Noise Resistant Method for Cardiac Pulse Wave Arrival Time Estimation

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***Abstract*—Pulse arrival time is the time interval which is needed for pulse wave to travel the distance from the heart to some distal place on the body. Almost all definitions of pulse arrival time estimation are based on high quality photoplethysmogram signals. However, when subject movement is involved movement artifacts dominate in the signal, e.g., records from orthostatic test, and estimation of pulse arrival time becomes complicated. The aim of this study is to present pulse arrival time estimation method which is based on instantaneous phase shift estimation between extracted fundamental frequency components and compare it with a classical method which based on photoplethysmogram signal derivative maximum. The results showed that the proposed method is better for pulse arrival time estimation when signals are noisy. The method yielded pulse arrival time with the highest agreement, accuracy, precision and lowest variability. There is high intraclass correlation when signal to noise ratio are 0 dB and 10 dB (0.5317 and 0.8630). The classical method incorrectly estimates pulse arrival time when are using real signals. However, larger dataset is needed in order to get statistically significant results. Variability of pulse arrival time and arterial blood pressure is higher in the vertical posture.**

***Index Terms*—Electrocardiography, orthostatic test, photoplethysmography, pulse wave arrival time.**

I. INTRODUCTION

Pulse arrival time (PAT) is the time interval which is needed for pulse wave to travel the distance from the heart to some distal place on the body (e.g., finger, forehead, earlobe, toe) [1]. Measurements of PAT have several applications. The main application is estimation of arterial blood pressure (ABP), because PAT is highly related with ABP [2]. Other applications, e.g., are estimation of baroreflex sensitivity [3], cardiac output [4], respiratory rate [5], arterial stiffness [6].

Electrocardiogram (ECG) and photoplethysmogram (PPG) signals are usually used for PAT estimation. Beginning point of PAT is the ECG R wave, because the ECG signal is well known and widely used. Also ECG R wave is around opening time of the aortic valve. The end point of PAT is not defined unambiguously. There are a few local places in PPG signal wave that are used as the end point of PAT (Fig. 1) [7], [8].

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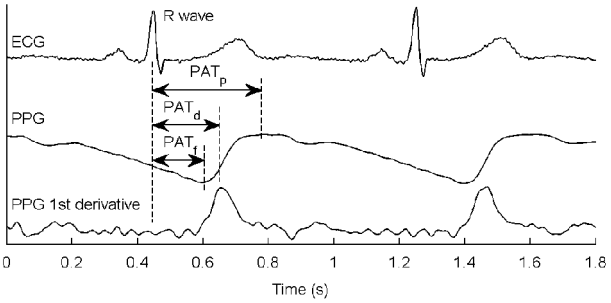

Fig. 1. Different pulse arrival time definitions: PAT_p – PAT from ECG R wave to PPG peak, PAT_d – to PPG derivative maximum, PAT_f – to PPG foot.

Almost all definitions of PAT relay on the high quality photoplethysmogram signal with clearly visible fiducial points on the PPG waveform. However, there are cases when PPG signals are noisy and this is especially visible when subject is moving. Also in some nonstationary cases PPG signal amplitude changes considerably, e.g., deep inspiratory gasp [9] or during orthostatic test (see signal example Fig. 2).

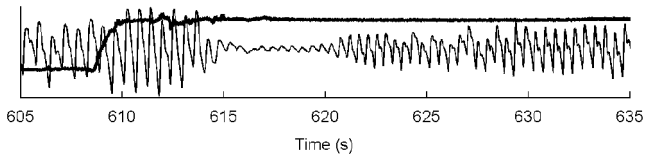

Fig. 2. Example of PPG signal amplitude changes during orthostatic test (forehead PPG – thin line, ACC (bold line) – accelerometer signal indicating change in posture of the subject).

The aim of this study is to present a PAT estimation method which is based on instantaneous phase shift estimation between extracted fundamental frequency components from multimodal cardiac signals (ECG and PPG) and to compare this method with a classical PAT estimation method based on PPG signal derivative maximum [10].

