Estimation of Pulse Arrival Time Using Impedance Plethysmogram from Body Composition Scales

Birutė Paliakaitė[1], Saulius Daukantas[2], Andrius Sakalauskas[2], Vaidotas Marozas[1,2]
[1]Department of Electronics Engineering, Kaunas University of Technology
[2]Institute of Biomedical Engineering, Kaunas University of Technology
Kaunas, Lithuania
birute.paliakaite@ktu.edu, vaidotas.marozas@ktu.lt

***Abstract*—Long-term periodic monitoring of cardiovascular function in unobtrusive way has been a challenge in sensor research lately. This work presents the investigation of the method for pulse arrival time (PAT) estimation using body composition scales. It employs the electrocardiogram and the impedance plethysmogram (IPG) which are recorded from palm and plantar electrodes already integrated into body composition scales. Four subjects were involved in the experiment. The IPG was acquired from a single-foot and foot-to-foot and compared to the reference method – photoplethysmography. The range of correlation coefficient obtained in different methods varied from 0.7 to 0.94 showing that small PAT variations can be tracked using the IPG signals. Such results suggest that body composition scales could be supplemented with additional parameter for the assessment of arterial stiffness. This function will make them truly multi-parametric device for periodic health monitoring at home.**

Keywords—long-term periodic health monitoring; multiparametric sensors; arterial stiffness.

I. INTRODUCTION

Arterial stiffness is recognized as an important contributor to the development of cardiovascular diseases. Central (aortic) stiffness is highlighted because of its independent predictive value for all-cause and cardiovascular mortalities, coronary events, fatal strokes in elderly subjects and patients with end-stage renal disease, hypertension and impaired glucose tolerance [1]. Meanwhile, the importance of peripheral (especially lower-limbs) stiffness is underestimated although it is involved in the development of peripheral artery disease [2] and diabetic peripheral neuropathy [3]. Therefore it is important to include a parameter, which is capable to assess central and peripheral stiffness and at the same time which is non-invasive and convenient enough to become part of long-term periodic monitoring of patients with chronic diseases.

Such parameter could be pulse arrival time (PAT) which is defined as the time interval between the R-wave of the QRS complex in the electrocardiogram (ECG) and the particular point in the pulse pressure wave recorded at the distal artery. The length of this time interval is inversely and non-linearly related to arterial stiffness: the shorter is the interval, the stiffer are the arteries. PAT measured from the heart to the foot includes the time needed for the pulse wave to travel through two different arterial paths: one from the heart to the femoral artery (central path) and another from the femoral to the plantar artery (peripheral path). This way PAT provides information about both central and peripheral arterial stiffness.

Different types of devices (Doppler probe, tonometer, oscillometric cuff, photoplethysmographic sensor, etc.) are used to record pulse waves at the distal point of the arterial tree. Most of devices are operator dependent and the measurement results rely on the placement of the device. Therefore they are inconvenient for patients eager to perform themselves (at home) a long-term periodic measurements. The solution can be the impedance plethysmography (IPG). It is noninvasive and cheap method to determine changing local composition of tissues (e.g. local blood content) and their respective volumes in the body [4]. It uses conductive metal surface electrodes which can be integrated into unobtrusive healthcare devices, e.g. bathroom scales, and used for the measurement of several physiological parameters at the same time, e.g. total body composition or the electrical activity of the heart. Ordinary electronic bathroom scales and body composition scales have already been modified to acquire different physiological signals [5, 6, 7]. The ECG is recorded from the handlebar electrodes and the ballistocardiogram from the strain gauges. The footpad electrodes are used for the recordings of the ECG, the lower-body electromyogram (EMG) and single-foot or foot-to-foot IPG. The lower-body IPG has been used only for the heart rate detection so far [7, 8]. Meanwhile, its suitability for the estimation of PAT in scales has not been investigated.

