Pulse Transit Time and Pulse Width as Potential Measure for Estimating Beat-to-Beat Systolic and Diastolic Blood Pressure

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Abstract

Two cardiovascular parameters of emerging interest suitable for estimation of non-invasive, beat-to-beat, and without cuff, blood pressure parameters are pulse width (PW) and pulse transit time (PTT). In this study the performance of both parameters in estimating beat-to-beat systolic blood pressure (SBP) and diastolic blood pressure (DBP) is analyzed. The overall data set used in the study includes synchronous electrocardiogram signal (ECG), pulse photoplethysmography signal (PPG) and continuous blood pressure signal of 16 healthy subjects during tilt table test, which provokes significant changes in SBP and DBP due to postural changes.

Blood pressure was estimated using a linear model and its coefficients were calculated for each subject by linear regression using only the data of 5 beats.

Results suggest that each of these two parameters can be used to estimate blood pressure, PW is better than PTT to detect pressure variations due to postural change, but together they are a potential measure for estimating beat-to-beat systolic and diastolic blood pressure. Mean estimation error and correlation between estimated and recorded series were 2,72±9,202mmHg (2,09±8,22%) ,r=0,509 for SBP and 2,16±5,994mmHg (4,07±10,47%), r=0,504 for DBP, respectively.

1. Introduction

Methods for continuously monitoring blood pressure from other physiological parameters have been widely studied. Most of these studies correlate blood pressure (BP) with pulse transit time (PTT), based on the relationship between BP and pulse wave velocity [1, 2].

Blood pressure is often estimated by means of linear models [2, 4-6], in which the variables are the extracted parameters from ECG and PPG, representing the response of the cardiovascular system. The most used parameter is PTT, although pulse amplitude and heart rate are also used.

Other interesting parameter is pulse width (PW). Awad et al. [3] have suggested that PW is more sensitive to changes in Systemic Vascular Resistance (SVR) than other indices of pulse wave. The SVR is determined by changes in artery diameter or changes in blood viscosity. Changes in PW provide valuable evidence with respect to changes in pulse wave velocity too.

The objective of this study is to compare PTT and PW as estimators of blood pressure based on the relationship between BP and pulse wave velocity. The performance of PTT and PW in estimating beat-to-beat systolic (SBP) and diastolic blood pressure (DBP) is analyzed. Blood pressure is estimated using a linear model, which is calibrated for each subject.

2. Methods

2.1. Data sets

The database was recorded during a tilt table test from 16 volunteers (10 male), aged 28,5 ±2,5 years, according to the following protocol: 4 min in early supine position, 5 min tilted head-up to an angle of 70 and 4 min back to later supine position. Table takes 18 s to tilt during transitions.

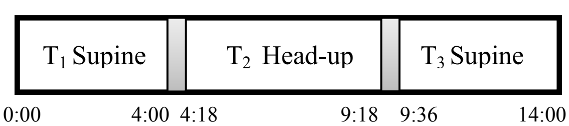

Figure 1. Tilt Test Protocol. Table takes 18 seconds to tilt during transitions, marked as filled area.

The PPG signal was recorded from index finger by Biopac OXY100C with a sampling rate of 250 Hz and the ECG lead V4 were recorded by Biopac ECG100C with a sampling rate of 1000 Hz. The BP signal was recorded with a sampling rate of 250 Hz by Finometer system.

2.2. Parameter extraction

For each beat, n, bounded by ECG R-R interval, the PTT*(n)*, PW*(n)*, SBP*(n)* and DBP*(n)* were calculated.

The ECG baseline was removed with a high pass filter with a cut-off frequency of 0,4 Hz and the 50Hz interference was attenuated with the non-linear technique used in [8]. Detection of ECG R-peak was made by an algorithm based in wavelet transform.

A low pass filter with a cut-off frequency of 35 Hz was applied to the PPG and BP signals, as well as a PPG artefact detector described in [7] to suppress artifactual PPG pulses. Points of interest in the BP and PPG signals, such as pulse and pressure apex, basal points, and onset and end pulse wave were automatically determined, as described in [8], from each beat previously detected in the ECG signal. Pulse transit time is taken as the time that elapses between an ECG R-peak and the instant when the PPG signal reaches 50% of amplitude between apex and onset points [8]. Pulse width is defined as the time between onset and end of pulse wave, it was extracted with the detector algorithm described in [8]. Parameters PTT and PW are plotted in Figure 2.

