Comparison of Pulse Rate Variability Derived from Digital Photoplethysmography over the Temporal Artery with the Heart Rate Variability Derived from a Polar Heart Rate Monitor

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Abstract — In the quest for an easy-to-use and cost-effective way for heart rate variability (HRV) analysis, we have developed a wireless digital photoplethysmographic (PPG) prototype device with PPG sensors integrated in wearable garments, such as a headband or wrist strap. Five minute recordings from twelve healthy adult female subjects were taken with purpose to compare pulse rate variability (PRV) variables (obtained with the PPG device) with HRV variables (obtained with the Polar heart rate monitor S810i) during resting conditions.

The mean difference between heart intervals derived from the Polar heart rate monitor and the PPG device was 6.3±4.0ms (0.84±0.52 beats per minute for heart rate). There was a statistically significant and high correlation between the heart intervals derived from both devices for all individuals, and between HRV and PRV variables. However, the relative difference between HRV and PRV variables could reach 50% for time domain (pNN50%) and 88.8% (HF power) for spectral domain variables.

Our results confirm that the developed wireless digital PPG prototype device is highly suitable for detection of heart rate during resting conditions. The compatibility of HRV and PRV variables should be interpreted with more caution.

Index Terms — digital photoplethysmography, heart rate variability, pulse rate variability

I. INTRODUCTION

Heart rate variability (HRV) is beat-to-beat changes in successive heart intervals, and since it is linked to autonomic nervous system, HRV analysis is a valuable method for investigation of different health states [1]. The conventional method for estimation of heart intervals for the HRV analysis is electrocardiography, measurement of the electric activity of the heart. Photoplethysmography (PPG), optical detection of a pulsatile blood volume changes in the vascular bed under the PPG sensor, can be also used. PPG has already gained popularity as an informative tool in clinical applications related mainly to the cardiovascular system [2], and compatibility of pulse rate variability (PRV) to HRV is also widely discussed [3-17]. Generally PRV is not accepted as a surrogate measurement of HRV [10], however, during stationary, resting conditions it has shown reliable results [3, 4, 14]. The most popular sites for PPG measurements are fingertips and earlobes – places where signal detection or quality could be negatively affected for patients with poor peripheral perfusion [18]; PPG sensor location over superficially located arteries could be a better alternative in these cases.

We have developed an easy-to use and cost-effective wireless digital (based on the measurements of the discharge time of the photodiode) PPG prototype device for heart rate and HRV measurements with PPG sensors integrated in wearable garments, such as a headband or wrist strap.

The aim of this study is to investigate the precision of the developed PPG device in heart rate estimation; and to compare obtained PRV variables with HRV variables. Polar heart rate monitor S810i was used as a reference device.

II. METHODS

A. Subjects and measurement protocol

Twelve healthy adult female subjects, aged 18 to 29 years (median = 20 years), participated in this study, approved by the local ethics committee. After obtaining an informed consent and instructing to sit quietly, a subject was seated in a comfortable seat while both the wireless digital PPG device with the sensor over the a. temporalis, and the Polar heart rate monitor S810i (Polar Electro Oy, Kempele, Finland) electrodes on the chest were attached. Once the devices were attached, the subject had a 5-minute adaptation period and then the 5-minute recording was taken. All measurements took place in a separate room.

Estimated heart intervals (HI) from the Polar heart rate monitor (Polar HRM) and the PPG device were exported and time-matched in Ms Excel 2003. Kubios HRV 2.0 (Biosignal Analysis and Medical Imaging Group, Department of Physics, University of Kuopio, Kuopio, Finland) was used for calculation of HRV and PRV variables. Pearson or Spearman correlation, when appropriate, and t-test or Mann-Whitney Rank Sum Test, when appropriate, were used for data statistical analysis with Sigmastat 3.1.

Heart intervals were estimated from all artifact free data (difference between two successive heart intervals <200ms);
HRV and PRV variables (STD RR – standard deviation of HI, RMMSSD - the square root of the mean squared difference of successive HI, pNN50% - percent of successive HI differences larger than 50 ms, VLFabs, LFabs, HFabs – absolute values of very low, low and high frequency power, LFn.u., HFn.u. – normalized values of low and high frequency power, LF/HF ratio – low to high frequency power ratio) were calculated from 256 consecutive HI from the more stable period of the recording. Autoregressive model was used for spectral parameter estimation. Two subjects were excluded from spectral analysis due to artifacts in either the PPG or Polar HRM signals.