In this study, we hypothesize that PAT from the heart to the foot can be estimated using palm ECG and the lower-body IPG recorded on the feet. The IPG signals are the sum of the local impedances of all segments between the voltage electrodes. It is expected that the influence of the lower parts of the legs on the total impedance measured between the feet is greater than that of the lower torso or thighs. This is because of smaller cross sectional area which determines greater local impedance [9]. Body composition scales with integrated handlebar and footpad electrodes for the ECG and IPG recording would become a multi-parametric system, which enables patients to perform periodical (e.g. every morning), unobtrusive measurements of PAT and other parameters related to their health status.

This paper describes technological implementation of the proposed method and primary experiments that were

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performed to compare it with the traditional method based on the photoplethysmography (PPG). Measurements of the IPG signals are carried out in two separate ways: from a single foot and between both feet – this was made in order to find the differences. We seek to demonstrate that PAT can be estimated by means of IPG measurement unit, which is integrated into body composition scales.

II. Materials and Methods

A. Measurement Setup

Commercially available body composition scales with footpad and handlebar electrodes (HBF-510, Omron, Kyoto, Japan) were used in this study. The ECG was recorded by two electrodes in the handlebar connected to the dual-channel wireless ECG transmitter (BioNomadix®, Biopac, Goleta, CA, USA). The lower-body IPG was recorded by four footpad electrodes connected to the electrical bioimpedance unit (EBI100C, Biopac) with the following settings: 400 μA_{rms} constant sinusoidal current at 50 kHz, gain of amplifier 1 Ω/V, bandwidth of demodulated signal filter from 0.05 Hz to 100 Hz. Data was acquired in two different tetrapolar electrode configurations. The first one used all four electrodes from the scales: two electrodes below the toes – to source current into the body and the other two below the heels – to measure voltage. It is called foot-to-foot measurement case. The second configuration employed only two electrodes from the scales to inject current below the toe and the heel of the same foot. The voltage was measured using two disposable electrodes, which were attached in the middle of the sole of the foot. It is called single-foot measurement case. The PPG signals were measured on the right big toe using the photoplethysmogram amplifier unit (PPG100C, Biopac).

The ECG, PPG and IPG signals were recorded at a 1 kHz sampling rate synchronously by the multichannel data acquisition system (MP150, Biopac) and stored by the included software (AcqKnowledge® Version 4.3, Biopac).

B. Subjects and Measurement Protocol

Four healthy subjects participated in the research (see Table 1). We asked each subject to stand still on the modified scales barefoot while holding the handlebar electrodes in their lowered hands. After waiting for the signal to stabilize 1 min length record was made. During inspiration effort intrathoracic pressure and stroke volume decrease, causing blood pressure to fall. These changes are followed by the successive increase of PAT (pulse pressure waves travel slower). During exhalation, the reverse is true [10].

C. Signal Processing

Signals were processed with Matlab® using algorithm shown in Fig.1. The ECG signals were digitally forward-backward filtered with the band-pass (0.7-35 Hz) filter. The IPG and PPG signals were forward-backward filtered with 8th-order low-pass (10 Hz) and high-pass (0.5 Hz) filters.

The ECG signals were rectified and smoothed with the forward-backward 16th-order moving average filter before the detection of R-waves. These characteristic peaks were found by readjusting the threshold to the signal level. According to the R-waves timing T_R the ECG signals were divided into R-wave to R-wave (RR) intervals. Afterwards the time instants of the local maxima of the first derivative of the IPG and PPG signals were defined as T_{D1} within each RR interval. PAT_{PPG} and PAT_{IPG} were estimated as the time difference between T_R and T_{D1} in the PPG and IPG signals that were obtained in foot-to-foot and single-foot measurement cases.

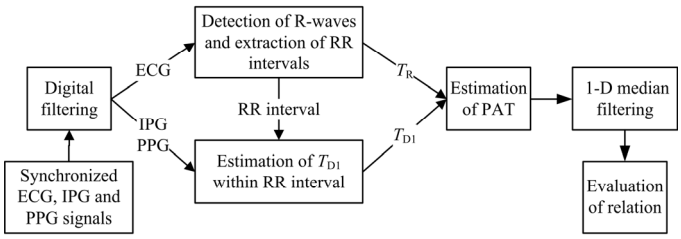

Fig. 1. Block diagram of signal processing algorithm.

