Low-Exertion Testing of Autonomic Cardiovascular Integrity Through PPG Signal Analysis

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Abstract

Activity of the autonomic nervous system (ANS) is closely related to the cardiovascular system (CVS). Thus, any disturbance of the ANS may have a negative impact on CVS function. This study investigates the feasibility to assess autonomic cardiovascular integrity by using photoplethysmogram (PPG) signals. PPG signals from 51 *subjects were recorded. Two complementary tests (cold pressor and slow deep breathing) were used as stress and relaxation stimuli. Nine features of PPG pulse wave were extracted. The results showed that the most sensitive feature to the sequence of complementary stimuli for autonomic cardiovascular integrity testing is the pulse amplitude variability – values of effect size to two cold pressor and one slow deep breathing stimuli were* 1.444*,* 1.129*, and* 1.030*, respectively. The obtained results may have significance in developing testing methodologies of assessing ANS for physically weak persons.*

1. Introduction

The autonomic nervous system (ANS) is a part of the peripheral nervous system and is responsible for the control of vital functions such as heartbeat, breathing, and digestion. Psychophysiological conditions such as stress [1, 2], anxiety and depression [3], or diseases such as stroke [4], frailty syndrome [5], and vascular aging [6] affect ANS performance. Activity of the ANS is closely related to the cardiovascular system (CVS); thus, any disturbance of the ANS may impact CVS function negatively. Therefore, methods are needed to test autonomic cardiovascular integrity.

It is desirable that these methods be sufficiently short-term and do not require physical solid endurance. For this purpose, the cold pressor (CP) and the slow deep breathing (SDB) tests are hypothesized to be particularly suitable for ANS and CVS testing. During the CP test, short-term physical stress activates the sympathetic nervous system, when the SDB test is related to activation of mainly the parasympathetic branch of the ANS. The CP test has been used clinically as a stress test to assess the autonomic function of the heart [7]. Study [8] states that SDB at resonant frequency - 6 breaths/min can help achieve maximum heart rate variability and balanced ANS.

Unlike other methods for CVS testing, such as 6-minute Walk, Chester Step, or Paced Step tests [9], the combined CP-SDB test method does not require intense physical work and is easy to perform. This type of test would be beneficial for post-stroke patients who cannot perform strenuous physical exercise.

In order to assess ANS and CVS interaction, heart rate variability parameters are commonly used in practice [10]. However, the majority of parameters require a long and stationary time window. This work proposes to use an alternative, faster-changing markers evaluated from photoplethysmogram (PPG) signals. PPG signals are sensitive to motion artifacts, but the proposed method does not require high-amplitude movements.

Sympathetic changes caused by many stressors can be captured by PPG [1, 2, 6]. Thus, the main novelty of this work is the analysis of PPG features on a new dataset. The aim of this study is to investigate the pulse wave features of PPG and to propose the most suitable markers to parameterize a rapidly changing signal and the effect of short-term stimuli.

2. Material and Methods

2.1. Study Population and Data Acquisition

In this study, a database composed of 51 healthy subjects was used. 10 of 51 signals whose pulse detection in long-

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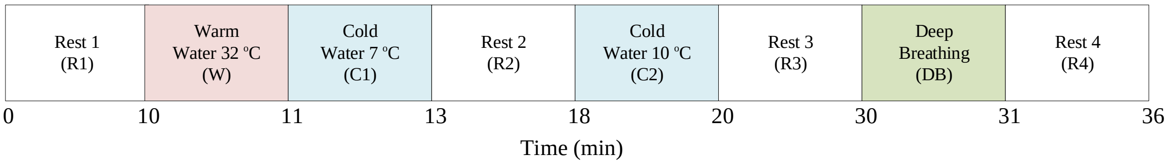

Figure 1. Stages of the study protocol.

term segments was unreliable due to artifacts were not analyzed. The mean age of the subjects was 36.93 ± 10.91 years and the body mass index - 23.86 ± 3.12 kg/m^2. PPG signals were recorded from finger of the right hand with the Nautilus 2.0 device developed by the Biomedical Engineering Institute (Kaunas, Lithuania) with a sampling rate of 1 kHz.

