Non-invasive Blood Pressure Estimation Using Phonocardiogram

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Abstract—This paper presents a novel approach based on pulse transit time (PTT) for the estimation of blood pressure (BP). In order to achieve this goal, a data acquisition hardware is designed for high-resolution sampling of phonocardiogram (PCG) and photoplethysmogram (PPG). These two signals can derive PTT values. Meanwhile, a force-sensing resistor (FSR) is placed under the cuff of the BP reference device to mark the moments of measurements accurately via recording instantaneous cuff pressure. For deriving the PTT-BP models, a calibration procedure including a supervised physical exercise is conducted for each individual. The proposed method is evaluated on 24 subjects. The final results prove that using PCG for PTT measurement alongside the proposed models, the BP can be estimated reliably. Since the use of PCG requires a minimal low-cost hardware, the proposed method enables ubiquitous BP estimation in portable healthcare devices.

Index Terms—cuff-less blood pressure, phonocardiogram (PCG), pulse transit time (PTT), pulse arrival time (PAT), mobile health (mHealth)

I. INTRODUCTION

Hypertension is one of the main reasons that increases the risk of cardiovascular diseases. Prevalence of raised blood pressure (BP) among adults is 26.4 percent for men and 23.1 percent for women worldwide and it is more pronounced in low-income countries [1]. BP is a periodic signal with the heart rate frequency and defined as the pressure applied on the vessel walls when the blood circulates throughout the body. The upper limit of BP is called systolic blood pressure (SBP) and its lower limit is called diastolic blood pressure (DBP).

Currently, auscultatory and oscillometry are the most common approaches for non-invasively BP measurement. However, these two methods require the use of a inflating cuff around the arm, which causes inconvenience for patients and also does not allow continuous BP monitoring. Therefore, since the patient's BP may change over time due to various mental or physical factors, a cuff-less non-invasive method, which can monitor BP continuously, would be desirable.

Various research efforts have been performed trying to provide methods for cuff-less and continuous BP measurement, among which using cardiovascular surrogate parameters, especially the pulse wave velocity (PWV), is the most common approach. In fact, PWV is the velocity of a pressure wave

The collected data set can be accessed using the following url link: www.kaggle.com/mkachuee/noninvasivebp.

propagation in vessels and can be estimated by the time that it takes for the pressure wave to travel from one point of the arterial tree (proximal point) to another one (distal point) within the same cardiac cycle. This time interval is called pulse transit time (PTT).

The main principle behind using PWV for BP estimation is that the blood flow in the arteries can be modeled as the propagation of pressure waves inside elastic tubes. According to [2], by assuming vessels like elastic tubes, the following formulation for PTT can be derived:

$$PTT = l \sqrt{\frac{\rho A_m}{\pi A P_1 [1 + (\frac{P - P_0}{P_1})^2]}},$$
(1)

where P is the fluid pressure (here BP), ρ is the blood density, A is the vessel cross section and P_0 , P_1 and A_m are individual-specific physical parameters. According to (1), the exact relation bewteen BP and PTT depends on the physical properties of the vessels and blood. Therefore, a calibration procedure is required for each individual to approximate this relation.

By solving (1) for *P*, BP can be written as a function of PTT:

$$BP = a_0 + \sqrt{a_1 + a_2 \frac{1}{PTT^2}},$$
(2)

where a_0 , a_1 , and a_2 are constant coefficients, which are functions of the individual-specific parameters of (1). (2) can be approximated by the following formulation:

$$BP = b_0 + b_1 P T T^{-1}, (3)$$

which describes a simple model for estimating BP. In this paper, the PTT-BP relation in (3) is used for the estimation of individual's BP. In order to fit this model, a linear regression with mean squared error cost function is used to calculate the subject-specific parameters of the model.

Futhermore, the majority of research papers in literature, exploit the electrocardiogram (ECG) and the photoplethysmogram (PPG) for the PTT calculation [3], [4]. In fact, using these two signals provides another cardiovascular parameter, which is called pulse arrival time (PAT) instead of PTT, where PAT includes pre-ejection period (PEP) in addition to PTT. Although PTT is related to BP, PEP can be affected by some factors other than variations in BP like myocardial contractility [5]. Furthermore, acquiring ECG signals requires the attachment of electrodes on the skin, which is inconvenient.

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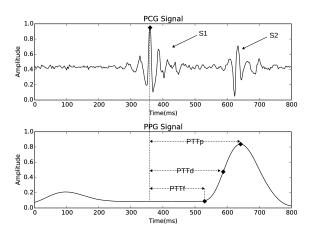


Fig. 1: Variations of PTT values corresponding to different characteristic points on PPG.