Each vector of estimated PAT values was processed with an order-3 median filter to eliminate outliers. After that linear regression analysis and Pearson correlation coefficient were used to evaluate the relationship among variables PAT_{IPG} and PAT_{PPG} wave-to-wave. The mean and the standard deviation of the difference $PAT_{IPG} - PAT_{PPG}$ were calculated to assess the agreement between methods. The variations of the absolute values of PAT were also displayed in box plots.

III. Results

Examples of the acquired ECG, IPG and PPG signals in foot-to-foot and single-foot impedance measurement cases for the subject S3 are shown in Fig. 2 and Fig. 3.

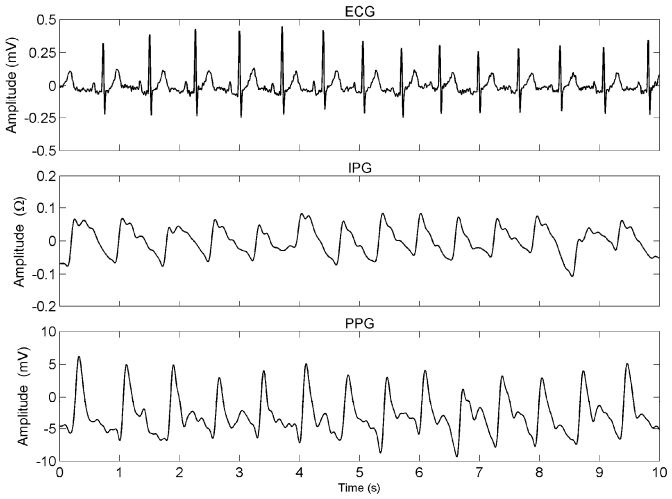

Fig. 2. Example of acquired signals in foot-to-foot IPG measurement case.

The EMG causes artifacts in all the signals. However, the ECG has the highest quality because it is recorded with the handlebar electrodes and is almost unaffected by EMG, which originates while standing. Meanwhile the quality of the IPG and PPG is lower. It is influenced by the muscle tension and stability of the lower body. The amplitude of the single-foot

TABLE I. INFORMATION ABOUT SUBJECTS AND RESULTS OF STATISTICAL ANALYSIS

Subject no.	Gender	Age	Height	BMI	Case	Correlation coefficient	Linear regression equation	$PAT_{IPG} - PAT_{PPG}$	
								Mean	*Standard deviation*
S1	F	21 yr	176 cm	18.2	Foot-to-foot	0.818	$PAT_{IPG} = 0.801 \cdot PAT_{PPG} - 18.0$	83.7 ms	7.94 ms
					Single-foot	0.895	$PAT_{IPG} = 0.992 \cdot PAT_{PPG} - 69.3$	71.9 ms	6.37 ms
S2	M	23 yr	185 cm	26.3	Foot-to-foot	0.707	$PAT_{IPG} = 0.801 \cdot PAT_{PPG} - 10.8$	76.9 ms	6.43 ms
					Single-foot	0.711	$PAT_{IPG} = 0.822 \cdot PAT_{PPG} - 0.5$	60.0 ms	7.43 ms
S3	M	32 yr	186 cm	22.8	Foot-to-foot	0.944	$PAT_{IPG} = 0.846 \cdot PAT_{PPG} - 24.8$	76.5 ms	2.86 ms
					Single-foot	0.840	$PAT_{IPG} = 1.150 \cdot PAT_{PPG} - 104$	53.4 ms	3.86 ms
S4	M	44 yr	182 cm	26.1	Foot-to-foot	0.743	$PAT_{IPG} = 1.030 \cdot PAT_{PPG} - 96.4$	89.0 ms	4.85 ms
					Single-foot	0.797	$PAT_{IPG} = 0.596 \cdot PAT_{PPG} + 50.9$	60.9 ms	5.39 ms

IPG is more than 10 times smaller than the amplitude of the foot-to-foot IPG as expected. The IPG signals measured between the feet are the outcome of the volume changes in major arteries of the feet, legs, thighs and lower torso while the IPG signals in a single foot mostly depends on the pulsation in plantar arteries.