II. METHOD

Figure 3 shows block diagram of the proposed algorithm. ECG signal processing is started with noise and artifacts (muscle activity, baseline drift and other) removal by using Butterworth bandpass filter (order 4, cut off frequencies 0.4 Hz and 45 Hz). Then R waves of ECG were detected. An auxiliary signal is generated by assigning time instances of

ECG R waves with 1 and the middle of the RR interval with -1 and setting the rest of the samples to zero. A harmonic signal is synthesized by cubic spline interpolation applied to this sequence of unit pulses. Generated monocomponent signal has instantaneous frequency equal to instantaneous heart rate.

In order to extract fundamental frequency component from PPG signal, first it was filtered with the narrowband Butterworth bandpass filter (cut off frequencies 0.2 Hz–3 Hz). Then normalization of signal magnitude was performed.

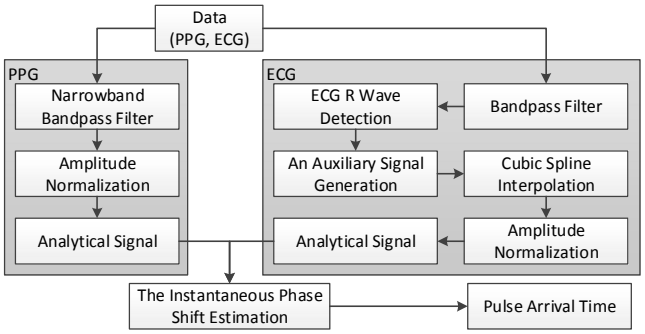

Fig. 3. Structural scheme of new PAT estimation method.

The amplitude normalization was implemented for both extracted monocomponent signals (ECG and PPG) by the iterative process consisting of Hilbert transform based signal envelope calculation followed by cubic spline interpolation between peaks and sample to sample division of the input signal by this curve. Process was repeated until amplitudes of the all signal peaks were either 1 or -1. The result of this processing is normalized "quasi" monocomponent signal with frequency equal to instantaneous heart rate (Fig. 4).

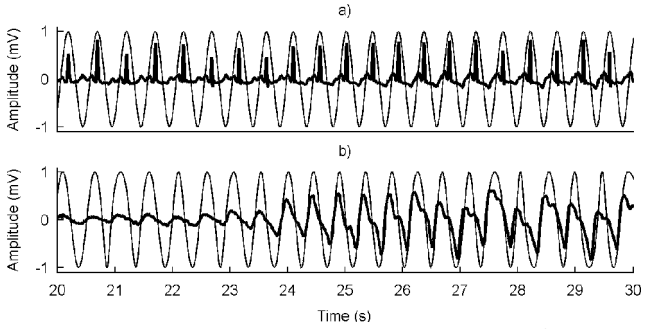

Fig. 4. Filtered ECG (a), PPG (b) (bold line) and their fundamental frequency components (v_{ECG} and v_{PPG} – thin line).

Both ECG and PPG monocomponent signals were transformed to analytic signals by using Hilbert transform:

$$v_{ECG}(t) = v_{ECG}(t) + jH\{v_{ECG}(t)\}, \quad (1)$$

$$v_{PPG}(t) = v_{PPG}(t) + jH\{v_{PPG}(t)\}. \quad (2)$$

The instantaneous phase shifts between ECG and PPG components which are equivalent to PAT evolution in time was calculated by the following relation [11]

$$PAT(t) = \frac{\Delta\varphi(t)}{2\pi} = arctg\left(\frac{\Im\left[v_{ECG}(t)\cdot v^{*}_{PPG}(t)\right]}{\Re\left[v_{ECG}(t)\cdot v^{*}_{PPG}(t)\right]}\right)\Big/2\pi. \quad (3)$$

In (3) $\varphi(t)$ is instantaneous phase shift, $v_{ECG}(t)$ and $v_{PPG}(t)$ are components of *ECG* and *PPG* analytic representation after Hilbert transform.

Statistical Analysis

Accuracy, agreement, precision and variability were used in this investigation. Mean absolute difference (MAD) is average of absolute difference. Mean difference (MD) is average of difference. MAD and MD range is from 0 to ∞. Standard deviation of mean difference (SDD) shows how much variation from the average exists. A low SD means that the data points are close to the mean, a high SD – the data points are distributed in a wide range. Coefficient of determination (CD) shows how well points of different data adapt to a line, CD ranges from 0 to 1. Coefficient of variation (CV) shows variability between different PAT (clean and noisy PPG signals). CV is as the ratio of the standard deviation to the mean [12]. Root mean square error (RMSE) shows accuracy between different PAT. RMSE range is from 0 to ∞ (lower values better accuracy). Intraclass correlation coefficient (ICC) show the assessment of agreement between two PAT estimation methods. ICC values range from -1 to 1 (0 – random agreement, -1 and 1 – perfect agreement). Limits of agreement show the precision of the PAT estimation [13].