As an alternative, in this paper, it is proposed to use phonocardiogram (PCG) instead of ECG for the proximal timing reference for PTT measurements. Basically, PCG is produced due to the opening and closing of heart valves. There are two dominant types of sounds in each cardiac cycle, which are known as S1 and S2. PCG S1-peak, instead of ECG R-peak, can be considered as the proximal timing reference for measuring PTT, as it physically represents the moment that blood leaves the heart and thus it is able to eliminate electromechanical delay of the ECG. Therefore, it can exclude PEP from the measurements to some extent. For the distal timing reference, a characteristic point on PPG, in the same cardiac cycle as the selected proximal point, is considered. This point could be either the point where PPG starts to rise in each cardiac cycle, or the point where the slope of PPG reaches its maximum, or the peak of PPG. PTT values corresponding to these points are called PTT_f , PTT_d and PTT_p , respectively (see Fig. 1). Using PCG is very desirable as it requires a simple circuitry to be acquired (e.g. a microphone circuitry).

II. DATA COLLECTION METHODOLOGY

A. Hardware Setup

The hardware setup used in this work, consists of a data acquisition board that is designed in our team, a portable computer, and a commercial BP monitor. The board is responsible for acquiring the vital signals (i.e. PCG and PPG) as well as the signal from a Force Sensing Resistor (FSR). The signal recording is performed synchronously from three separate channels at the fixed sampling rate of 1KHz. The board is connected to the portable computer via Universal Serial Bus (USB) protocol and transfers data frames of 1-second length (see Fig. 2). Moreover, a software is developed for the computer, which is responsible for saving the time series data from the channels and reference BP values.

In this setup, reflection PPG using 530 nm (green) wavelength was captured from the finger of the subject in the left hand. For PCG, a electret condenser microphone, which is connected to a diaphragm by means of a hollow tube was used. The diaphragm was placed on the subjects chest

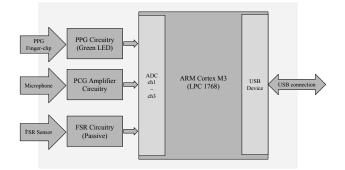


Fig. 2: Block diagram of the sampling hardware device.

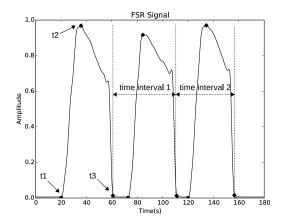


Fig. 3: The key moments on the FSR signal. Time intervals corresponding to t_3 moments are indicated.

and its location was fixed with a chest belt. Reference BP measurements during the calibration procedure, were taken from upper arm in the right hand with a digital automatic BP monitor (Model M3, OMRON, Japan). FSR was placed under the inflatable cuff in order to measure the instantaneous applied pressure by the cuff. As the cuff inflates and deflates, using FSR is an effective and novel approach to distinguish the reference BP measurement time instances during the signal recording.

B. Data Acquisition Procedure

In total, 24 healthy subjects in the age range of 21-50 years were included in our experiments. For perturbing BP for the calibration procedure, all the subjects underwent a same supervised physical exercise (running about 3 minutes at 8 km/h). This physical exercise would cause their BP to rise in a discernible way. Immediately after the exercise, the subject would sit upright and the data collection process starts. During data collection, the subjects were told not to speak and remain stable. For each subject, several reference BP measurements were taken. Since each subject sits during the data collection after the exercise, the measured BP is generally decreasing through the measurements.

Signal	Filter	Low	High	Order
Name	Туре	Cutoff	Cutoff	
FSR Signal	IIR, Low-Pass	0.3Hz	-	3
PPG	IIR, Band-Pass	0.5	20	3
PCG	IIR, Band-Pass	20	240	3

TABLE I: Filter Specifications

III. PROCESSING PIPELINE

A. Preprocessing

For the preprocessing purpose, at first, all four signals are filtered using median filtering to remove the impulsive noise. Afterwards, a statistical normalization is applied to each of the signals. At the end of this stage, frequency selective filtering is done on normalized signals. The filter specifications for each of the acquired signals in the data collection phase are represented in Table I.

B. PTT Measurement and Post-Processing

At first, all the signals are divided to time intervals corresponding to the reference BP measurements. In each measurement of BP using the automatic BP monitor, there are three key moments: the moment that cuff inflation starts (t_1) , the moment that cuff deflation starts (t_2) , the moment that cuff deflation ends and measured SBP and DBP values are read by the automatic BP monitor (t_3) . These moments can be detected with the aid of the FSR signal, as it indicates instantaneous applied pressure by the cuff. The middle of consecutive t_3 values are used to divide the two main signals (i.e. PCG and PPG) to the desired time intervals (see Fig. 3).

PTT values corresponding to each of reference BP measurements are calculated from corresponding time intervals. An averaging is done on the extracted PTT values in each of the time intervals to provide one PTT value for each of the reference BP measurements in each time interval. Here, a weighted averaging is used in a way that puts more emphasis on PTT values closer to t_3 moments, since these moments indicate time instances when reference measurements are read.

IV. RESULTS AND DISCUSSIONS

For testing the models for each subject, leave-one-out separation of the dataset to train and test sets is employed. It is ensured that there is no overlap between the train and test data. Table II presents the performance of the proposed method. Criteria for performance evaluation are mean absolute error (MAE), standard deviation (STD) and correlation coefficient (r) of the estimation.

