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Estimation of blood pressure variability during orthostatic test using instantaneous photoplethysmogram frequency and pulse arrival time

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ABSTRACT

The beat-to-beat blood pressure and heart rate variability provide information about the dynamic features of cardiovascular control mechanisms. Pulse arrival time can be used for assessment of blood pressure and is inversely related to it. The hypothesis of this study is that pulse arrival time and changes in photoplethysmogram signal waveform (instantaneous photoplethysmogram signal frequencies) could be used as the surrogate parameters for blood pressure variability estimation. The aims are: (1) to present instantaneous photoplethysmogram signal frequencies extraction algorithm; (2) to quantify variability of heart rate, systolic and diastolic blood pressure, pulse arrival time and instantaneous photoplethysmogram frequencies during orthostatic test and assess their interrelation.

The experimental protocol by using orthostatic test was designed to stimulate autonomic nervous system of the body and observe its reaction. The data were recorded from fourteen healthy subjects. During exercise, physiological and motion signals (electrocardiogram, photoplethysmogram, accelerometer, and continuous arterial blood pressure) were recorded. Two systems for synchronous recordings of physiological data were used: Cardioholter 6.2-8E78 and Portapres Model-2. Classical signal processing algorithms were applied to obtain R–R intervals, systolic, and diastolic blood pressure. Hilbert transform was used for pulse arrival time estimation and Hilbert–Huang transform for instantaneous photoplethysmogram signal frequencies extraction.

Time-domain and frequency-domain parameters show that heart rate, blood pressure, pulse arrival time, and instantaneous photoplethysmogram signal frequencies have different variability in different postures of the body (vertical and horizontal). Variability of R–R intervals is higher in horizontal posture, meanwhile, variability of blood pressure, pulse arrival time, and instantaneous photoplethysmogram signal frequencies are higher in vertical posture. Pulse arrival time and instantaneous photoplethysmogram signal frequencies have the same trends as blood pressure. Results showed that the differences between vertical and horizontal (supine and standing) positions are statistically significant ($p < 0.05$).

Changes of blood pressure, pulse arrival time, and instantaneous photoplethysmogram signal frequencies variability are interrelated during orthostatic test. The results support the assumption that pulse arrival time and instantaneous photoplethysmogram signal frequencies can be used as the surrogate parameters for blood pressure variability estimation.

1. Introduction

An information regarding the dynamic features of cardiovascular control mechanisms can be obtained by analyzing the beat-to-beat blood pressure (BP) variability (BPV) and heart rate (HR) variability (HRV) [1]. Heart rate variability has became the conventionally accepted term to describe variations of both heart rate and R–R intervals (RRI). HRV is used as a non-invasive technique for the evaluation of autonomic nervous system [2]. It is known that the properties of HRV are related to subject's gender, age, fitness level, body position, temperature, left ventricular size, hormonal status, and drugs or stimulants used [3].

Blood pressure variability can be described by two parameters: systolic (SBP) and diastolic (DBP) BPV. Recently, interest has grown in blood pressure variability analysis [4]. A large number of clinical trials confirmed that abnormal short-term and long-term BPV may independently contribute to target organ damage [5] and cardiovascular events [6] which influences mortality not only in hypertensive patients, but in subjects with diabetes mellitus and chronic kidney disease [7] as well. Therefore, blood pressure

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Table 1
Characteristics of the subjects.

	Subjects ($n = 14$)
Age (year)	25.00 ± 3.07
Height (cm)	176.53 ± 7.66
Weight (kg)	70.93 ± 10.60
BMI (kg/m^2)	22.72 ± 2.55

Values are mean ± standard deviation.
BMI – body mass index.

variability (not only BP average) should be taken into consideration for the management of patients as well.

In this study, among other cardiovascular parameters, pulse arrival time (PAT) was estimated – 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, earlobe, toe, and forehead) [8]. Studies have shown that PAT could be used for non-invasive BP estimation [9,10]. It is expected that short-term variability of PAT and BP are highly correlated in certain circumstances [11]. Pulse arrival time usually is estimated as time delay between electrocardiogram (ECG) R wave and maximum of the first derivative of photoplethysmogram (PPG) signal.

One common cardiovascular test used in clinical practice and in this study is the orthostatic test (body position change). It is suitable to stimulate autonomic nervous system of the body and observe its reaction [12].

It is assumed that changes of PPG signal morphology are correlated with changes in BP [13]. Instantaneous frequencies (IF) reflect subtle changes in signal waveform and are obtained from PPG signal using Hilbert–Huang transform [14] and so can be used for BPV estimation. In this study application of this method for BVP estimation is investigated.