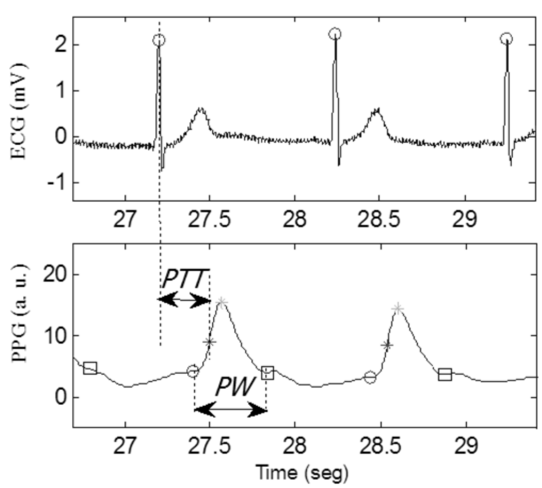

Figure2. Example of ECG and PPG signal, PTT and PW representation.

For each beat detected in the ECG, parameters PTT, PW, SBP and DBP were estimated, resulting in series $\mathrm{PTT}(n)$, $\mathrm{PW}(n)$, $\mathrm{BP}_{\mathrm{Sys}}(n)$ and $\mathrm{BP}_{\mathrm{Dias}}(n)$.

2.3. Linear models

Beat-to-beat systolic and diastolic blood pressures were estimated using the following linear models:

$$BP_a^{S,D}(n) = C_{a0}^{S,D} + C_{a1}^{S,D}\mathrm{PTT}(n) \quad [a]$$

$$BP_b^{S,D}(n) = C_{b0}^{S,D} + C_{b1}^{S,D}\mathrm{PW}(n) \quad [b]$$

$$BP_c^{S,D}(n) = C_{c0}^{S,D} + C_{c1}^{S,D}\mathrm{PTT}(n) + C_{c2}^{S,D}\mathrm{PW}(n) \quad [c]$$

Where $BP_b^{S,D}(n)$ represents the series of estimated BP, superscript refers SBP or DBP and subscript refers type model a, b or c.

Coefficients were estimated for each subject by the linear regression method, taking as reference some points in the SBP*(n)* and DBP*(n)*, respectively. Coefficients estimation were studied using different sets of reference points: a range of 25 consecutive beats extracted from T_1 Supine, T_2 Head-up, T_3 Supine and Transition positions, or 5 non-consecutive beats equally spaced extracted from: T_1 Supine, T_2 Head-up, T_3 Supine and Transition positions, or during the whole measurement interval.

2.4. Performance evaluation

To evaluate and compare the results of these models, the absolute error (e_A) and the relative error (e_R) for each beat and each subject were calculated as follows:

$$e_A{}^{S,D}(n) = \mathrm{BP}_{\{\mathrm{Sys,Dias}\}}(n) - BP^{S,D}(n)$$

$$e_R{}^{S,D}(n) = \frac{\mathrm{e_A}{}^{S,D}(n)}{\mathrm{BP}_{\{\mathrm{Sys,Dias}\}}(n)} \times 100$$

The mean of $e_A{}^{S,D}(n)$, $e_R{}^{S,D}(n)$ and standard deviation were computed for every subject, and then intersubject mean was calculated (E_A, E_R).

The linear Pearson correlation coefficient was calculated between measured and estimated BP. Additionally, p-values were computed for testing the hypothesis of no correlation against the alternative of nonzero correlation. If p value is small (less than 0,05) the correlation is significantly different from zero.

3. Results

The relationship between PTT and PW was analyzed by computing its linear Pearson correlation. Results were significant (ρ<0,05) for 14 subjects, being their correlation -0,52$\pm$0,18 (mean $\pm$ std). This means that the relationship is mainly inversely proportional, as can be clearly seen in Figure 4.

Variations in PW induced by the tilt of the table are more significant than variations in PTT, which remain more in the same range. Mean PTT at T_1 Supine and T_2 Head-up position were computed for each subject, and then their difference was calculated. The intersubject mean PTT variation between T_1 Supine and T_2 Head-up position is 2,8% of its initial value whereas the same computation for PW is 18,7%.