According to Table II, the estimation of the model when PTT_f is used for PTT measurements is not as accurate as estimation using PTT_d or PTT_p , where these two performs approximately the same for both SBP and DBP estimation. In this paper, PTT_p is used for PTT measurements for the sake of the evaluation of results.

The estimation versus target regression plots are presented in Fig. 4. The r value, for SBP and DBP estimations, calculated for the data of all 24 subjects, are 0.84 and 0.86, respectively.

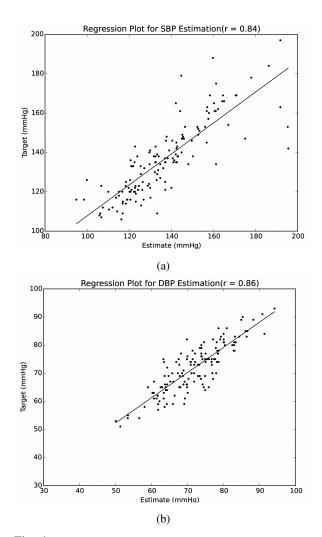


Fig. 4: Regression Plots for (a) SBP Targtes and (b) DBP Targets.

The achieved results prove that a strong correlation exists between estimation and target values for both SBP and DBP.

Fig. 5 demonstrates the Bland-Altman plots for estimations. Based on Fig. 5, a large range of target values can be estimated with low errors (ranges for SBP and DBP targets are [106 mmHg , 197 mmHg] and [51 mmHg , 93 mmHg], respectively). Also, the limits of agreement (mean $\pm 1.96 \times STD$) are indicated, i.e., $0.16 \pm 1.96 \times 11.08$ mmHg for SBP and $0.04 \pm 1.96 \times 4.53$ mmHg for DBP.

A. Comparison with Other Works

Table III presents a comprehensive comparison between the performance of the proposed method in this paper (using PTT index) and a number of other works in literature, which use PAT or PTT to estimate BP. According to this table, in comparison with the methods which use alternatives other than PCG (e.g. ballistocardiogram (BCG) [7]) to measure PTT, the results for this work are more promising (r = 0.84 versus r =0.70 for SBP estimation). The r value obtained in this work for the estimation of SBP, is close to the r value obtained in other works using the PAT index for the estimation of SBP (e.g., r = 0.87 in [6] and r = 0.83 in [3]). What is

		SBP (mmHg)			DBP (mmHg)			
		MAE	STD	r	MAE	STD	r	
Γ	PTT_f	10.33	14.94	0.71	4.40	5.67	0.78	
	PTT_d	7.37	11.09	0.84	3.68	4.68	0.85	
	PTT_p	7.47	11.08	0.84	3.56	4.53	0.86	

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Work	Number of	Estimation M		nation Methodology	SBP (mmHg)		g)	DBP (mmHg)		g)
	Subjects	Signals	Index	Calibration Interventions	MAE	STD	r	MAE	STD	r
This Work	24	PCG & PPG	PTT	Running Exercise	7.47	11.08	0.84	3.56	4.53	0.86
[6]	14	ECG & PPG	PAT	Treadmill Exercise	-	5.3	0.87	-	2.9	0.30
[3]	63	ECG & PPG	PAT	Cycle Ergometer Exercise	-	10.10	0.83	-	-	-
[7]	15	BCG & PPG	PTT	Deep Breathing + Sustained Handgrip		8.58 1	0.70		5.81 ⁻¹	0.66

¹ Approximated from the corresponding Bland-Altman plot.

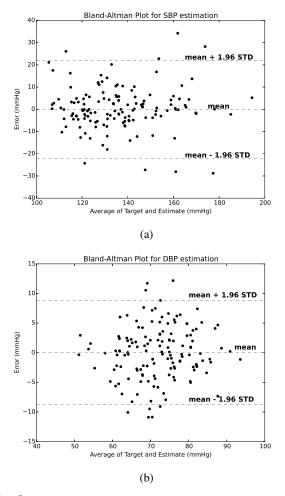


Fig. 5: Bland-Altman Plots for (a) SBP Targtes and (b) DBP Targets.

worthy to be mentioned is the fact that DBP estimations in this paper, have encouraging accuracies compared to other studies (by comparison of r values). This fact is more pronounced when we consider the fact that in many studies in literature, correlation coefficients associated with DBP estimations are significantly less than those of in SBP estimations (see [6] and [8] for example). More importantly, the proof of the possibility of using PCG for BP estimation with comparable performance is one of the achievements of this paper.

V. CONCLUSION

In the present study, the problem of continuous and cuff-less BP estimation based on PTT was addressed. To achieve this goal, the proposed method in this paper, establishes a cuff-less BP estimation processing pipeline using vital signals such as PCG and PPG as inputs. This study showed that PCG signal can be employed for the purpose of BP estimation. This is desirable since PCG requires minimal low-cost equipment to be recorded and even commercial portable devices such as smartphones can be easily adapted for this purpose.

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TABLE II: The SBP a	nd DBP Estimation Results
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