The study was performed in a quiet, closed, and temperature-controlled (24 ± 1 °C) room at the same time of day (08:00 - 13:00) for each study participant. Before the study, each subject was introduced to the study protocol. The protocol (Figure 1) consists of four *Rest* stages - $R1$, $R2$, $R3$, and $R4$, two *Cold Water* stages - $C1$ and $C2$, corresponding to the CP test, one *Warm Water* stage W, and one *Deep Breathing* stage DB, corresponding to the SDB test. The approximate immersion depth of the left arm in water at the $C1$, $C2$, and W stages was up to half the forearm.

The study was approved by the Kaunas Region Biomedical Research Ethics Committee (No. BE-2-24). A signed, written consent to participate in the study was obtained from all participants. The study was conducted in accordance to the ethical principles of the Declaration of Helsinki. Identifiable information was removed from the collected data to ensure subject anonymity.

2.2. Signal Processing

PPG signal processing consisted of signal preprocessing, signal demodulation, pulse detection, calculation of signal derivatives, and estimation of pulse wave features extracted from PPG (Figure 2).

In order to minimize the noise and movement artifacts from PPG, the signal was filtered by a zero-phase 2^{nd} order Butterworth bandpass filter with the passband 0.5 - 10 Hz. The upper cut-off frequency of 10 Hz ensured that high-frequency noise was eliminated, and the amplitudes of waves of signal second derivative were detected in most cases.

PPG signal amplitude demodulation was performed to ensure that amplitude fluctuations did not affect the morphology of the PPG signal. In order to demodulate PPG, the upper and lower envelopes of the signal were evaluated. The pulse amplitude variability PAV was estimated as the difference between these envelopes. The demodulated signal was obtained by dividing the preprocessed PPG by the PAV feature (Figure 3). The extracted amplitude envelope of the PPG signal provides information about changes in vasoconstriction and cardiac output.

In this work, PPG pulse detection was based on the low-complexity Mountaineer's Method for Peak Detection (MMPD). MMPD algorithm can dynamically adapt to conditions where a sudden decrease in PPG signal amplitude is expected [11].

The calculation of the first three derivatives ($PPG'(t)$, $PPG''(t)$, and $PPG'''(t)$) was performed by using the lowpass derivative (LPD) method, implemented as a digital filter $H(z)$.

2.3. Pulse Wave Features

The estimation of pulse wave features was based on the analysis of derivatives of PPG, finding the amplitudes of a, b, c, d, e, and f waves of $PPG''(t)$ [1,2].

In this work, seven pulse wave features of demodulated PPG were analyzed (Figure 4): systolic and diastolic areas of PPG pulse A_{s} and A_{d}, respectively; slope coefficients $S_{\text{b-c}}$ and $S_{\text{b-d}}$ of the straight lines between amplitudes of b and c, and b and d waves, respectively; time intervals $T_{\text{a-b}}$, $T_{\text{b-c}}$, and $T_{\text{b-d}}$ estimated from fiducial points of $PPG''(t)$. The envelope-based PAV feature was also analyzed. In addition, the change in pulse-to-pulse interval PP during the study was evaluated.

2.4. Statistical Analysis Methods

In this work, samples of $R1 - C1$, $R2 - C2$, and $R3 - DB$ stages of the study protocol were compared in order to investigate the impact of CP and SDB tests on pulse wave features of PPG. The Anderson-Darling test found not Gaussian distribution in the analyzed data. A nonparametric paired Wilcoxon signed-rank test was used to estimate the p-value. In addition, the effect size was evaluated. The Cohen's d-values were used for this purpose.

3. Results

The variation of pulse wave features in one of the signals recorded in the study and the boxplot diagrams are shown in Figure 5 and Figure 6, respectively. In Figure 5 can be

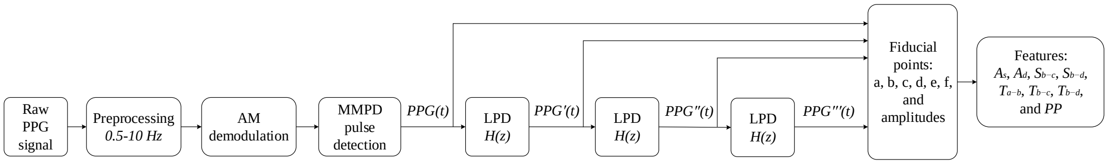

Figure 2. The block diagram of estimation of pulse wave features extracted from PPG signal.

