Correlation Analysis in a Pulse Wave Velocity Evaluation

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Abstract. *In this paper, methods for a time delay evaluation of phonocardiographic (PCG) signals are presented to estimate a pulse wave velocity (PWV) in a cardiovascular system of a human body, especially in arterial segments of an arterial tree selected. A measuring method used for the pulse wave registration is fully non-invasive. Electronic phonendoscopes – pressure/acoustic converters – were used as signal transducers. The PWV estimation was carried out using correlation analysis of PCG signals, square of raw PCG signals and the first derivations of PCG signals. Signal processing, i.e. filtration, standardization, etc. was implemented in a Matlab environment using created application. A set of subjects examined in this experiment consists of five young healthy volunteers.*

Keywords

Correlation analysis, phonocardiographic (PCG) signal, pulse wave velocity (PWV), cardiovascular system, blood pressure.

1. Introduction

From the technical viewpoint, the cardiovascular system consists of two major parts: pulse pump (heart) connected to elastic tubes (arterial tree). Mechanic and geometric dynamic properties of human arterial tree, i.e. a condition of the cardiovascular system, are closely related to the pulse wave velocity (PWV) in this system [1]. The pulse wave in a systemic arterial circulation arises during a systolic phase of the heart activity, especially throughout a systole of the left heart ventricle. In the heart systole, a small blood volume of higher pressure is injected into an input artery of the systemic circulation – aorta. The process takes effect as a blood pressure increment, local arterial distension, and augment of blood velocity. These manifestations – pulse waves – take temporal effect only and have quasi-periodic character, so-called heart rate variability.

Nowadays a risk of a cardiovascular system disorder is significant; therefore a monitoring, eventually long-term monitoring, of its condition is more and more relevant. The non-invasive measuring methods are suitable for this goal especially. Commercial systems of the PWV measurement

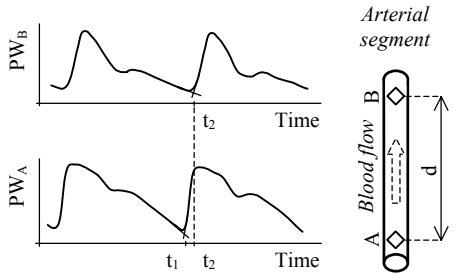

Fig. 1. Example of the time delay estimation of pulse waves. PW_A and PW_B are pressure pulse waves measured on the A and B positions, respectively, in the arterial segment; d is the length of the artery between A and B, t_1 and t_2 are positions of the PW_A and PW_B foots, respectively.

are based mainly on an evaluation of pressure curves, in other words a time distance between corresponding pressure pulses is evaluated [9, 10], as shown in Fig. 1, where the method of a signal foots (points of tangents intersections) distance is used. The position of the signal foot is minimally affected by the mechanical properties of arteries and a return blood flow. Other approach used in commercial systems is a direct measuring of a blood distribution velocity, e.g. ultrasound devices with Doppler measurement mode. A goal of this study is an implementation of another approach to a non-invasive blood PWV measurement in a human cardiovascular system and signal processing, i.e. using a phonocardiography (PCG) by phonendoscopes and following correlation analysis.

2. Measurement

In this study, the non-invasive measuring method – phonocardiography – is applied for the registration of PCG signals. Electronic phonendoscopes (sound sensors) are used as the PCG signal transducers, equipped by a band-pass filter with cutoff frequencies from 20 to 200 Hz or 20 to 2000 Hz. Selection of sensing positions on the human body is limited by the sensor type and proportions, i.e. the heart and palpable arteries, for example carotid and cubital arteries are acceptable.

