has attracted the attention of many researchers in recent years because of its low cost, simplicity and ability to measure even without being in direct contact with the skin [14], where the signal has been evaluated for many clinical systems. Measuring blood pressure, measuring oxygen saturation, detecting peripheral diseases, measuring cardiac output and respiration rate are some commercial applications technologies that have been implemented based on PPG signal [13, 14].

The relationship between PTT and BP depends on the arterial walls mechanical behaviour. Moens-Korteweg equation is the basis for estimating the BP from PTT under the assumption that the artery is a passive, purely elastic tube and thin wall [15]. The equation of Moens-Korteweg is related to the Pulse Wave Velocity (PWV), where the PWV is related to the diameter of the artery (d), its elasticity (E: Young's modulus), the density of the blood (ρ), the thickness of the wall (t) and the gravitational constant (g). Equation (1) represents this relation [16]:

$$PWV = \sqrt{\frac{gtE}{\rho d}} \tag{1}$$

On the other hand, the pulse wave velocity is the distance between the two points over the pulse transit time, which leads to Eq. (2):

$$PWV = \frac{D}{PTT} = \sqrt{\frac{gtE}{\rho d}} \tag{2}$$

Later, it was found that the elasticity of the vascular wall is not a constant as it depends on the blood pressure [17, 18]. That leads to Eq. (3):

$$E = E_0 e^{\gamma P} \tag{3}$$

where E_0 is the elastic modulus at zero pressure, γ is a coefficient ranging from 0.016 to 0.018 $mmHg^{-1}$ and P *(mmHg)* is the blood pressure [17]. By applying Eq. (4), Eq. (3) can be transformed into Eq. (4):

$$PWV = \frac{D}{PTT} = \sqrt{\frac{gtE_0 e^{\gamma P}}{\rho d}} \tag{4}$$

Based on the Moens-Korteweg equation, Shriram et al. [19] developed a new system for measuring SBP from PTT. The relationship between BP and PTT is presented in Eq. (5):

$$BP = \frac{1}{\gamma}\left[\ln\left(\frac{L^2 d\rho}{E_0 t}\right) - 2\ln(PTT)\right] \tag{5}$$

By considering small changes of PTT in the range of BP changes, equation (5) can be expanded to a linear approximation as shown in Eq. (6) [18]:

$$BP = -A\,(PTT) + B \tag{6}$$

where A and B are two constants ratios for a certain patient, determined by the properties and the state of patient's vessels [18]. From Eq. (6), it can be concluded that there is a linear relationship between PTT and BP. The linear regression coefficients for SBP are [5]:

$A = 0.6524\ mmHg.s^{-1}$

$B = 207.16\ mmHg$

By applying these values in Eq. (7), the linear equation for finding SBP will be:

$$SBP(mmHg) = -0.6524PTT + 207.16 \tag{7}$$

3. System Identification

According to Rao and Unbehauen [20], system identification is an established field of control systems, using linear and non-linear models. System identification has been initially used for discrete time domain systems and recently used in continuous time domain analysis. It can be classified into three categories based on the problem characteristics: criterion, class of models and class of input signals. The system identification approach has the advantage over the traditional techniques to not requiring experiment perturbation [6].

Autoregressive Exogenous (ARX) is one of system identification approaches that is used for continuous time models. In ARX the system's output is a linear combination of input-output added to that of a prediction error [21]. The ARX model is used to build a bank of predictors from the state sequence by estimating the similarity between the input and the output signals [22]. The standard equation of the ARX system is shown in Eq. (8).

$$y(t) = \sum_{k=1}^{n} a_k y(t-k) + \sum_{k=0}^{m} b_k x(t-k) + e(t) \tag{8}$$

where a_k, and b_k are unknown parameters that define $h(t)$, the impulse response of the system, n and m represent the model order and $e(t)$ is an unobserved residual error [6, 23].

4. Methods

This section is divided into four subsections: the first section describes the data acquisition, the second shows the pre-processing on the PPG signal, the third is the application the ARX system identification to estimate the PTT and the fourth section shows how SBP is established from estimated PTT.4.