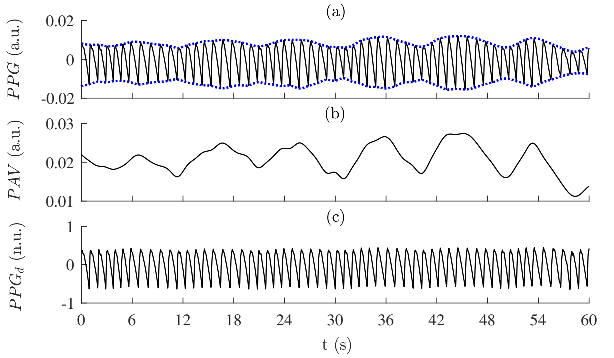

Figure 3. PPG amplitude demodulation during the DB stage: (a) PPG with the upper and lower envelopes; (b) PAV - difference between the upper and lower envelopes; (c) PPG_d - demodulated PPG signal.

seen that the estimated pulse wave features are suitable and sensitive enough to characterize a short-term stimulus in a rapidly changing PPG signal. Figure 6 shows the statistical distribution of the features among 41 subjects during the study protocol.

p-values between comparative stages $R1-C1$, $R2-C2$, $R3-DB$ of the study protocol are shown in Table 1. Cohen's d-values are shown in brackets. It can be seen that PAV, $S_\text{b-c}$, $T_\text{a-b}$, $T_\text{b-c}$, and PP pulse wave features showed the highest statistical significance of the differences. However, the largest effect size was shown by the PAV feature.

Table 1. p and d values between comparative stages of the study protocol. Large effect size is marked with * ($|d| > 0.8$).

$Feature$	$R1-C1$	$R2-C2$	$R3-DB$
PAV	< 0.001 (1.444^*)	< 0.001 (1.129^*)	< 0.001 (1.030^*)
A_s	0.020 (0.395)	< 0.001 (0.320)	0.646 (-0.129)
A_d	0.035 (0.286)	0.002 (0.282)	0.627 (-0.151)
$S_\text{b-c}$	< 0.001 (-1.071^*)	< 0.001 (0.182)	< 0.001 (0.156)
$S_\text{b-d}$	0.004 (0.502)	0.025 (0.185)	0.693 (0.156)
$T_\text{a-b}$	< 0.001 (0.676)	< 0.001 (0.830^*)	0.396 (-0.142)
$T_\text{b-c}$	< 0.001 (1.201^*)	< 0.001 (1.264^*)	0.009 (-0.273)
$T_\text{b-d}$	0.943 (0.121)	0.160 (0.261)	0.221 (-0.128)
PP	< 0.001 (0.968^*)	< 0.001 (1.079^*)	0.902 (0.023)

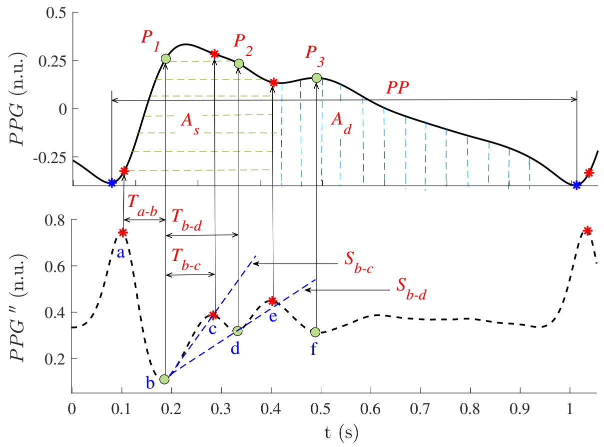

Figure 4. Detection of the amplitudes of a, b, c, d, e, and f waves of $PPG''(t)$ and estimation of pulse wave features of PPG; P_1 - amplitude of the 1^{st} systolic wave, P_2 - amplitude of the 2^{nd} systolic wave, and P_3 - amplitude of the diastolic wave.