Global estimation results are given for the proposed linear models. Coefficients were obtained using 5 beats selected equally spaced of the whole measurement interval, these sets of reference points was the one who shows better result. The absolute error mean, its deviations, and the linear Pearson correlation between measured and estimated SBP and DBP for each model are respectively presented in table 1 and table 2.

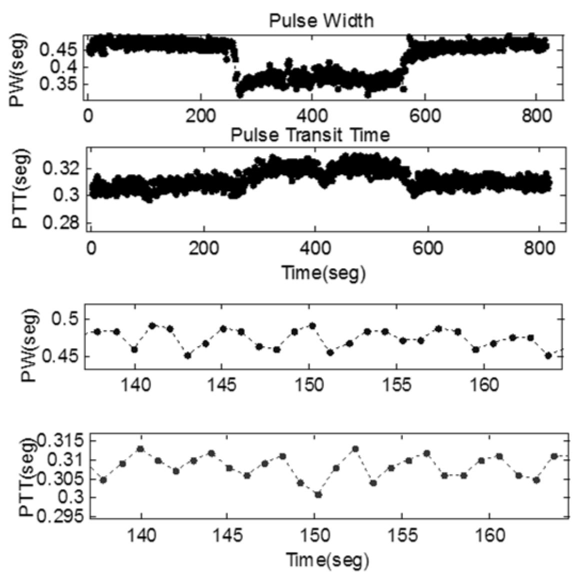

Figure 4. Subject 4 PTT*(n)* and PW*(n)* plotted above, and a closed view of 30 seconds below.

Table 1. Mean correlations between estimated and measured BP. Mean relative estimation error, Mean absolute error E_A.

Model	Correlation (*p*)	$E_R \pm Std$ (%)	$E_A \pm Std$ (mmHg)
BP_a^S	0,290 (0,000)	4,09 ±9,16	4,40±10,16
BP_b^S	0,383 (0,021)	2,60±8,09	3,25±9,47
BP_c^S	0,509 (0,000)	2,09±8,22	2,72±9,20
BP_a^D	0,240 (0,048)	4,60±10,82	2,80±6,74
BP_b^D	0,403 (0,026)	3,01±8,94	2,41±5,58
BP_c^D	0,504 (0,000)	4,07±10,47	2,16±5,99

Table 2. Mean absolute error E_A(mmHg), of VLF (0-0,04Hz), LF(0,04-0,15Hz) and HF(0,15Hz-0,4) bands.

	E_A ±std (mmHg)		
Bands	BP_a^S	BP_b^S	BP_c^S
Total	4,40±10,16	3,255±9,471	2,728±9,202
VLF	4,02±9,47	3,029±8,560	2,563±8,561
LF	0,01±3,37	0,014±4,039	0,017±3,755
HF	0,004±1,96	0,004±2,542	0,002±2,392
	BP_a^D	BP_b^D	BP_c^D
Total	2,808±6,746	2,412±5,588	2,161±5,994
VLF	2,803±5,858	2,122±4,655	2,086±4,990
LF	0,008±2,413	0,005±2,332	0,007±2,513
HF	0,003±1,531	0,003±1,551	0,003±1,789

The Association for the Advancement of Medical Instrumentation (AAMI) establishes for BP estimation that the mean estimation error should be less than 5 mmHg and the standard error must be below 8mmHg for SBP and DBP [9]. The mean absolute estimation error presented satisfies these criteria.

Figure 5 shows how the estimation with [c] model is able to follow the big pressure variations when the subject goes from one position to another, while Figure 6 shows that the estimation is able to follow the fine detail and it is better in a LF band than in others.