4.1. Data acquisition and experimental protocol

PPG data were collected from seventeen healthy volunteers, aged between 20-28 years in the supine position and resting condition. Two 90 seconds raw PPG signals were recorded from each subject. The record with the least amount of noise from the two recorded PPG signals was selected for further processing. The most significant challenge encountered during data acquisition was the motion artefacts because the PPG measurement is very sensitive to tissue or patient movement or the probes. The PPG data were collected simultaneously from two locations (carotid and toe) for each subject. Pulse sensors with 500 Hz sampling frequency were used to collect the PPG data. A simple in-house pulse sensor system was designed, implemented and maintained for this research. It consists of a pair of green LED light and photodetector that was implemented to work with the Arduino board [10]. PPG signal is acquired by placing the pulse sensor on the subject's artery. BP was measured from each subject using OMRON cuff blood pressure before start collecting the signals.

4.2. Preprocessing on PPG signals

4.2.1. Filtering

MATLAB was used to preprocess and analyze the signal as it offers many built-in tool boxes and algorithms. Removing the baseline from the signal is the first step of preprocessing the PPG signal by detrending it. The second step is to remove the noise that is caused by motion artifacts or any other thing. A Finite Impulse Response (FIR) bandpass filter with 50^{th} order and [0.001 Hz - 0.04 Hz] cut-off frequencies that are used to remove the very low and high frequencies that are caused by respiration. Figure 1 shows a 10 seconds typical PPG signal after detrending it to eliminate the DC component and remove the noise from the signal. The black solid line represents the PPG signal that is collected from the carotid and red dotted line signal represents a PPG signal that is collected from the toe.

4.2.2. Mirroring

The main idea is to work on only the rising side of each pulse, which is also referred as the anacrotic phase of the signal where it is the duration from the starting point to the maximum peak of the pulse, then mirroring it to get a more stable representation of the signal. Figure 2 shows one PPG pulse where (a) is showing the original PPG pulse and (b) showing the mirroring part of anacrotic PPG.

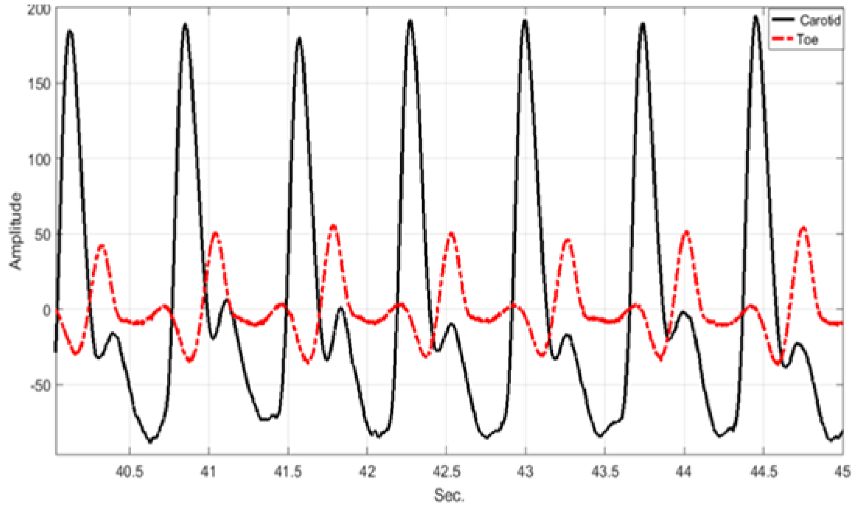
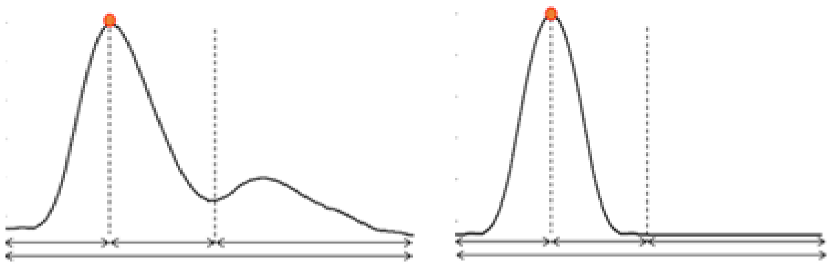


Fig. 1. Typical PPG signals.