4. Discussion

In this study, low-exertion testing of autonomic cardiovascular integrity method through PPG signal analysis was proposed. Nine PPG pulse wave features were analyzed. The PAV feature showed the largest effect size. Thus, it can be assumed that amplitude-based features are more sensitive to ANS stimuli such as CP and SDB tests than pulse wave features of demodulated PPG. Our previous studies [2] also showed that PPG amplitude is quite sensitive to mental stress. The results of this study have demonstrated that PPG amplitude-related features are also sensitive to short-term physical stress. Although previous studies by other authors [1] have not demonstrated an essential relationship between stress and PPG amplitude.

Most of the features do not differ significantly in a statistical sense when comparing $R3$ and DB stages, except PAV and S_{b-c}. These results may have been influenced by a relatively short duration of the DB stage (1 minute). It can be predicted that prolonged deep breathing would cause a stronger activation of the parasympathetic nervous system. Furthermore, it remains unclear whether the same results would have been obtained if the subjects had ex-

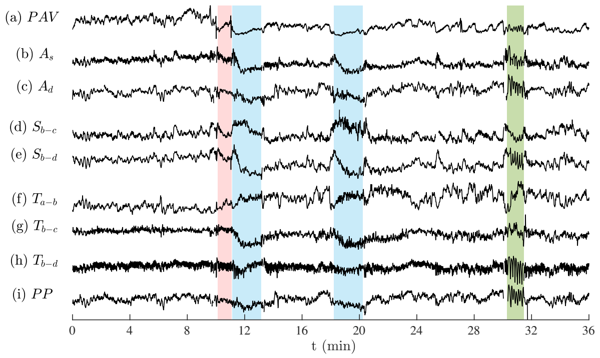

Figure 5. The variation of pulse wave features of PPG: (a) pulse amplitude variability PAV, (b) systolic area A_s, (c) diastolic area A_d, (d) slope coefficient $S_\mathrm{b\text{-}c}$, (e) slope coefficient $S_\mathrm{b\text{-}d}$, (f) time interval $T_\mathrm{a\text{-}b}$, (g) time interval $T_\mathrm{b\text{-}c}$, (h) time interval $T_\mathrm{b\text{-}d}$, (i) pulse-to-pulse interval PP.

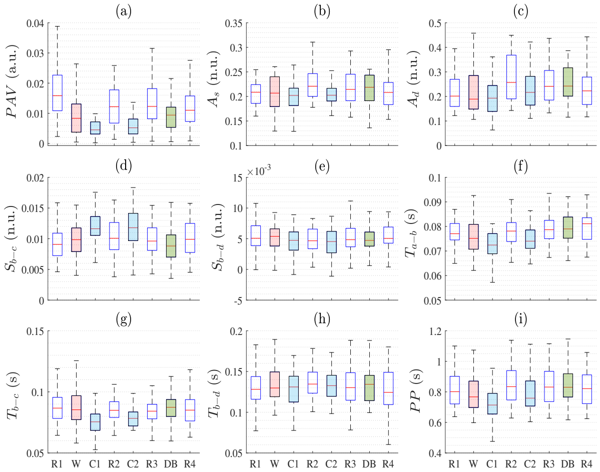

Figure 6. The boxplots of pulse wave features of PPG: (a) pulse amplitude variability PAV, (b) systolic area A_s, (c) diastolic area A_d, (d) slope coefficient $S_\mathrm{b\text{-}c}$, (e) slope coefficient $S_\mathrm{b\text{-}d}$, (f) time interval $T_\mathrm{a\text{-}b}$, (g) time interval $T_\mathrm{b\text{-}c}$, (h) time interval $T_\mathrm{b\text{-}d}$, (i) pulse-to-pulse interval PP.

haled with their mouths open or with different inhale and exhale duration.

5. Conclusions

The results of this study showed that the envelope-based feature PAV of PPG signal is the most suitable parameter for assessing of autonomic cardiovascular integrity during complementary cold pressor and slow deep breathing tests. These results may have significance in developing methodologies of assessing autonomic cardiovascular integrity for physically weak persons.

Acknowledgments

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