Five volunteers were examined in the experiment. The set of examinants was consisted of young men aged 23.4±1.6 years. Cardiovascular disorders or disorders with

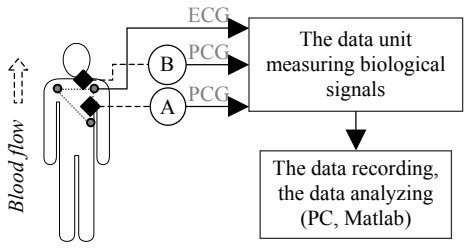

Fig. 2. The block diagram of the PWV experimental measurement, *A* and *B* are transducers (electronic phonendoscopes) complemented by the three-lead ECG.

with influence on a function to the cardiovascular system were not known in all cases. Two PCG signals were recorded simultaneously, on a heart and a left carotid artery (more details are in literature [7]), supplemented by three-lead ECG recording as shown in Fig. 2. The data preprocessing consists of PCG data filtration and the data standardization by its maximal value of each recorded signal. The filtration was implemented by a finite impulse response band-pass filter of order 500 with lower and upper cutoff frequencies at 15 Hz and 45 Hz, resp. to remove influences of other biological processes, e.g. breathing. In the experiment, the data were pre-filtered, digitized and transferred to a PC in a real-time mode. The next (off-line) data processing and analysis were implemented in Matlab.

3. Methods of the PWV Estimation

3.1 The Pulse Wave Velocity Calculation

For the pulse wave velocity (PWV) estimation, two values are needed – the length of the arterial segment d between PCG sensing positions and a time delay Δt of corresponding pulse waves as depicted in Fig. 1. Other words, time delay is the time needed for the pulse wave distribution from the first to the second sensing points. The PWV is

$$PWV = \frac{d}{t_2 - t_1} = \frac{d}{\Delta t} \ . \tag{1}$$

Distance d of measuring points can be estimated only approximately in non-invasive measurements. It was measured using a standard measuring tape. Time delay Δt estimation depends on the type of the pulse wave measuring mode chosen, as described in detail in the next chapter.

3.2 The Time Delay Estimation

The time delay estimation of corresponding pulse waves (simultaneously measured) depends on the measuring mode selected. Standard methods used in most of clinical experiments are based on the registration of changes in the arterial blood pressure [4, 12]. The example of pressure curves is shown in Fig. 1, where the time delay assessment is also denoted by intersecting tangents, i.e. positions of the pulse wave foots t_1 and t_2. Methods of the evaluation (time delay, shape of pulse, etc.) of these positive pulsating – pressure signals – are described in [2, 3, 8].

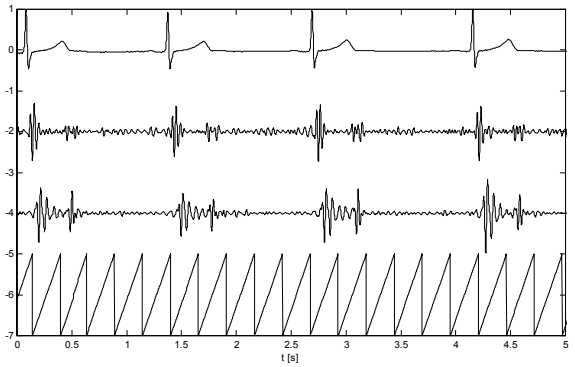

Fig. 3. Examples of signals measured. The time axis (horizontal) is graduated in seconds. The ECG signal is of the relative amplitude *-1* to *1*, the PCG ones from the heart and the left carotid artery are of the relative amplitude *-3* to *-1* and *-5* to *-2*, respectively. The last one is the parity check signal.

The measuring method used in this experiment provides PCG alternating signals in the frequency range of 20 Hz to 50 Hz approximately. Recorded PCG signals are filtrated and standardized by reason of objective mutual comparing and processing. The example of pre-processed signals is shown in Fig. 3. Because the PCG signals (Fig. 3) have other qualitative parameters, namely shape and frequency range, compared with pressure signals (Fig. 1), the same methods of the time delay estimation of the pulse wave signals cannot be used. Even though the PCG signals are not typical technical signals, i.e. they are influenced by many biological quasi-periodic and non-periodic impacts, a standard signal processing method (correlation analysis [5, 6]) to the time delay estimation was implemented. PCG signals have two typical grapho-elements, as shown in Fig. 3, the dominant one corresponds to the beginning systole of the left heart ventricle [11]. The time delay of corresponding PCG signals is determined as a position of a maximum of its cross-correlation function

$$PCG_{12}(\tau) = \frac{1}{2N} \sum_{k=-N}^{N} PCG_2(k+\tau) \cdot PCG_1(k) \ . \tag{2}$$