(a) Original PPG pulse. **(b) Mirroring part of anacrotic PPG.**

Fig. 2. One pulse of PPG signal.

The determination of the starting point and maximum peak in each cycle are done by applying find peaks, which is a built-in function in MATLAB. The maximum peak of the pulse is represented by the red dot. The rising part of the PPG pulse is flipped and replaced the falling part. However, the length of the pulse does not equal to the original because of the falling part, which is also referred to as the catacrotic part is longer than the anacrotic. Thus, the rest of pulse after the flipped anacrotic signal was considered zeros until the end of the original pulse.

The full length of the new segment of PPG is determined and the length of the flipped segment is determined as well, then the difference between the two segments is calculated and normalize it to the last value of the flipped segment. Figure 2(b) shows the new PPG pulse that contains only the rising phase of the PPG. Figure 3 shows the mirrored PPG signal with a comparison to the typical signal. The modified signal will result in a more accurate estimation of the PTT using system identification.

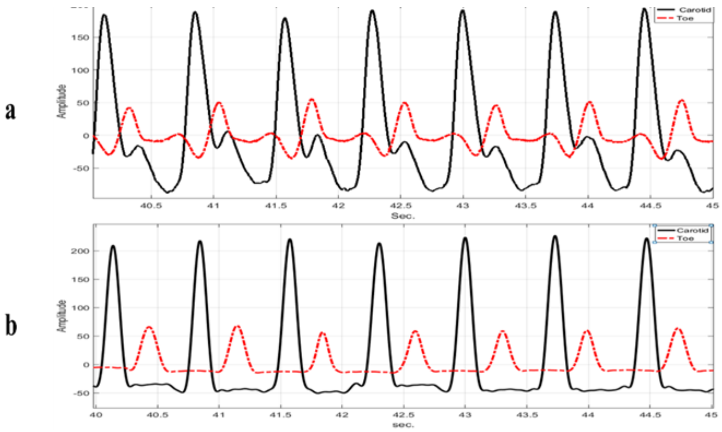


Fig. 3. PPG signals (a) before mirroring and (b) after mirroring.

4.3. System identification procedure

The mirrored rising part of the PPG signal is stable hence, will give reliable results. In our model, the carotid PPG signal is assigned as the input signal to the system, while the toe PPG signal is considered as the output to the system. An ARX model is optimally designed by trying different orders. The PTT is estimated by using the delay time between the input and output signals [12]. Therefore, the steps of calculating the PTT are:

- The carotid PPG waveform is assigned as the input $x(t)$ signal to the system.
- The toe PPG signal is assigned as the output $y(t)$ signal to the system.
- The signal is divided into 3 seconds segments and the ARX system identification is applied to each segment.
- Identify the $h(t)$, which is the step response of the system.
- According to the ARX standard equation, the step response and fitness function are calculated.
- The PTT is estimated by calculating 10% of the maximum peak of the step response [10].

5. Results and Discussions

An experimental test was executed on the PPG data collected from seventeen healthy volunteers, aged between 20-28 years in resting position. For each subject, the PTT was estimated for calculating the SBP. Figure 4 shows the correlation between the estimated PTT and the calculated SBP (SBP_{calc}) using Eq. (7).

From Fig. 4, it is noticeable that the estimated PTT and SBP_{calc} are highly correlated with R^2=0.98. In Fig. 4, not all the points appear because some subjects have the same values so that they stacked on top of each other. Table 1 shows the subject's gender, PTT, SBP measured using cuff BP measurement, SBP calculated from PTT and the relative error percentage that is calculated by using Eq. (9) [5]:

$$Error = \left|\frac{PTT\ calc - PTT\ meas}{PTT\ meas}\right| \times 100\% \quad (10)$$