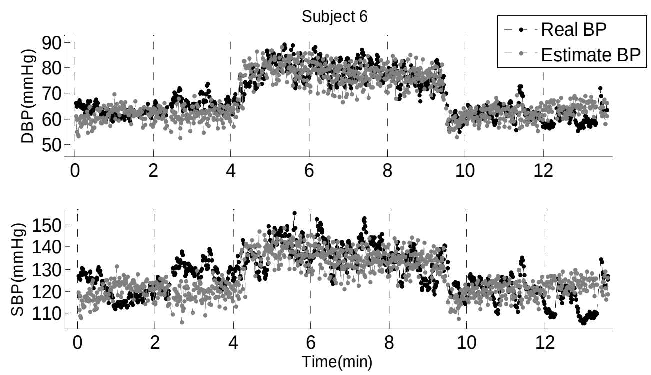

Figure 5. Measured and estimated DBP and SBP during the complete study of subject 6. The difference between the mean DBP in Supine1 and Head-up position is 14 mmHg, the same value for estimated DBP is 16mmHg.

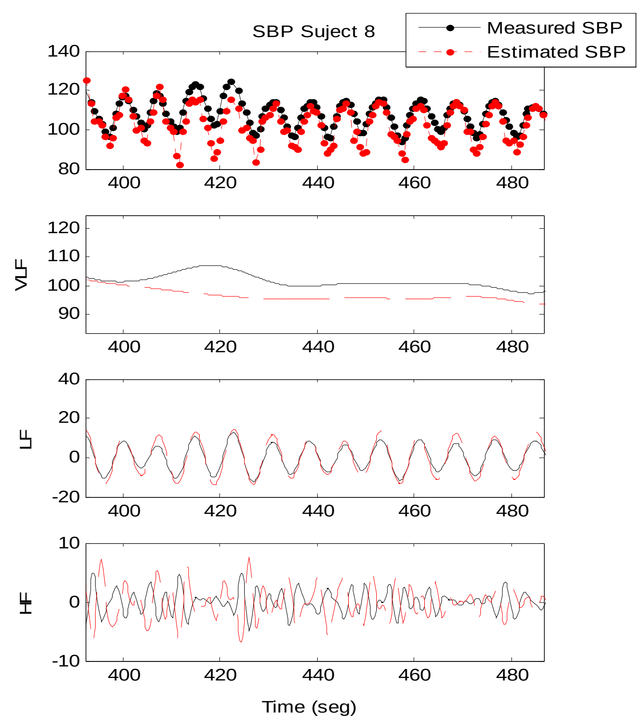

Figure 6. Measured and estimated DBP and SBP and filtered signal corresponding bands.

4. Discussion

The relationship between PW and PTT is inversely proportional in most of the cases analyzed in this study.

PTT is almost a direct measurement of pulse wave velocity while PW is affected for both pulse wave velocity and reflected wave velocity. The hydrostatic pressure change due to the change position is reflected in wave velocity. Besides, a change in SVR provokes a change in wave velocity. That is why PW is more sensitive to changes in SVR and body positions.

Different sets of reference points for coefficient estimation were studied.

For the range of 25 consecutive beats, the best moment selection is at high BP variation, like transition time. In the case of 5 beats a few subject had acceptable results in transition time selection and best general result were using non-consecutive beats equally spaced extracted from the whole measurement interval.

The selection of 5 beats is as good as the range of 25 beats. Using only 5 beats to calibrate the model is easier to implement, because it can use a simple cuff pressure measured device and a continuous pressure measured device it is not needed.

In this study, three models have been proposed which can be used for estimating SBP and DBP. PW is a better estimator than PTT. Furthermore, PW has the advantage over PTT of no needing the ECG recording. Nevertheless, estimation errors obtained from combination $BP_c^{S,D}$ are lower than those obtained from PTT $\left(BP_a^{S,D}\right)$ or PW $\left(BP_b^{S,D}\right)$ individually, and its correlation between measured and estimated BP is higher, demonstrating the advantage of combination.

Mean estimation error obtained was 2,72±9,202mmHg (2,09±8,22%) ,r=0,509 for SBP and 2,16±5,994mmHg (4,07±10,47%), r=0,504 for DBP. The estimation results are acceptable according to AAMI criteria. Both PW and PTT parameters reflect the changes in pulse wave velocity, which is an indicator of the cardiac response and artery tone. PW is more sensitive to changes in SVR. Then, combined together provide more information of the cardiovascular system and therefore there are best estimated pressure results.

5. Conclusions

PTT and PW can be used to estimate blood pressure. PW showed better performance than PTT detecting BP variations related to postural changes, and combining them represents a powerful method for estimating beat-to-beat SBP and DBP, fulfilling the AAMI criteria.

Acknowledgements

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