ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2012. No. 7(123)
ELEKTRONIKA IR ELEKTROTECHNIKA

SIGNAL TECHNOLOGY

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Comparison of Point-to-Point and Multipoint Human Artery Pulse Wave Transit Time Measurement Algorithms

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crossref http://dx.doi.org/10.5755/j01.eee.123.7.2384

Introduction

Pulse wave velocity (PWV) or pulse transit time (PTT) measurement is the most validated and widely accepted method and tool for the assessment of arterial stiffness and is considered as the most promising method of noninvasive continuous blood pressure measurement [1].

The pulse transit time is defined in several ways in the literature. However, in most of the works the PTT is determined by the R-wave on the ECG (electrocardiogram) and the peak of the pulse wave on finger photoplethysmography (PPG). So far, there is no well-established methodology, which aspires to a high accuracy and convenience. The proposed method is based on pulse waveform recording, which is very variable for many reasons.

One of them – selection of the physical origin of the signal recording, for example, based on the ultrasonic Doppler effect [2], the mentioned ECG-PPG (electrocardiogram- photoplethysmography) measurement system [3], various force sensors [4] and the bioimpedance method [5]. Although these methods are well known and widely used, they have some disadvantages. Doppler ultrasound device is expensive, bulky and has a lot of reflected noise. In the ECG-PPG measuring system the amount of light is variable due to uneven contact of a finger, causing inconvenience to consumers for longer use. Signal is highly dependent on temperature and the number of open capillary on the finger. The pressure sensor must firmly touch patient's body, which can also be a discomfort to users. Bioimpedance measurements, being sensitive to movements, allow to measure continuous pulse waves anywhere in the body, and the discomfort is minimal.

Many researchers use a variety of electronic and virtual filters for noise elimination that change the form of the pulse waveform and its time parameters. Because of that the ECG and PPG phase shifts can be different.

The third reason – the diversity of the selected PTT identification points. The ECG R-wave peak is beyond doubt and dispute. Some researchers measures PPT from of ECG R-wave peak to wave pulse peak [6], others - before the start of pulse wave by using tangent intersection method [7], the thirds – to a maximum gradient of the rising wave [7].

In all cases, there are physiological errors. The determined accuracy of the PTT is affected by isovolumetric ventricular contraction time (PEP), which is the time between the ECG R-wave peak and the pressure change beginning in the aorta. In this range the ventricles are shriveled but all heart valves are closed. With this method the PTT is not a real pulse wave propagation time in the arteries [8]. R wave can be just as a reference measuring time signal.

It is more appropriate to measure the PTT between the two pulse waves, one wave is recorded from the aortic arch or the carotid artery. PTT is usually measured using the ‘‘foot-to-foot’’or “point-to-point” time method from various waveforms. The ‘‘foot’’ or “point” of the wave is defined at the steep rise of the wave front begins or begin of systole. The transit time is the time of travel of pulse wave from the one ‘‘foot’’ of the wave to other “foot”. In addition, distance should be measured precisely because small inaccuracies may influence the absolute value of PTT. The shorter the distance between two recordings sites, the greater the absolute error in determining the transit time. It is reasonable to assume that accuracy will increase if the time interval between the many selected key points of waves will be measured.

The aim of our investigation is to compare the accuracy of the point-to-point (PTT) measurement methods with multipoint measurement methods.

Methods

The research was carried out with the healthy persons at their supine state. Each wave of measurement was made 3-4 minutes over a period. The ECG and two-channel electroplethysmograph was used to register pulse waves. Time constant of output with this equipment was 3s. Six electrodes were used. Two current injection electrodes were placed as following: one – above the knee and the ankle.

One pair of voltage measurement electrodes was placed around the knee and the other – in the area of tarsus. The distance between them was equal to from 32 to 40 cm (36.2 ± 2.75 cm). Signals from bioimpedance amplifier were discretized by means of 16-bit analog to digital converter with a 1 kHz sampling rate, with 450 samples set. The R-wave of the simultaneously recorded ECG was used as synchronization trigger for all signals (Fig. 1).