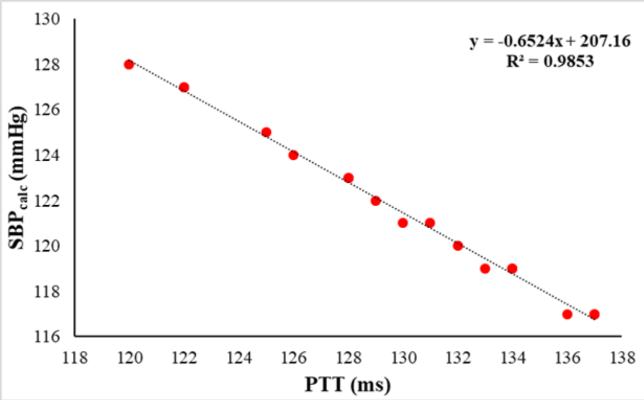


Fig. 4. Correlation of PTT and *SBP*$_{calc}$.

Table 1. Comparison between calculated SBP from PTT and measured SBP using cuff measurement system.

Subject no.	Estimated PTT (ms)	SBP_calc (mmHg)	SBP_meas (mmHg)	Relative error (%)	Absolute error (mmHg)
S1	122	127	123	3.25	4
S2	126	124	123	0.81	1
S3	134	119	122	2.46	-3
S4	130	121	118	2.54	3
S5	120	128	125	2.4	3
S6	128	123	120	2.5	3
S7	136	117	127	7.87	-10
S8	132	120	128	6.25	-8
S9	128	123	129	4.65	-6
S10	137	117	118	0.85	-1
S11	125	125	129	3.1	-4
S12	129	122	128	4.69	-6
S13	134	119	115	3.48	4
S14	131	121	120	0.83	1
S15	137	117	122	4.1	-5
S16	122	127	132	3.79	-5
S17	133	119	124	4.03	-5

Table 1 shows that the calculated SBP (SBP_{calc}) is close to the measured SBP (SBP_{meas}) with an absolute mean error of 3.39. The results show the robustness of the proposed method for measuring an accurate SBP depending on estimated PTT from PPG signals using ARX system identification. The proposed method gives very close results compare to the most commonly used method for estimating the PTT, which is the time interval between the *R* peak of the ECG and the maximum peak of the PPG [3, 5]. The advantage of using the proposed method over the ECG-PPG method is it depends on two PPG signals, which means same sensors are used for data acquisition with same properties and preprocessing steps rather than using two different sensors for detecting the ECG and PPG with different wavelength and properties. This advantage will pass the needs for calibrating the signals.

For further validation, this technique should be evaluated and tested on a bigger number of the subject population including normal subjects and hypertensive subjects with larger age variation and for future work, a suitable solution should be investigated for DBP calculation. The main limitation of the study is the inability to calculate the DBP. As DBP is an important clinical measure. Another limitation is the study was only tested on a small number of subjects who are healthy and young.

6. Conclusion

PPG signals have been reported as being able to be used to determine many cardiovascular parameters and arterial stiffness. In this paper, a new method has been described and investigated to estimate the pulse transit time from the rising part of the PPG signal using ARX system identification approach. The estimated PTT has been utilized for calculating the systolic blood pressure. A comparison was done between the calculated SBP and measured SBP using a cuff measurement system to validate the results. The comparison shows that the calculated results are good and in the accepted range of SBP with a relative mean error of 3.39%.

Nomenclatures

A	Constants ratios for a certain patient
a_k	Unknown parameters
B	Constants ratios for a certain patient
b_k	Unknown parameters
d	Diameter of the artery
D	Distance between two points
E	Young's modulus
$e(t)$	Unobserved residual error
E_0	Elastic modulus at zero pressure
g	Gravitational constant
$h(t)$	Impulse response of the system
m	Model order
n	Model order
P	Blood pressure, $E = E_0 e^{\gamma P}$
t	Thickness of the wall

Greek Symbols

γ	Coefficient ranging from 0.016 to 0.018 $mmHg^{-1}$
ρ	Density of the blood

Abbreviations

ARX	Autoregressive Exogenous
BP	Blood Pressure
DBP	Diastolic Blood Pressure
ECG	Electrocardiograph
FIR	Finite Impulse Response
PPG	Photoplethysmography
PTT	Pulse Transit Time
PWV	Pulse Wave Velocity
SBP	Systolic Blood Pressure
SI	System Identification

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