The hypothesis is that pulse arrival time and instantaneous PPG frequencies could be used as the surrogate parameters for blood pressure variability estimation. The aims are: (1) to present instantaneous PPG signal frequencies extraction algorithm; (2) to quantify variability of heart rate, systolic and diastolic blood pressure, pulse arrival time, and instantaneous PPG frequencies during orthostatic test and assess their interrelation.

2. Materials

2.1. Subjects

The recordings from 14 volunteers (4 female, 10 male) aged 20–29 years were investigated (Table 1). The subjects were instructed to avoid substances which have influence to cardiovascular system (alcohol, caffeine) and smoking for 6 h before the examination. The subjects were normotensive, non-obese and were taking no medication for the duration of the study.

2.2. Protocol

The database was recorded during orthostatic test, according to the following protocol: 10 min stabilization period (rest in supine position), 10 min early supine position, 5 min standing position, 5 min later supine position (Fig. 1). The subjects were asked to change body position (to stand up and to lie down) slowly and these intervals were cutted out and not used for the following analysis.

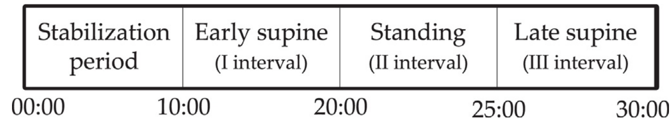

Fig. 1. The protocol of orthostatic test.

Synchronous ECG, PPG, accelerometer (ACC) and BP signals were recorded in early supine, standing, and later supine positions. Parameter sequences obtained from RRI, systolic and diastolic BP, PAT, first and second instantaneous PPG signal frequencies (IF1 and IF2, respectively) were divided into a three parts: I interval (early supine), II interval (standing), and III interval (late supine).

2.3. Equipment

Two systems for synchronous recordings of physiological data were used for data collection. ECG, PPG, and ACC signals were acquired by using Cardioholter 6.2-8E78 (BMII, Lithuania) [15]. I, II, and III leads of ECG were recorded and lead II were used, PPG and ACC signals were recorded from subject's forehead. Sampling frequency of ECG was 500 Hz, PPG – 250 Hz, ACC – 50 Hz. Continuous arterial blood pressure was acquired by using a non-invasive continuous finger BP measurement and recording system Portapres® Model-2 (Finapres Medical Systems B.V., Netherlands) [16]. Sampling frequency of BP signal was 100 Hz.

3. Algorithms and statistical analysis

3.1. RR interval detection

First stage of ECG signal processing was removal of noise and artifacts (muscle activity, baseline drift, and other) using Butterworth high-pass filter (order 4, cut-off frequency 0.4 Hz) and 50 Hz notch filter. In the second stage R waves were detected using modified Tompkins algorithm [17]. All detected R waves were used for HRV analysis (Fig. 3a) and in other algorithms.

3.2. Pulse arrival time estimation

Pulse arrival time was estimated by using the algorithm described in [18]. Fig. 2 shows a block diagram of PAT estimation algorithm. The monocomponent auxiliary ECG signal with the frequency of instantaneous HR was generated based on the detected R peak positions. Cubic spline interpolation was used in the auxiliary signal modelling process. After that the amplitudes of the auxiliary signal were normalized. Instantaneous frequency of this signal was equal to instantaneous HR. RRI was estimated as the time interval between two successive R wave peaks in ECG signal (Fig. 3a).

Fundamental frequency from PPG signal was extracted by filtering it with narrowband Butterworth bandpass filter (order 4, cut-off frequencies 0.4 and 3 Hz). The obtained signal is similar to harmonic wave. The amplitude of this signal was normalized as well.

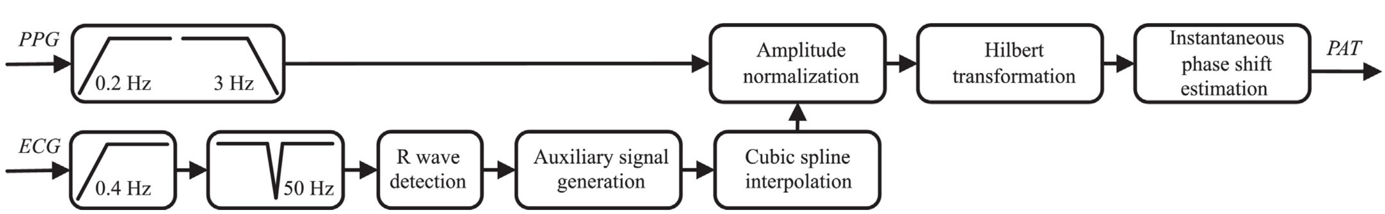

Fig. 2. Structural scheme of PAT estimation algorithm.