B. Technical parameters of wireless digital PPG device

The wireless digital PPG prototype device consists of two parts: (1) wearable garment with integrated PPG signal measurement and transmission unit, and (2) laptop with software for signal capturing via Bluetooth and real-time HI detection, and PRV variable calculation (Fig.1.).

Fig.1. Wireless digital prototype device: (1) headband with integrated PPG signal measurement and transmission unit, and (2) laptop with software for signal capturing via Bluetooth and real-time heart interval detection, and PRV variable calculation.

Technical parameters: a sampling frequency – 1 kHz, a 875 nm light emitting diode (LED), and a photodiode with a daylight filter and peak spectral response wavelength at 880nm. The device has an integrated LED driver that provides stable power throughout the battery’s discharge range. LEDs were driven by 55 ± 15 mA (5 mA stepping), so that no perceptible warming of the upper tissue layer was produced. A digital analog converter was used to regulate the LED current. Block diagram of the wireless digital PPG prototype device is shown in figure 2.

Fig. 2. Block diagram of the wireless digital PPG prototype device.

The main idea of the digital PPG is that the LED emits constant amount of light, and due to changes in blood volume and flow characteristics in tissue under the sensor, different amount of light is absorbed and reflected. A photodiode (PD) is charged by central processing unit in 30-microseconds. The PD acts like a capacitor that exponentially discharges in time. Discharge is proportional to the amount of the reflected light detected by the PD.

Discharge time is captured by a microcontroller and therefore does not require software resources. One measurement composes a single point on a time-axis of PPG waveform. The PPG signal is restored digitally without standard ADC-conversion [19].

C. PPG signal processing

Signal was filtered by second-order reverse phase Butterworth filter in frequency range 0.2-8 Hz. Heart intervals were calculated as a distance between two feet of consecutive PPG waveforms. The feet of the PPG waveforms were estimated in the following way:

- 1st derivative was evaluated from the PPG signal;
- first maximum of derivative was found;
- threshold function was calculated:

\[
g_j = \begin{cases} f_j, & f_j < f_{j-1} \\ g_{j-1}, & f_j > f_{j-1} \\ \frac{g_j}{1 + \frac{s}{k}}, & \text{otherwise} \end{cases}
\]

where \( f_j \) is j-th sample of derivative signal, \( f_{j-1} \) is previous sample, \( s \) is the sample rate, \( k \) is the threshold decay coefficient.

- from the site where the threshold function crosses the 1st derivative signal, the nearest zero-crossing point was found; this corresponds to foot position.

III. RESULTS

The mean difference between heart intervals derived from the Polar HRM and the PPG device was 6.3 ± 4.0 ms (0.84 ± 0.52 beats per minute for heart rate). An example of consecutive heart intervals, detected with the Polar HRM and the wireless digital PPG device is demonstrated in figure 3.

Fig. 3. Consecutive heart intervals detected with the Polar HRM and the digital PPG device (a fragment of one subject’s data).
There was a statistically significant and high correlation between the heart intervals derived from both methods for all subjects (mean $r = 0.987 \pm 0.009$, $p < 0.001$; example of one subject data shown in figure 4), and between HRV and PRV variables: $r_{STD} = 0.988$, $r_{RMSSD} = 0.964$, $r_{pNN50} = 0.997$, $r_{VLFabs} = 0.988$, $r_{LFabs} = 1.00$, $r_{HF} = 0.988$, $r_{LF/n.u.} = 0.962$, $r_{HF/n.u.} = 0.962$, $r_{LF/HF}\text{ratio} = 0.976$ ($p<0.001$ for all cases).

There were no statistically significant differences between HRV and PRV variables estimated with the Polar HRM and the PPG device, however, the relative difference between variables was quiet remarkable: 0.3 to 50 % for time domain and 0.16 to 88.8 % for spectral domain variables (figure 5).

The relative difference was expressed mostly in $pNN50\%$, HF power and LF/HF ratio.

**IV. CONCLUSION**

Our results confirm that the developed wireless digital PPG prototype device is highly suitable for detection of heart rate during resting conditions. The compatibility of HRV and PRV variables should be interpreted with more caution, especially $pNN50\%$, HF values and LF/HF ratio.

**ACKNOWLEDGMENT**

Financial support from European Social Fund, project number 2009/0211/1DP/1.1.1.2.0/09/APIA/V1AA/077, is highly appreciated.

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