III. DATA

A. Synthetic Signals

PPG signal was modelled as phase modulated two harmonic waves with variable period and amplitude. The heart rate was 50 bpm–90 bpm (horizontal posture) and 90 bpm–120 bpm (vertical posture). Mathematical model of acquired PPG signal

$$s(t) = A_n(t)\cdot\sin\left(2\pi f_n(t)\right) + \eta(t), \quad (4)$$

where $A_n(t)$ – nonstationary amplitude of harmonic component; n – harmonic number; $n = 1\ldots2$; $f_n(t)$ – frequency (Hz), which changes randomly from 0.83 Hz to 1.33 Hz for horizontal posture and from 1.37 Hz to 2 Hz for vertical posture, $\eta(t)$ – noise component.

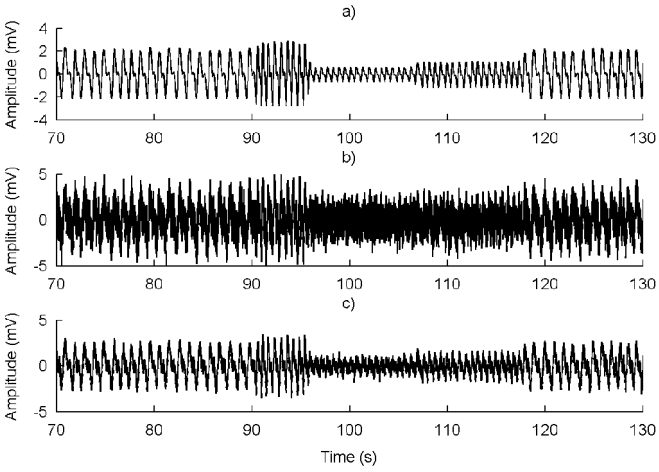

Fig. 5. Synthetic clean and noisy PPG signals: clean PPG signal (a), noisy PPG signal (SNR 0 dB) (b), noisy PPG signal (SNR 10 dB) (c).

Variations of the modelled PPG signal amplitudes are

similar to the real variations of PPG signal amplitude during orthostatic test (Fig. 5a).

ECG signal was modelled as phase modulated signal with R wave peaks (unit impulses). ECG RR interval and PPG peak to peak (PP) interval is almost equal. ECG R waves were modelled in the middle of PPG signal PP interval. PAT values are higher when the subject is lying (horizontal posture) and lower when standing (vertical posture).

The noise component $\eta(t)$ was modelled by using white Gaussian noise. Four levels of noise component were chosen in order to get signal to noise ratios (SNR) 0 dB (Fig. 5(b)), 10 dB (Fig. 5(c)), 20 dB and 30 dB. Then these noisy twenty paired (ECG and PPG) signal realizations (each 180 cycles (123.75 s– 194.75 s) were used in experiments.

B. Real Signals

Synchronous signals were acquired for 20 year old healthy female volunteer during orthostatic test which was accomplished in 3 stages: 1) 10 min. lying (horizontal posture), 2) 5 min. standing (vertical posture), 3) 5 min. lying (horizontal posture) [14].

Data were acquired by using two physiological signals recording systems. ECG, PPG and ACC (accelerometer) signals were acquired by using CARDIOHOLTER6.2-8E78 (BMII, Lithuania). PPG and ACC signals were recorded on subject's forehead. ECG signal sampling frequency – 500 Hz, PPG – 250 Hz, ACC – 50 Hz. Continuous arterial blood pressure was acquired by using a non-invasive continuous finger blood pressure measurement and recording system Portapres® Model-2 (Finapres Medical Systems B. V., Netherlands). ABP was recorded throughout the experiment (orthostatic test). ABP signal sampling frequency – 100 Hz.

