Continuous Blood Pressure Prediction from Pulse Transit Time Using ECG and PPG Signals

Shrimanti Ghosh, Ankur Banerjee, Nilanjan Ray, Peter W Wood, Pierre Boulanger, Raj Padwal

***Abstract*— High blood pressure (BP) is the most common cause of death and disability in the world, and is the largest contributor to heart and kidney disease. Current methods of measuring and monitoring blood pressure require either invasive procedures or intermittent inflation of a cuff to restrict blood flow. Thus a non-invasive method for continuous blood pressure monitoring is needed. Pulse transit time (PTT), has been reported to be highly correlated with blood pressure but data examining the effect of posture and activity on PTT based BP estimation are very limited. In this paper, PTT was computed using the windowed correlation between ECG and PPG signals. Continuous blood pressure was estimated using a previously published linear regression model. In fourteen healthy subjects, BP was estimated using PTT in 5 different positions (recumbent, seated, standing, walking, cycling) for each subject according to a preset protocol. Accuracy was increased when sparsified, preprocessed PPG signals were used. Furthermore, the observed errors of PTT measurement were within 1% of manual PTT measurement. The Root-Mean-Squared Errors (RMSE) in systolic and diastolic blood pressure between the reference standard oscillometric cuff-based device and the estimated BP from PTT were lowest when seated or standing and highest when walking or cycling. The mean difference ±standard deviation (SD) of the difference between the PTT-based estimated systolic BP and the reference standard was 0.07±5.8 mmHg in the seated position; however, this increased to 4.4±20.9 and 10.2±16.0 when walking and cycling respectively. Therefore, PTT-based BP estimation was reasonably accurate while stationary but not during motion and further improvements in estimation are required before its use for the estimation of ambulatory BP.**

***Keywords*— Electrocardiography(ECG), Photoplethysmography(PPG), Pulse Transit Time(PTT), Blood Pressure(BP), Moving Window Maximum, Cross-Correlation.**

I. Introduction

High blood pressure is the most common cause of death or disability world-wide and a major risk factor for a number of serious diseases, including cardiovascular and kidney disease [1]. In current clinical practice, BP measurement is performed either invasively by an intra-arterial catheter or noninvasively by cuff using either oscillometric or auscultatory methods. Invasive measurement is continuous in nature but carries risk (infection, bleeding, thrombosis) and is used only for critically ill patients and not for patients with chronic hypertension. Intermittent cuff inflation, the gold standard for BP measurement in chronic hypertension, is non-invasive but does not allow for continuous blood pressure measurement [2]. Development of an accurate continuous non-invasive BP measurement technique would revolutionize hypertension diagnosis and management [3]. Recent technological advances, such as wearable sensing and smartphones, have increased the feasibility of developing a non-intrusive continuous BP monitor system [4-7].

PTT is the time that takes the pulse pressure waveform to propagate through a length of the arterial tree [8]. PTT can be defined as the time between the R-peak of the electrocardiogram (ECG) signal and the peak of the photoplethysmogram (PPG) signal, when measured within the same cardiac cycle [2] (see Fig 1). PTT has been reported to be highly correlated with BP, which raises the potential for PTT to be used for continuous BP monitoring, including for continuous ambulatory monitoring [2].

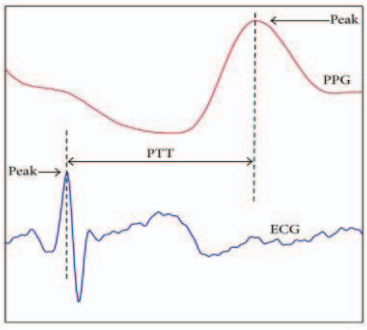

Figure. 1 Definition of Pulse Transit Time

Physiologically, PTT represents the time delay between electrical systole in the heart (i.e., the R-wave of the ECG) and the detected peripheral pulse wave (usually measured at the finger). Electrical systole occurs just before mechanical systole, in which blood is ejected from heart through the aorta to the peripheral blood vessels [10].

In this study PTT was calculated by applying a signal processing technique to the ECG and PPG signals. The accuracy of this method was assessed against the manually obtained PTT. Then the systolic blood pressure (SBP) and the diastolic blood pressure (DBP) were estimated from PTT using a linear BP-PTT regression equation [11].