PCG_1 is the PCG signal from the heart, PCG_2 is the PCG signal from the carotid artery and $2N$ is the number of samples of analyzed signals (corresponding to the signal duration T in the time-domain).

The time delays Δt were determined by analyzing of three sorts of PCG signals for each examined subject, i.e. the basic PCG signal (PCG signal measured and pre-processed by filtration and standardization only), a square of PCG signal and a first derivative of the PCG signal. It means the cross-correlation analysis, as described in the equation (2), was applied in all three cases for each examined subject. In another step of the signal analysis, an effect of the selected length of analyzed signal to a variation of results (time delay Δt and pulse wave velocity PWV) was examined. The correlation analysis was implemented in all cases to 4 different lengths of analyzed PCG signals. The selected lengths were from 5 to 20 seconds (approx. 5 to 20 heart beats, respectively) with 5 seconds step, see Tab. 1.

4. Results

In this experiment three methods were implemented to estimate the time delay of the PCG signals measured on five examinants (volunteers). Afterwards, the pulse wave velocity was estimated as the time position of the maximum of cross-correlation function (2) of two corresponding PCG signals measured simultaneously (see Tab. 1). The relationship of the mean value of the pulse wave velocity and its standard deviation *PWV* ± *std* on the length of analyzed signal *T* is shown in Fig. 4 for every subject examined. The length *T* of the analyzed signal does not match exactly to the length of measured signal. The length of measured signal is cut down in the phase of signal pre-processing. Actual length is then shorter.

Subj.	T (s)	PWV (m·s^{-1})			
		Method 1	Method 2	Method 3	Mean ± std
1	20	12.1	11.5	12.1	11.9 ± 0.29
	15	11.5	11.5	11.5	11.5 ± 0.00
	10	11.5	11.5	11.5	11.5 ± 0.00
	5	11.0	11.0	11.0	11.0 ± 0.00
2	20	4.5	4.5	4.5	4.5 ± 0.00
	15	4.5	4.4	4.5	4.5 ± 0.03
	10	4.5	4.4	4.5	4.5 ± 0.03
	5	4.7	4.9	4.8	4.8 ± 0.11
3	20	3.8	3.9	3.9	3.9 ± 0.02
	15	3.7	3.8	1.0	2.8 ± 1.31
	10	1.0	1.0	1.0	1.0 ± 0.00
	5	1.0	1.0	1.0	1.0 ± 0.00
4	20	12.9	12.9	15.0	13.6 ± 1.01
	15	12.9	12.9	15.0	13.6 ± 1.01
	10	12.9	12.9	15.0	13.6 ± 1.01
	5	11.3	5.3	12.9	9.8 ± 3.25
5	20	7.1	6.5	6.5	6.7 ± 0.26
	15	7.1	4.3	6.5	6.0 ± 1.23
	10	3.0	4.3	6.5	4.6 ± 1.45
	5	3.0	4.3	6.1	4.5 ± 1.25

Tab. 1. Values of the pulse wave velocity *PWV* and its mean values with standard deviations *mean* ± *std* obtained by correlation analyses of the basic PCG signal (method 1), the square of the PCG signal (method 2) and the first derivation of the PCG signal (method 3). These methods were applied on the signal of length *T* for every subject.