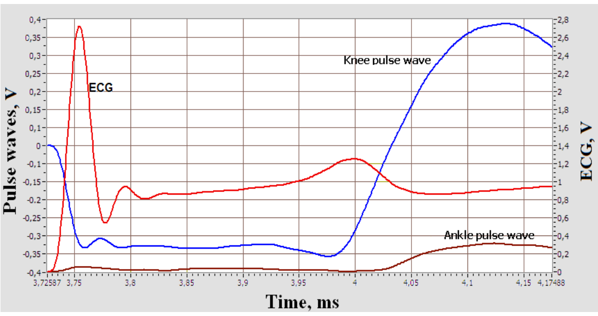

Fig. 1. Triggered ECG signal, knee and ankle Pulse wave

Algorithms for PTT estimation

All data was initially filtered by an infinite impulse response (IIR) filter with a magnitude frequency response that is maximally flat at 0 and at half the sampling frequency. Numerator order sets the IIR filter is 3, denominator 5, and cutoff frequency sets 30 Hz at which the magnitude response of the filter equals – 3 dB. First and second derivatives were computed by applying successive forward method, by the following equation

$$y_j = \frac{x_{i+1} - x_i}{dt}. \quad (1)$$

Following indicators for the PTT measurements were used are illustrated in Fig. 2.

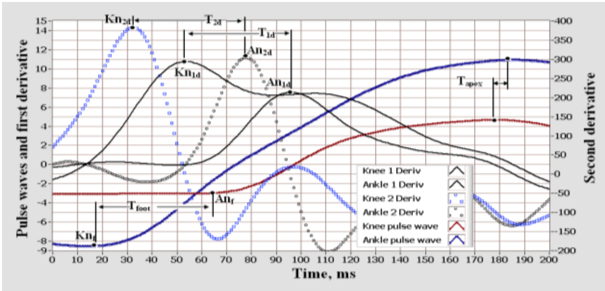

Fig. 2. Poin to point measure of time: RR_Kn_{foot}, T_{foot}, T_{apex}, T_{1d}, and T_{2d}

For the point measurement methods we assigned the following indicators (Table 1): $\mathbf{RR\_Kn_{foot}}$, $\mathbf{T_{foot}}$, $\mathbf{T_{apex}}$, $\mathbf{T_{1d}}$, and $\mathbf{T_{2d}}$. $\mathbf{T_{1d\_corel}}$, $\mathbf{T_{2d\_corel}}$, $\mathbf{T_{1d\_phase}}$, and $\mathbf{T_{footR}}$ indicators were obtained using multipoint method. As an example of multipoint we provide cross-correlation function between the two waves of the second derivative (Fig. 3). The program was created and elaborated with LabVIEW 2010. The program enables the control of the experiment and allows graphic presentation after the measurement as well as the recording of signal data into the files for the consequent calculations of PTT between the two pulse waves and statistical processing of the results.

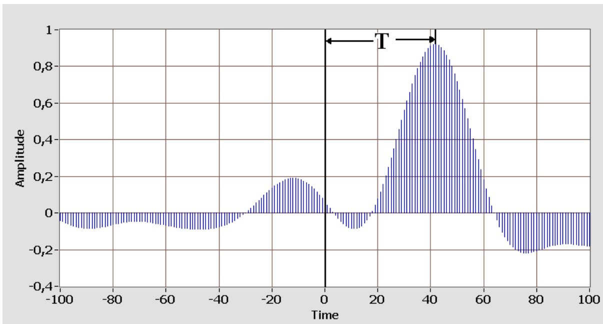

Fig. 3. Cross-correlation function between the two waves of the second derivative

For the calculation of PTT we used the points between the start of waves (foot to foot), the peak points (Peak to Peak), and integrated multipoint cross-correlation and cross-spectral methods and algorithms. Each derived variable abbreviations and explanations presented in Table 1. Descriptive statistics with SPSS software are presented including: mean, standard deviation (σ), and range. For estimation stability of data measure such as the coefficient of variation (CV = 100× σ/mean) provide an index of the dispersion of mean values between studies.

Table 1. Derived PPT variable abbreviations and explanations

RR	time between the R-waves of ECG
$RR_{\_foot}$	time from peak of EKG R wave to the beginning of pulse wave minimum from knee
T_{foot}	time between the minimum points of two pulse waves
T_{apex}	time between the peaks of two pulse waves maximum
T_{1d_corel}	time calculated using cross-correlation method between the first derivatives of both pulse waves
T_{2d_corel}	time calculated using cross-correlation method between the second derivatives of both pulse waves
T_{1d}	time between maximum values of first derivatives of fronts in both pulse waves
T_{2d}	time between maximum values of second derivatives of fronts in both pulse waves
T_{1d_phase}	time calculated between the first derivatives of both pulse waves using the cross-spectral method
T_{2d_phase}	time calculated between the second derivatives of both pulse waves using cross-spectral method
T_{footR}	Time was found between the two waves emerging at the beginning found regressive.

Results

It was investigated the 18 young people ranging in age from 18 to 25 years (21 ± 2 years). Systolic blood pressure of the subjects ranged from 100 to 155 (130 ± 15) mmHg, and diastolic 70 to 100 (82 ± 10) mmHg. During all the tests it was observed graphical window of each measurement, which was followed by three curves: ECG, pulse wave in the areas of knee and ankle (Fig. 1).

