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A comprehensive assessment of cardiovascular autonomic control using photoplethysmograms recorded from the earlobe and fingers

A R Kiselev[1,2], S A Mironov[3], A S Karavaev[4], D D Kulminskiy[4], V V Skazkina[5], E I Borovkova[5], V A Shvartz[2], V I Ponomarenko[5] and M D Prokhorov[4]

[1] Department of New Cardiological Informational Technologies, Research Institute of Cardiology, Saratov State Medical University n.a. V.I. Razumovsky, Saratov, Russia
[2] Department of Surgical Treatment for Interactive Pathology, Bakulev Scientific Center for Cardiovascular Surgery, Moscow, Russia
[3] Central Clinical Military Hospital, Moscow, Russia
[4] Saratov Branch of the Institute of Radio Engineering and Electronics of Russian Academy of Sciences, Saratov, Russia
[5] Department of Nano- and Biomedical Technologies, Saratov State University, Saratov, Russia

E-mail: kiselev@cardio-it.ru

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Abstract

We compare the spectral indices of photoplethysmogram variability (PPGV) estimated using photoplethysmograms recorded from the earlobe and the middle fingers of the right and left hand and analyze their correlation with similar indices of heart rate variability (HRV) in 30 healthy subjects (26 men) aged 27 (25, 29) years (median with inter-quartile ranges) at rest and under the head-up tilt test. The following spectral indices of PPGV and HRV were compared: mean heart rate (HR), total spectral power (TP), high-frequency (HF) and low-frequency (LF) ranges of TP in percents (HF% and LF%), LF/HF ratio, and spectral coherence. We assess also the index *S* of synchronization between the LF oscillations in HRV and PPGV.

The constancy of blood pressure (BP) and moderate increase of HR under the tilt test indicate the presence of fast processes of cardiovascular adaptation with the increase of the sympathetic activity in studied healthy subjects. The impact of respiration on the PPGV spectrum (accessed by HF%) is less than on the HRV spectrum. It is shown that the proportion of sympathetic vascular activity (accessed by LF%) is constant in the PPGV

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of three analyzed PPGs during the tilt test. The PPGV for the ear PPG was less vulnerable to breathing influence accessed by HF% (independently from body position) than for PPGs from fingers. We reveal the increase of index S under the tilt test indicating the activation of interaction between the heart and distal vessels. The PPGV spectra for finger PPGs from different hands are highly coherent, but differ substantially from the PPGV spectrum for the ear PPG. We conclude that joint analysis of frequency components of PPGV (for the earlobe and finger PPGs of both hands) and HRV and assessment of their synchronization provide additional information about cardiovascular autonomic control.

Keywords: photoplethysmogram, heart rate variability, low-frequency oscillations, healthy subjects, earlobe, finger, tilt test

Introduction

Photoplethysmography is one of the methods employed for the assessment of peripheral circulation (Allen 2007). Photoplethysmogram (PPG) signal is used by many authors for evaluating the peripheral blood flow, peripheral vascular resistance, arterial stiffness, cardiogenic output, and respiratory rate (Sahni 2012, Kohjitani *et al* 2014, Wander and Morris 2014, Wijshoff *et al* 2015). However, the mechanisms of PPG signal formation are not studied enough. Moreover, the technical characteristics of different optical sensors often hamper the standardization of the PPG registration procedure and interpretation of the results of PPG signal analysis. Thus, it is important to develop the notion of mechanisms of PPG formation.

For studying the autonomic cardiovascular control using PPG, the pulse rate variability (PRV) and photoplethysmographic waveform variability (PPGV) are usually exploited. In particular, PRV is usually used as an acceptable surrogate of heart rate variability (HRV) (Gil *et al* 2010) because of the high correlation and coherence between the spectral estimates for HRV and PRV. However, there are known limitations for such interpretation of PRV (Wong *et al* 2012, Shin 2015).

Qualitatively different information is given by PPGV representing a beat-to-beat PPG waveform variability, characterizing fluctuations in peripheral blood flow. PPGV reflects mainly the mechanical consequence of respiration, manifesting itself in high-frequency (HF) oscillations (Bernardi *et al* 1996, Dash *et al* 2010, Javed *et al* 2010, and regulation of vascular tone by the sympathetic nervous system, manifesting itself in low-frequency (LF) oscillations (Bernardi *et al* 1996, Middleton *et al* 2011b, 2011c). Spectral analysis of PPGV is employed for different medical tasks. For example, it is used for studying heat-stress inductions on peripheral blood flow (Elgendi *et al* 2015), autonomic vascular response to blood volume reduction (Gesquiere *et al* 2007, Middleton *et al* 2008, Javed *et al* 2010), and identification of high-risk acute coronary syndromes (Middleton *et al* 2011a).