Shrimanti Ghosh, Nilanjan Ray and Pierre Boulanger are with the Department of Computing Science, University of Alberta, Edmonton, Alberta, Canada (e-mail: shrimant@ualberta.ca, nray1@ualberta.ca, pierreb@ualberta.ca).

Ankur Banerjee, Peter W Wood and Raj Padwal are with the Department of Medicine, University of Alberta, Edmonton, Alberta, Canada (e-mail: abanerje@ualberta.ca, pwwood@ualberta.ca, rpadwal@ualberta.ca).

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II. METHODOLOGY

A. BioRadio Device

Real time acquisition of ECG and PPG signals was performed using the BioRadio (Great Lakes Neurotechnologies, Valley View, OH) device. The BioRadio is a wearable biomedical device with programmable channels for recording and transmitting combinations of human physiological signals. From the BioRadio, 3 channels of ECG and one channel of PPG were captured. These data were recorded by the local pod (attached to the subject) and streamed wirelessly in real-time using the built-in software BioCapture.

B. Automated Pulse Transit Time Computation

As it is compulsory to synchronize ECG and PPG correctly as shown in Fig 2(a), a customized algorithm was designed to compute PTT automatically. Once data were collected from BioRadio, they were analyzed and processed using the proposed algorithm below using MATLAB. Cross-correlation between the adjacent peak points of ECG and PPG signals in the same cardiac cycle was used to compute PTT [12]. The PPG signal was smoother than ECG signal (i.e. the number of outliers is less than that of the ECG signal). For that reason, sparsification of PPG signal was performed by computing a moving window maximum on the PPG signal. After detecting the maxima, only these maximum values of the PPG signal were used for further processing. This process converts the PPG signal into a very sparse signal (shown in fig. 2(b)) that ultimately increased the accuracy and also the efficiency (computational time) of the proposed algorithm.

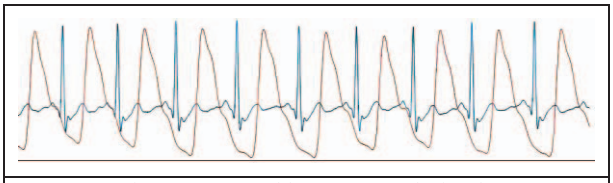

Figure 2(a). ECG(blue) & PPG(red) signals

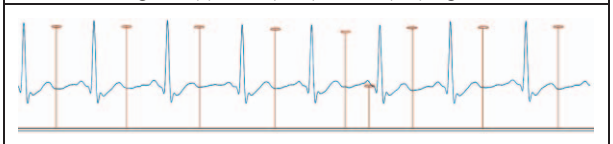

Figure 2(b). ECG(blue) & sparsified PPG(red) signals

In normal situation, for healthy subjects, the PTT value typically is 70 to 200 ms [9]. Therefore, from the automated PTT calculation, detection of abnormal cases is also possible. The algorithm is explained as follows:

Algorithm:

Step 1: Start.
Step 2: Read the ECG and PPG data and store the values into two different arrays.
Step 3: Perform Gaussian Smoothing on the two signals.
Step 4: Find the moving window maximum of the PPG signal. Retain only the maximum points of the PPG signal, making the signal very sparse.
Step 5: Compute the sliding window cross correlation between the ECG and the sparsified PPG signals. In this case, the index of maximum correlation is the required PTT value.
Step 6: Find the maximum value of cross-correlation as well as the position of the maximum correlation.
Step 7: Remove the noise in the PTT signal by using the median filter which is a non-linear digital filter.

In this way continuous PTT was computed automatically. To check the accuracy of the proposed method, the PTT values were compared to the reference standard, which was defined as manual PTT calculation (i.e. calculating the peak to peak distance of the ECG and PPG signals manually using MATLAB). The observed errors of PTT measurement were within 1% of the manual measurement. Root-mean-squared-error (RMSE) values were calculated with and without sparsification.

C. Blood Pressure Prediction

Several BP measurement methods are now available [10, 11]. In this study, BP was measured using a validated oscillometric device as the reference standard (WatchBP Office, MicroLife, Widnau, Switzerland) [13]. Oscillometric BP measurement is considered the gold standard method for the evaluation of chronic hypertension in clinical medicine [14].