Table 2. Statistical analysis of investigated indicators

Time indicators	**Mean, ms**	**σ, ms**	**CV, %**	**CV individual**	
				Mean, %	**σ, %**
RR-interval	870	132,2	15,2	5,9	2,3
RR_Kn_{foot}	184	20,6	11,2	4,8	2,8
T_{foot}	11	26,7	251,2	17,1	130,2
T_{apex}	2	9,4	471	19,7	206,4
T_{1d}	36	5,9	**16,4**	**9,2**	**3,5**
T_{2d}	41	6,5	**16,0**	**8,4**	**2,7**
T_{1d_corel}	29	7,2	24,9	15,2	16,3
T_{2d_corel}	38	6,4	**17,0**	**8,8**	**3,4**
T_{1d_phase}	39	5,8	**15,0**	15,5	8,8
T_{2d_phase}	39	5,4	**13,9**	17,4	14,5
T_{footR}	35	6,8	**19,5**	16,2	11,2

250-300 pulse waves of the each person were analyzed continuously. Each individual data were analyzed statistically, which results are presented in Table 2. The variability of physiological processes reveals the most accurately measured indicators, namely the average standard deviation of the RR intervals (σ=132,2ms). This parameter shows that the others indicators measured for these individuals which rely on RR interval are also variable and to achieve the PTT measurement accuracy is difficult. The results showed that the lowest (from 2.7% to 3.5%) individual coefficients of variation found using three measurement algorithms/parameters (PTT): T_{1d}, (t=36±5,9ms) T_{2d} (t=41±6,5ms) and T_{2d_corel} (t=38±6,4ms). Less stable measurement was found using T_{1d_phase} (t=39±5,8ms) algorithm, even lower T_{footR}, (t=35±6,8ms) T_{2d_phase} (t=39±5,4ms) and T_{1d_corel} (t=29±7,2ms). Using point to point measurements we found that the greatest amount of PTT was when it was used the tops of the second derivatives, and the lowest in search of waves beginning with regressive method. The difference was about 6 ms.

With the multipoint method the maximum time period was found in the calculation of the phase latency between the derivatives of the waves and an exceptionally short time was observed when it was calculated the cross-correlation function between the first derivatives of the waves. The difference was about 10 ms.

The remaining algorithms showed poor results. Since PTT time parameters were different, the question arose whether this difference is crucial. In addition, according to the different distances between the measurement electrodes, to eliminate their influence the PTT data were converted into units of PWV (cm/s). Among all the PWV velocity parameters using Student t-distribution it was calculated the difference in terms of credibility with him the same and also evaluated the amount of difference (Table 3).

Table 3. PWV statistical indicators and the differences between them expressed by the Student (N=18)

	T_{1d} corel	**$T_{2d\_}$ corel**	**T_{1d}**	**T_{2d}**	**$T_{1d\_}$ phase**	**$T_{2d\_}$ phase**	**T_{foot} R**
T_{1d_corel}	0,00	5,84	5,72	6,70	6,99	6,42	4,96
T_{2d_corel}		0,00	-3,98	10,4	**1,52**	**2,12**	**-2,30**
T_{1d}			0,00	7,65	3,34	4,08	**-1,43**
T_{2d}				0,00	**-2,07**	**-2,80**	-4,10
T_{1d_phase}					0,00	**0,29**	**-2,88**
T_{2d_phase}						0,00	**-2,79**
PWV cm/s	**1292**	958	995	889	928	940	1042
σ, cm/s	253	157	150	143	114	101	177
CV, %	19,6	16,4	15,1	16,1	12,3	10,8	17,1

As can be seen from Table 2, the time interval measurement was most stable using the algorithms of the first and second order derivatives of the waves peaks, although as observed in Table 3, the average values were significantly different (t = 7.5, p <0.001). Using cross-spectral analysis calculation algorithm, the phase shift between the waves of both derivatives was obtained very stable and differed low from the other parameters, except the **T_{1d_corel}**. Also it was found the beginning of the wave (**T_{footR}**), which was identified by linear regression between the intersection of the horizontal line in the beginning of wave and the line of derivative of the rising wavefront. The time parameters found between the two minimum values of the waves in the beginning of the wave and between the two maximum peaks were very unstable and unreliable. It is clear that the distance between the measurement points is decreasing; the measurement precision must be increasing. Monitoring PWV derived units, it can be seen the big differences: from 1292cm/s to 889cm/s, while measuring the PTT the differences was only 6-10ms.

Compared with point to point method results, we can suggest that stable results are obtained when the time is measured between the waves peaks found in the first order derivative.