An influence of the PCG signal length *T* to a dispersion of the time delay Δ*t* and pulse wave velocity *PWV* was investigated using analyzing of variance. In order to implement this analysis the mean value of Δ*t* and *PWV* was calculated for all three methods across all examinants and corresponding signal lengths, i.e. the PWV average value of the PCG signals 20 seconds long, acquired by the method 1 was computed as the mean value of corresponding pulse wave velocities of all subjects, etc. For every mean value a variance was calculated. Acquired values are presented in Tab. 2. A graph of the relationship between the variance of the average value of the time delay Δ*t* on the analyzed PCG signal length is shown in Fig. 5 for all three analysis methods. A graph of the relationship between the variance of the average value of the pulse wave velocity *PWV* on the analyzed PCG signal length is shown in Fig. 6 for all three analysis methods.

Method	T (s)	Δt (s)		PWV (m·s^{-1})	
		Mean	Var	Mean	Var
1	20	0.0396	0.0007	8.1	14.2
	15	0.0398	0.0007	7.9	13.5
	10	0.0926	0.0125	6.6	22.3
	5	0.0936	0.0128	6.2	17.6
2	20	0.0400	0.0007	7.9	13.4
	15	0.0430	0.0006	7.4	15.7
	10	0.0894	0.0127	6.8	20.9
	5	0.0934	0.0126	5.3	10.4
3	20	0.0394	0.0007	8.4	19.3
	15	0.0864	0.0132	7.7	25.0
	10	0.0860	0.0130	7.7	24.9
	5	0.0870	0.0133	7.1	18.3

Tab. 2. Values of the mean value *mean* and variance *var* of the time delay Δ*t* of corresponding PCG signals and the pulse wave velocity *PWV* across all examinants for any methods and different length *T* of analyzed signals.

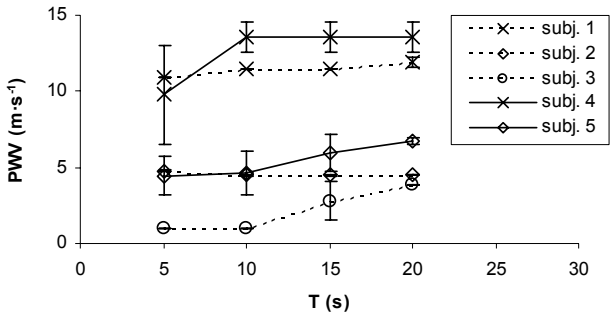

Fig. 4. The relation of mean values of pulse wave velocity (*PWV*) with its standard deviations to lengths of analyzed PCG signals (*T*) for every subject.

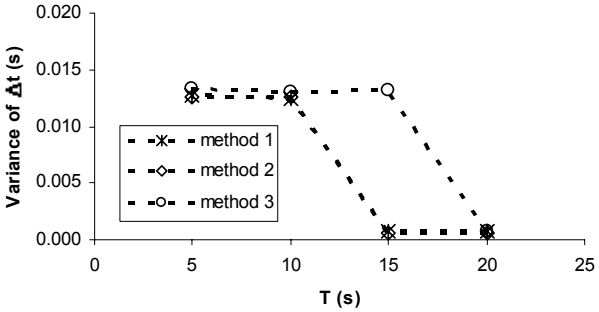

Fig. 5. The relation of variances of estimated time delays (Δ*t*) on lengths of analyzed PCG signals (*T*) for every method.

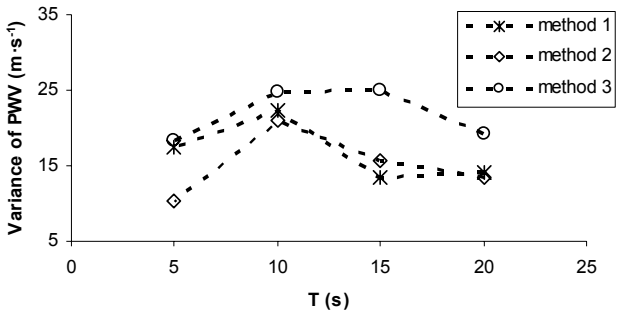

Fig. 6. The relation of variances of estimated pulse wave velocities (*PWV*) on the lengths (*T*) of analyzed PCG signals for every method.