R-waves of the QRS complexes are followed by the IPG (decrease in impedance) and PPG peaks. These peaks do not appear at the same time: the PPG is delayed because its measurement is performed at the most distal point (toe). Moreover pulse waves reach arteries (represented by the IPG) before they reach capillaries (represented by the PPG).

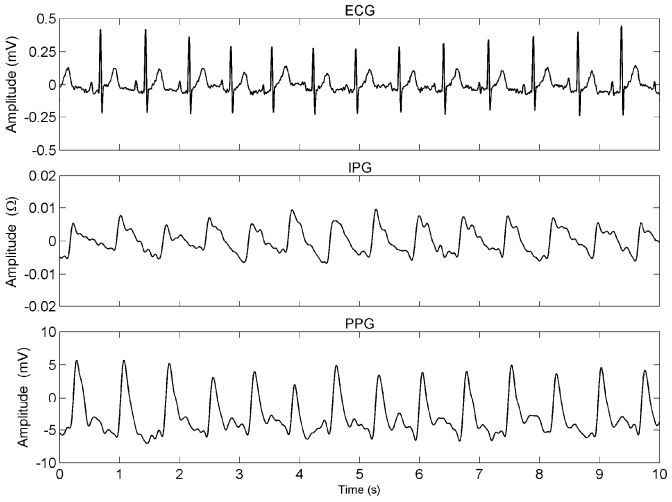

Fig. 3. Example of aquired signals in single-foot IPG measurement case.

Fig. 4 and Fig.5 present the results of the PAT evaluation in two different cases for the subject S4. Values are depicted before and after the adjustment of the median filter. The delay is evident between PAT_{IPG} and PAT_{PPG} in both cases.

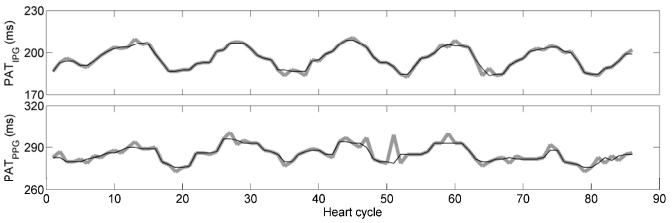

Fig. 4. Example of estimated PAT in foot-to-foot IPG measurement case (thick gray line - before, thin black line - after median filter).

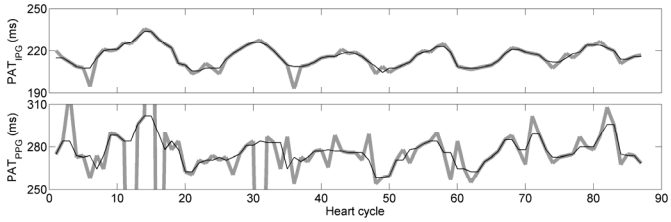

Fig. 5. Example of estimated PAT in single-foot IPG measurement case (thick gray line - before, thin black line – after median filter).

The results of the analysis performed to evaluate relationship and agreement between different methods of PAT estimation are summarized in Table 1. The correlation coefficient testifies good correlation between PAT_{IPG} and PAT_{PPG} in both cases. The difference between PAT_{IPG} and PAT_{PPG} is higher for the foot-to-foot IPG measurement. There are no consequential distinctions among these differences for the separate subjects.

The spread of the absolute values of PAT for all the subjects is illustrated in the Tukey boxplot in Fig.6. The notches of the boxes do not overlap meaning that the medians are significantly different at the 5% significance level. PATs derived from the PPG signals are higher than those derived from the IPG signals for all the subjects. Moreover, foot-to-foot PAT_{IPG} is apparently lower than single-foot PAT_{IPG}. The results of the oldest subject S4 are characterized by the lowest PAT values.