According to some authors (Middleton *et al* 2011a, 2011b, 2011c), slow oscillations in PPGV have potentially important clinical applications. Some of our previous clinical studies on cardiovascular autonomic control were based on the analysis of synchronization of LF oscillations in HRV and PPGV measured on the middle finger of the subject's hand (Kiselev *et al* 2012a, 2012b, 2014). The analysis of this synchronization showed its clinical efficiency. However, the origin of LF oscillations in PPGV remains insufficiently understood.

The PPG signal can be recorded from different parts of subject’s body (fingers of hands, earlobes, etc). Standardization of PPG measurement from different parts of the cardiovascular system (CVS) is still an open question. The features of PPG oscillations depend on the place of measurement (Chan *et al* 2010, Middleton *et al* 2011c, Schäfer and Vagedes 2013). The conventional place for PPG measurement is a finger on a hand. However, physical activity results in artifacts in finger PPG. To overcome these difficulties, sometimes a PPG sensor is placed on an earlobe, shoulder, or inside the auditory canal (Vogel *et al* 2007). Chan *et al* (2012) reported that PPGV in the ear includes a major contribution from arterial pressure and muscle sympathetic nerve activity, which is consistent with the results of other authors (Desgranges *et al* 2011).

Li *et al* (2014) have shown that the radial pulse waves are not the same as PPG during exercise in either the pulse parameter or the pulse pattern. Pulse phase difference between PPG measured on different parts of CVS was used by some authors for clinical diagnostics, for example, diagnosis of hemodynamically significant patent ductus arteriosus (Goudjil *et al* 2014). Thus, the PPG measured on different parts of subject’s body may have different properties and give different estimations of cardiovascular autonomic control.

Knowledge of the mechanisms of PPGV formation is very important. The joint employment of HRV and PPGV allows one to obtain a more comprehensive assessment of cardiovascular autonomic control. The present paper deals with solving this problem. We compare the spectral indices of HRV and PPGV estimated using PPGs recorded from the earlobes and fingers in healthy subjects at rest and under the head-up tilt test. We assess also the index S of synchronization between the LF oscillations in HRV and PPGV.

Material and methods

Subjects

Design of this study was approved by the Ethics Committee of the Saratov Research Institute of Cardiology (Saratov, Russia) in 2013, and written informed consent was obtained from all subjects who participated in this study.

Our study included 30 healthy subjects (26 men and four women). The health of all subjects was confirmed by the results of clinical investigation in the Central Clinical Military Hospital (Moscow, Russia). The anthropometric characteristics of the healthy subjects included in the study are presented in table 1.

Signal recording

We used a passive head-up tilt test to stimulate adaptation reactions in cardiovascular autonomic control and evaluate it (Montano *et al* 1994, Takase *et al* 1996, Suzuki *et al* 2006). The electrocardiogram (ECG), PPGs from the middle finger of the right and left hand (denoted below as PPG(R) and PPG(L), respectively), PPG from the earlobe (denoted below as PPG(ear)), and respiration were simultaneously recorded during 10 min in healthy subjects at each stage of the head-up tilt test. An example of recorded PPG signals is shown in figure 1.

All subjects were investigated in the afternoon fasting under spontaneous breathing. The signals were measured in a quiet, temperature-controlled room. All signals were sampled at 250 sps and digitized at 14 bits. The record of respiration was used to control evenness of breathing. All experimental signals were recorded using a standard electroencephalograph analyzer EEGA-21/26 ‘Encephalan-131-03’ (Medicom MTD Ltd, Taganrog, Russia (www.medicom-mtd.com/en/products/eega.html)).

Table 1. Anthropometric characteristics of the studied healthy subjects.

Parameter	Level
Age (years)	27 (25, 29)
Height (m)	1.79 (1.70, 1.85)
Weight (kg)	78 (70, 83)
BMI (kg m^{-2})	24.0 (22.1, 25.7)

Note: Data are presented as Me (Q1, Q3).