5. Discussion

Utilization of the correlation analysis to estimate the time delay of corresponding PCG signals is convenient due to the influence of heart rate variability (HRV). HRV is a quasi-periodicity of the ECG and PCG signals caused by other biological factors. This is used with advantage in correlation analysis because secondary maxims of PCG cross-correlation function are smaller by reason of HRV (Fig. 7).

Standard for interpretation of pulse wave velocity values is not created yet. Common values of spreading velocity of pulses in the arterial tree are from 2 $m \cdot s^{-1}$ to 8 $m \cdot s^{-1}$ approx., as noted in [3] e.g. Values of the mean PWV shown in Fig. 4 can be considered as standard values only for subject 2 and 5. Values of PWV of object 1 and 4 are slightly above the upper limit, noted in [3] but not considered as standard of PWV values evaluation, as result from Tab. 1 and Fig. 4. This aberration is caused most likely by an adrenergic reaction. First three values of PWV of object 3 (Fig. 4) are below the lower limit of acceptance, but

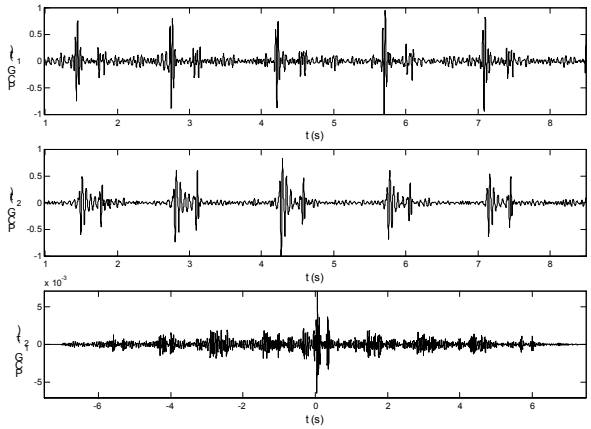

Fig. 7. A demonstration of PCG signals measured and its cross-correlation function. $PCG_1(t)$ is the PCG signal of heart, $PCG_2(t)$ is PCG signal of the left carotid artery, $PCG_{12}(t)$ computed cross-correlation function of PCG_1 and PCG_2.

wrong values of mean PWV are caused by the breakdown of some of the evaluative methods, see Tab. 1.

The other reason of the variety of PWV values is the approximate assessment of the arterial segment length. The estimation of the arterial segment length is based on the projection of known anatomical arterial tree to the body surface between measuring points. This feature influences the acquired results of PWV. One length of the arterial segment is used in whole long-term monitoring of the patient. This all cause inaccurate absolute values of PWV but enable observing the PWV trend that is major parameter of the cardiovascular system condition.

Insufficiency of some methods is caused by lower quality of measured PCG signal. As a result of the analysis of variance of the time delay Δt of PCG signals (see Fig. 5) can be concluded, that the variance has a decreasing character with the increasing length (in the interval from 5 to 20 seconds) of analyzed signal. Results of the analysis of pulse wave velocities (Fig. 6) are not so explicit. A small increasing of the variance of the PWV of method 1 is caused by computing of the PWV, because the lengths of selected arterial segments are different for every subject.

6. Conclusion

Estimation of the time delay of PCG signals, PWV especially, by the correlation analysis and the investigation of the dependence between the length of analyzed PCG signals and variance of results were the principal aim of this experiment. Five young volunteers aged 23.4 ± 1.6 years were examined. For all examined subjects there were not known diseases with any influence on the cardiovascular system or its function. Analysis of PWV variance for every method across all subjects was implemented to PCG signal of 4 lengths. As expected, using the longer PCG signals (more periods, the signal length 20 seconds seems to be sufficient, i.e. 20 periods approximately) to determine the time delay Δt led to decrease of the variance of the Δt.

Acknowledgements

The described research was financially supported by the Czech Grant Agency under grant No. 102/03/H086, by the grant No. 10/83086/13137 of the Czech Technical University, and by the research program MSM 210000012.

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