IV. RESULTS

A. Synthetic Signals

Table I summarizes PAT estimation results at different noise level. High ICC values are obtained when SNRs are 0 dB and 10 dB (0.5317 and 0.8630 respectively), whereas for classical method ICC are only 0.0690 and 0.4043. Agreement of both methods is similar when SNR is 20 dB and more. The accuracy of PAT estimation by the different methods was evaluated by the mean absolute difference, mean difference and RMSE of clean and noisy PPG signal. Our proposed method was more accurate than classical method, when SNR was 0 dB and 10 dB (MAD – 49.07 ms and 23.26 ms, MD – 14.10 ms and 3.42 ms, RMSE – 66.96 ms and 34.57 ms), whereas accuracy of classical method was poor (MAD – 174.67 ms and 60.84 ms, MD – -106.85 ms and -25.52 ms, RMSE – 249.47 ms and 111.13 ms). When SNR are 20 dB and over accuracy of both methods becomes similar (Table I).

The proposed PAT showed higher precision than classical method. It can be seen from low SDD and narrow limits of agreement especially when the SNR was 0 dB and 10 dB (Table I).

Coefficient of variation estimates PAT variation between clean and noisy PPG signal. CV of PAT of the proposed method was lower than 10 %, whereas of classical method CV was bigger than 20 %, when SNR was 0 dB CV was almost 60 % (Table I).

Assessed parameters show that agreement, accuracy and precision of the proposed PAT estimation method are higher than of the classical PAT estimation method. The differences are the largest when SNRs are 0 dB and 10 dB.

B. Real Signals

Both (classical and proposed) methods were applied to real multimodal ECG and PPG (forehead) signals, recorded during orthostatic test. Figure 6 compares the classical and the proposed PAT estimation methods by showing PAT changes during orthostatic test (horizontal and vertical postures).

It can be observed that PAT values estimated by the new method are consistently higher in comparison to classical method. The reason is different definitions of PAT parameter. PAT estimated by the classical method is interval from ECG R wave to PPG derivative maximum, whereas PAT of new method is interval from ECG R wave to approximate PPG peak.

TABLE I. CORELATION, AGREEMENT, ACCURACY AND PRECISION (20 SYNTHETIC SIGNALS AVERAGE) BETWEEN PAT OF CLEAN AND NOISY PPG SIGNALS USING TWO DIFFERENT PAT ESTIMATION METHODS.

SNR, dB	Mean Absolute Difference, ms		Mean Difference, ms		SD of Mean Difference	
	Classical Method	New Method	Classical Method	New Method	Classical Method	New Method
0	174.67 ± 12.28	49.07 ± 5.69	-106.85 ± 14.72	14.10 ± 8.40	225.72	64.93
10	60.84 ± 6.28	23.26 ±3.39	-25.52 ± 9.28	3.42 ± 4.49	108.26	34.13
20	22.30 ± 1.35	10.59 ± 1.27	-4.21 ± 2.59	0.07 ± 2.63	29.67	19.87
30	13.63 ± 0.65	6.10 ± 1.42	-4.27 ± 0.84	-0.59 ± 1.46	17.01	13.52
SNR, dB	**Coefficient of Variation, %**		**Coefficient of Determination**		**Intraclass Correlation Coefficient**	
	Classical Method	New Method	Classical Method	New Method	Classical Method	New Method
0	58.38 ±3.17	9.43 ± 0.98	0.1059 ± 0.0460	0.3169 ± 0.1056	0.0690 ± 0.0428	0.5317 ± 0.0947
10	38.37 ± 3.30	8.84 ± 0.88	0.2614 ± 0.0551	0.7551 ± 0.0827	0.4043 ± 0.0693	0.8630 ± 0.0490
20	23.96 ± 0.65	9.04 ± 0.81	0.8340 ± 0.0445	0.9179 ± 0.0245	0.9078 ± 0.0269	0.9561 ± 0.0139
30	22.70 ± 0.64	9.09 ± 0.56	0.9397 ± 0.0100	0.9591 ± 0.0238	0.9670 ± 0.0046	0.9784 ± 0.0128
SNR, dB	**RMSE, ms**		**Limits of Agreement, ms**			
	Classical Method	New Method	Classical Method		New Method	
0	249.47 ± 15.65	66.96 ± 7.46	-549.26 ± 34.84	335.57 ± 25.88	-113.54 ± 17.90	141.38 ± 15.96
10	111.13 ± 15.39	34.57 ± 5.63	-237.71 ± 35.31	186.67 ± 20.93	-63.48 ± 11.54	70.32 ± 11.94
20	29.97 ± 4.41	20.03 ± 3.75	-62.37 ± 10.02	53.95 ± 7.10	-38.87 ± 7.40	39.01 ± 8.17
30	17.52 ± 1.22	13.60 ± 4.17	-37.61 ± 2.36	29.08 ± 3.07	-27.08 ± 7.66	25.90 ± 8.90