Multipoint methods are close to each other and the difference is the first and second order derivatives of the waves. Exceptional results shows cross-correlation function obtained from the first order derivative (PWV = 1292 cm/s). It is significantly different from all other results. Immediate results with each other is obtained when it is used the $\mathbf{T_{2d\_corel}}$ (PWV = 958 ± 157 cm/s), $\mathbf{T_{footR}}$ (PWV = 1042 ± 177 cm/s) and $\mathbf{T_{2d\_phase}}$ (PWV = 940 ± 110 cm/s) calculation algorithms.

These results shows that the second derivative (acceleration) of the pulse wave front, which is directly linked to heart used energy enables to identify velocity of the pulse wave with higher accuracy when the multipoint analysis algorithms is used.

Conclusions

Comparative analysis showed that using the different algorithms for the pulse wave analysis the results are different. Only stability of incoming parameters in dynamics lets to select several algorithms. Statistically, most stable results were achieved when the time rates were measured between maximum peaks of the wave fronts of the first and second order derivatives. Multipoint (cross-correlation and cross-spectral) analytical methods showed that accurate results can be obtained from the second-order derivatives of the pulse wave. It can be argued that the averaged results of these algorithms allow getting closer to an even more accurate value.

Acknowledgements

The authors thank the Project LLII-061 Development of Joint Research and Training Centre in High Technology Area (Latvia-Lithuania Cross Border Cooperation Programme Under European Territorial Cooperation Objective 2007-2013. Subsidy Contract No: LV-LT/1.1./LLII-061/2010/) for the possibility to complete a scientific research.

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Received 2012 03 16
Accepted after revision 2012 05 12

A. Stankus, Z. Lukosius, D. Aponkus, A. Andziulis, V. Stankus, M. Kurmis, U. Locans. Comparison of Point-to-Point and Multipoint Human Artery Pulse Wave Transit Time Measurement Algorithms // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 7(123). – P. 95–98.

The purpose of the study is to compare the accuracy of point-to-point measurement method of pulse wave propagation time from the multi-point. Electroimpedance method recorded pulse waves in the knees and ankles. Both the ECG signal and the digitized 16-bit analog-digital converter with a frequency of 1 kHz per channel. The study was conducted with 18 healthy volunteers, 20-22 years in the supine position for 3-4 minutes. With the help of LabVIEW tools created by the nine algorithms each subject were analyzed 250-300 pulse waves, highlighting the figure of the coefficient of variation. Their comparison showed that the analysis of pulse waves using different algorithms give different results. The most stable were made when times were measured between the highest peaks of the first derivatives of the forward pulse wave fronts. Similar results were found cross-correlation and cross-spectral analysis of second derivatives of the forward pulse wave fronts. It can be argued that the results of these algorithms allow the parameters obtained by averaging closer to the true results. Ill. 3, bibl. 8, tabl. 3 (in English; abstracts in English and Lithuanian).

A. Stankus, Z. Lukošius, D. Aponkus, A. Andziulis, V. Stankus, M. Kurmis, U. Locans. Tiesioginio ir daugiataškio žmogaus arterijos pulsines bangos sklidimo laiko matavimo algoritmų palyginimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 7(123). – P. 95–98.

Tyrimo tikslas – palyginti tiesioginių (point-to-point) PTT matavimo metodų tikslumą su daugiataškiais (multipoint) matavimo metodais. Elektropletizmografiniu būdu registravome pulsines bangas kelio ir čiurnos srityse. Abu signalai ir EKG kiekvienam kanalui buvo diskretizuojami per 16 bitų analoginį skaitmeninį keitiklį 1kHz dažniu. Tyrimas buvo atliktas su 18 sveikų asmenų (20–22 metų) jiems gulint 3–4 minutes. Naudojantis LabVIEW priemonėmis sukurtais devyniais algoritmais buvo analizuojamos jų kiekvieno 250–300 pulsinės bangos, išryškinant rodiklių variacijos koeficientą. Lyginamoji analizė parodė, kad pulsinės bangos analizei panaudojus įvairius algoritmus buvo gauti skirtingi rezultatai. Stabiliausi rezultatai pasiekti, kai laiko rodikliai buvo matuojami tarp priekinio bangų fronto pirmos eilių išvestinių maksimalių viršūnių. Panašūs rezultatai gauti atliekant priekinio bangų fronto antros eilės išvestinių kroskoreliacinę ir krosspektrinę analizę. Galima teigti, kad naudojant šiuos algoritmus gautų rezultatų suvidurkinimas leidžia priartėti prie tikrosios vertės. Il. 3, bibl. 8, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).