I. Protocol:

During calibration process, each subject was attached to the ECG electrodes and the pulse oximeter in the seated position. By calibration, it is meant that, entering the BP that corresponds to a known PTT enables derivation of a subsequent BP when a future PTT is measured. ECG and PPG data recording and streaming from BioRadio were initiated. Four cuffed BP measurements were taken after the ECG and PPG data extraction and used for calibration.

After calibration, PTT was then calculated over 20 heartbeats - 10 beats taken immediately prior to initiating the cuffed measurement and 10 beats taken immediately after the cuffed measurement had ceased. Measurements were performed in 5 different scenarios (recumbent, seated, standing, walking at a regular pace and cycling at a comfortable pace). The proposed algorithm was used to predict BP and was compared to the actual oscillometric BP measurement.

II. Calibration:

The standard method for constructing a calibration curve or straight line from PTT to BP was employed as follows:

- Measure the PTT and cuff BP from the subject in the rest condition i.e. the normal seated position

typically used for BP measurement in the clinic to train the regression model.

- Define a mathematical model between the PTT and BP in terms of (typically) two unknown parameters that depend on subject data.
- Estimate the parameters for that subject by fitting the model to the PTT–BP measurements.

Then subsequent BP values can be calculated for each subject from the PTT, measured under different conditions (recumbent, seated, standing, walking, cycling) and compared to the cuff-based oscillometric reference standard [15, 16]. The mathematical relationship between PTT and BP has previously been studied using physical models and empirical regression models [10, 11]. Most of the physical models are based on the Moens–Kortweg and Bramwell–Hill equations, using an assumed function to relate the elastic modulus to BP [11].

Experimental studies have indeed shown that 1/PTT, rather than PTT, is linearly related to BP over a wide BP range. In this study, the linear regression model was used to predict BP continuously from PTT that is shown below:

$$BP = \frac{a}{PTT} + b \quad (1)$$

The unknown parameters a and b are subject-dependent or subject-specified parameters. A least square algorithm was applied to determine the unknown coefficients, during the calibration process. Herein the linear regression model analysis and determination of coefficients were performed separately in each subject.

III. Results and Observations

In the study, the data is taken from fourteen healthy subjects (8 women and 6 men) with no prior hypertension were studied. Baseline characteristics are summarized in Table 1.

TABLE I. Baseline Characteristics of the 14 subjects

Subject No.	Age/ Gender	Height (cm)	Weight (kg)	Calibration	
				PTT (ms)	*Measured SBP/DBP (mmHg)*
1	25/M	172.5	72.6	88	129/72
2	28/M	185.6	109.6	87	137/86
3	27/F	170.0	76.9	93	109/69
4	55/F	167.0	71.2	100	119/77
5	22/M	171.5	66.1	103	111/67
6	33/M	171.4	81.7	94	128/78
7	39/F	173.5	66.5	92	123/86
8	28/F	168.8	62.7	84	107/72
9	25/F	166.6	52.4	94	108/64
10	27/M	184.2	99.0	103	112/67
11	41/F	161.2	70.8	88	112//75
12	52/F	170.2	67.6	88	114/80
13	54/F	180.2	75.5	93	112/71
14	25/M	187.2	80.7	90	134/93

In the following Table 2 & 3, RMSE values in SBP and DBP prediction (with and without sparsification) are summarized.

TABLE II. RMSE Comparison in mmHg Between Measured and Calculated **SBP With and Without Sparsity**

	Recumbent	Seated	Standing	Walking	Cycling
With Sparsity	8.0191	5.0637	6.1082	19.2422	17.9353
Without Sparsity	8.9083	6.5119	8.3313	20.8162	19.1278

Unit of RMSE is mmHg

TABLE III. RMSE Comparison in mmHg Between Measured and Calculated **DBP With and Without Sparsity**

	Recumbent	Seated	Standing	Walking	Cycling
With Sparsity	7.0670	6.3694	5.8375	9.6987	10.5284
Without Sparsity	9.2466	7.4087	6.1547	11.8634	11.8371

Unit of RMSE is mmHg

From the above results it is shown that the root-mean-squared error between measured and calculated SBP/DBP in case of accurate PTT computation (using signal sparsity), is less than the inaccurate PTT calculation (without using sparsity).