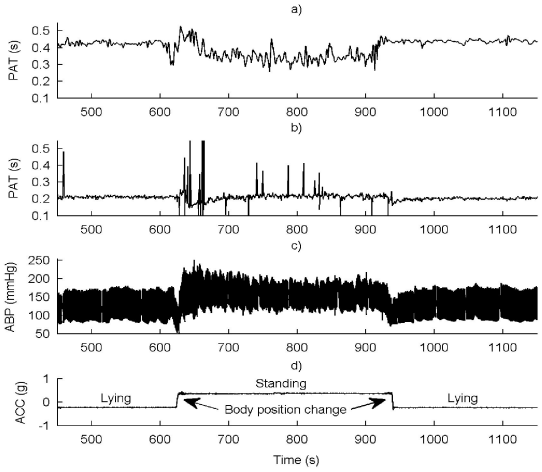

Fig. 6. PAT estimation results during orthostatic test: PAT estimated with proposed method (a), PAT estimated with classical method based on PPG derivative maximum (b), continuous ABP (c), accelerometer signal (d).

There is an interesting difference between two PAT estimation methods. Classical method results show that PAT increases when subject stands up (body position changes from horizontal to vertical) and decreases when subject lies down again while proposed method shows opposite changes. Synchronously recorded continuous ABP (Fig. 6(c)) solves this discrepancy pointing out to the proposed method as the right method to estimate PAT.

The goal of this study was to develop a reliable method for estimation of PAT in nonstationary conditions e.g., orthostatic test (posture changes). With such a method reliable PAT variability could be obtained which is important for e.g., continuous noninvasive blood pressure estimation [2] or evaluation of subjects' autonomic nervous system [15].

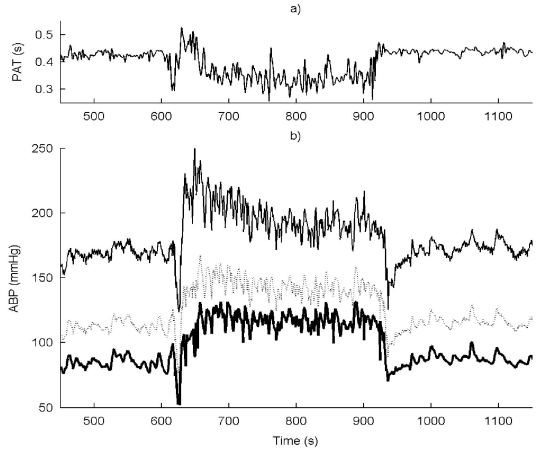

Fig. 7. Variability of PAT and ABP during orthostatic test: PAT estimated with proposed method (a), systolic ABP (thin line), diastolic ABP (tight line), mean ABP (dotted line) (b).

V. CONCLUSIONS

Results show that proposed PAT estimation method has better performance than the method under comparison at all SNR levels. The most significant improvements were observed at low SNR levels 0 dB and 10 dB e.g., mean absolute difference decreased 3-4 times, coefficient of variation 7–9 times. Thanks to the proposed method for robust extraction of fundamental frequencies from cardiac signals and averaging of phase shifts within individual heart cycles.

Opposite trends were noticed in PAT parameter evolution during orthostatic test for both methods under comparison (Fig. 6(a) and Fig. 6(b)). This controversy can be explained by taking into account biophysical Moens-Korteweg model describing relationship between arterial blood pressure and pulse arrival time where PAT has inversely proportional relation to ABP [2]. It can be concluded that the results obtained with the proposed method obey biophysical model (compare high inverse correlation between estimated PAT and systolic blood pressure in Fig. 7). These results confirm accuracy and validity of the proposed method for estimation of PAT parameter during nonstationary conditions.

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