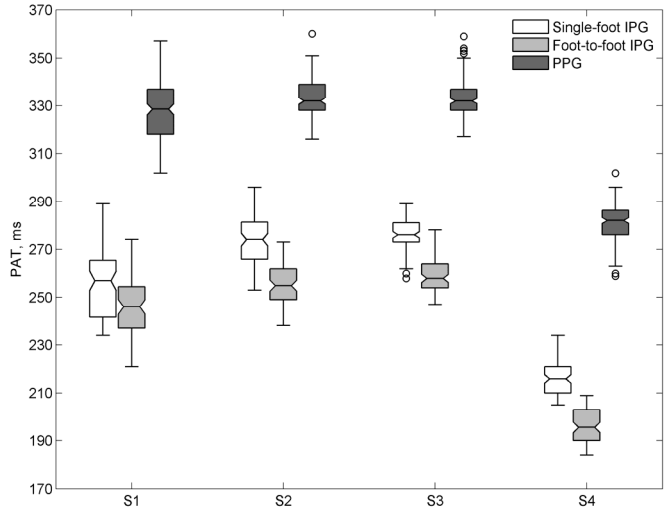

Fig. 6. The Tukey boxplot of the absolute values of PAT

IV. Discussion and Conclusions

The aim of this study was to demonstrate that PAT can be estimated by using IPG and ECG sensors, which are integrated into body composition scales. Results of the experiment showed that PAT evaluated by the method introduced here correlates with PPG-based PAT.

No significant difference in correlation was found when comparing single-foot and foot-to-foot PAT_{IPG}. However, it is evident that single-foot IPG represents more of the distant volume changes (closer to the PPG). It describes propagation of pulse wave in aorta and one leg specifically while foot-to-foot IPG depends on hemodynamics in aorta and both limbs. The peak in the IPG measured foot-to-foot appears earlier compared to the other configuration, meaning that it is determined not only by the volume changes in the plantar arteries.

PAT values for the oldest subject were the lowest, which indicates the highest degree of the arterial stiffness (Fig. 6). Ageing is closely related to the alterations in the walls of the central arteries. This preliminary findings demonstrate that the IPG signals are applicable for the evaluation of central arterial stiffness.

The suitability of the IPG for the estimation of PAT was also verified in study [11]. Upper-body peripheral PAT was assessed from the IPG and ECG signals obtained with a handheld device and compared to the PPG-based PAT. Since it is easy to apply PPG sensor on the finger and the quality of the signals is high the necessity of IPG-based upper-body PAT evaluation method is questionable. By contrast, the application of the PPG sensor on the toe or somewhere on the foot is complicated and the results highly depend on subject's motion. In this case, IPG integration into body composition scales would help to estimate lower-body PAT in a simple manner.

There are some limitations of this study and their mitigation is included into the further works. Firstly, the desirable amplitude of the IPG signals ensuring the immunity to the noise could not be obtained because the current output of the electrical bioimpedance unit was fixed to 400 μA_{rms}. This parameter is highly important to the single-foot IPG measurements. The ability to change the output current will be provided by the custom-made bioimpedance unit integrated into body composition scales. Secondly, the reliability and efficiency of the algorithm for the estimation of PAT are not maximized. It will be achieved through the development of the steps used for the detection of the characteristic points in the ECG and IPG signals. Moreover, quite a small group of the subjects determines the lack of robustness in the findings. A wider group of subjects with different health status will be included to investigate the suitability of the IPG for the monitoring of the arterial stiffness.

Furthermore, the concept of the PPG as the reference method is different from the IPG. PPG sensors, tonometers, ultrasound probes etc. record pulse pressure wave at the precise point enabling accurate measurement of the distance which is traveled by the pulse wave. The average absolute value of pulse wave velocity as a marker of arterial stiffness can be calculated and compared to the normal range. Meanwhile, the IPG represents the volume, so the true point of the measurement site remains conditional or unknown. The estimation of the average absolute value of pulse wave velocity is restricted but the variation is precisely measured. The main idea of the long term monitoring is the tracking of the changes in parameters defining health status; the absolute values are not that important. The proposed method for the estimation of PAT meets this requirement.

Further investigations involve an in-depth study of the IPG-based evaluation of arterial stiffness on body composition scales. Also exploration of other health parameters which can be assessed by using the IPG signals integrated into this multiparametric system will be included. The development of the composition scales to extend their potential of application in long-term monitoring of patients with chronic diseases remains the main purpose.

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