In the next Table 4., mean and standard deviations (in mmHg) are computed for SBP and DBP with accurate PTT values (using signal sparsity).

TABLE IV. Performance Results of Different Positions on All Subjects (Mean Value ± Standard Deviation)

	Recumbent	Seated	Standing	Walking	Cycling
SBP	4.6 ± 9.6	0.07 ± 5.8	0.7 ± 6.7	4.4 ± 20.9	-10.2 ± 16.0
DBP	6.64 ± 5.2	-2.1 ± 7.3	-4.3 ± 3.8	-2.64 ± 10.4	-3.0 ± 13.1

The Bland-Altman plots for SBP and DBP of the data are shown in Fig. 3 & 4. Data for 3 postures (seated, standing & walking) of all 14 subjects were plotted and the analysis reveals agreement limits of Mean ± 1.96 SD.

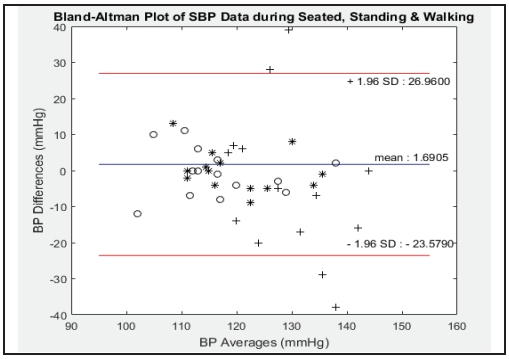

Figure 3. Bland-Altman plot of SBP of all 14 subjects obtained during seated (*), standing (o), walking (+). Limit-Of-Agreement for SBP was mean ± 1.96SD that is 1.69 ± 1.96(12.89).

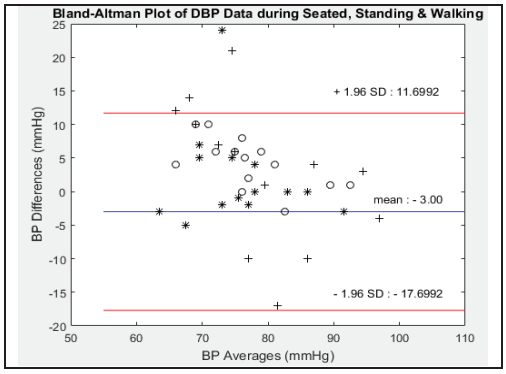

Figure 4. Bland-Altman plot of DBP of all 14 subjects obtained during seated (*), standing (o), walking (+). Limit-Of-Agreement for DBP was mean ± 1.96SD that is -3.00 ± 1.96(7.4996).

From the Bland-Altman plot analysis, it was obtained that for both SBP and DBP 8 out of 84 pairs of data points were located beyond the agreement limits (mean ± 1.96 SD).

IV. Conclusion

In this study, cuff-less, continuous BP was estimated using pulse transit time during variations in posture and activity. To show the importance of accurate PTT computation, we estimated BP with and without sparsification. Without executing the pre-processing (sparsification) of the PPG signal the acquired PTT values were not accurate. But the least square algorithm was able to predict BP with a high bias in the constants of (1). As a result, constant or average SBP and DBP values were obtained which is not admissible since BP varies and fluctuates minute to minute. Therefore, sparsification should be used when estimating BP using PTT.

The linear regression model predicted the BP from PTT comparatively better during recumbent, seated and standing positions. However, walking and cycling introduce baseline noise into both the ECG & PPG signals, making it more difficult to accurately determine the desired peaks. This limits accurate determination of BP. If we consider a difference between the experimental BP measurement and reference standard of less than 5±8 mmHg as indication of acceptable accuracy [17], then the PTT-based estimation in this study appears sufficiently accurate while seated or standing but not in other positions. One limitation of our data is that the sample size was relatively small.

Overall, PTT-based measurement shows promise in the seated or standing position but is inaccurate with movement. This inaccuracy must be addressed in future research before this technique can be considered acceptable for ambulatory BP estimation.

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