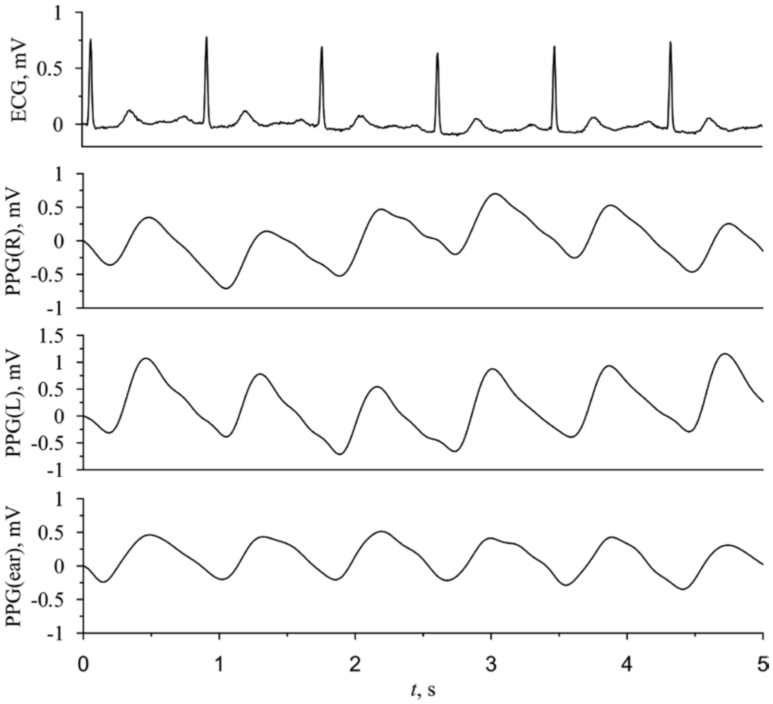

Figure 1. An example of simultaneous records of studied signals.

We excluded from the analysis the series with forced inspiration and delays in breathing. For further analysis only records without artifacts, extrasystoles, and considerable trends were left.

The head-up tilt test protocol includes the following stages:

(1) In a preliminary stage lasting 10 min, the subject was laying in a horizontal position without signal recording.
(2) The signals were recorded within 10 min in the horizontal position of subject's body.
(3) The subject was put passively in a vertical position with a tilt angle of about 80°. To exclude the transients the signals were not registered within 5 min.
(4) The signals were recorded within 10 min in the vertical position of subject's body.

Signal processing

The spectral analysis of HRV was carried out in accordance with the methodological recommendations (Task Force of the European Society of Cardiology and the North American

Society of Pacing and Electrophysiology 1996). We calculated the following indices: index LF (spectral power density integrated in 0.04–0.15 Hz band and measured in ms^2), index HF (spectral power density integrated in 0.15–0.4 Hz band and measured in ms^2), LF/HF ratio, total power index TP (spectral power density integrated in 0–0.4 Hz band and measured in ms^2), LF% (LF/TF ratio measured in percent), and HF% (HF/TF ratio measured in percent). Besides the spectral indices, we analyzed the mean heart rate (HR).

The power spectra of PPGV were calculated directly from the PPG signals. Then, using an approach similar to the one used for the HRV analysis, we calculated for these spectra the spectral indices LF, HF, TP, LF/HF, LF%, and HF%. Similarly to PPGs, we used the following notations: PPGV(ear), PPGV(R), and PPGV(L).

One of the problems of PPG employment is the difficulty of interpretation of PPG waveform absolute values. The signal at the output of PPG sensor is proportional to an unknown coefficient, the value of which depends on a number of factors such as optical features of the subject's skin, blood pressure (BP) values, placement of sensor, electrical and optical characteristics of the sensor, and room illumination and temperature. The interpretation of PPGV absolute values is an open question that goes beyond the subject of our paper. In the present paper, the PPG signals were measured in conventional units (cu). These units are the values of discrete samples of PPG waveform proportional to the signal at the PPG sensor output. Since the coefficient of proportionality between the volume blood flow and cu is unknown, the interpretation of absolute values of LF, HF, and TP indices is difficult. However, the dimensionless ratios LF/HF, LF%, and HF% have the similar sense as for HRV.

We studied also the coherence function between the PPGV(ear), PPGV(R), and PPGV(L). Coherence (sometimes called magnitude-squared coherence) was proposed by White and Boashash (1990). It is based on the calculation of cross-spectral density between two signals under investigation. Its value is close to 1 at the given frequency if the phases and amplitudes of the signals are correlated at this frequency and is close to 0 otherwise. This is a well-known statistic which is widely used for the analysis of biomedical data (Leocani and Comi 1999, Barbosa *et al* 2000). The statistical analysis included the calculation of pointwise significance of the coherence function by constructing amplitude adjusted Fourier transform surrogate data (Theiler *et al* 1992, Schreiber and Schmitz 1996).

To estimate the synchronization between the LF oscillations in HRV and PPGV we used the method proposed by us recently (Karavaev *et al* 2009). At first, we extracted a sequence of R–R intervals from the ECG signal. Then, we obtained R-R equidistant (RRE) intervals from a not equidistant sequence of R–R intervals by using cubic β-splines and resampling. To extract the LF components of RRE and PPG signals we filtered these signals using a bandwidth FIR filter. To calculate the phases of the obtained LF oscillations we applied a Hilbert transform (Pikovsky *et al* 2001) and calculated the instantaneous phase difference. The regions of phase synchronization were detected as the regions of almost constant phase difference. For automated detection of phase synchronization epochs we used a procedure based on a linear approximation of instantaneous phase difference in a moving window. Lastly, index S was calculated as the relative time of synchronization between the considered LF oscillations (Karavaev *et al* 2009).

Statistical analysis

Continuous variables are reported as medians with inter-quartile ranges, Me (Q1, Q3). Minimum (Min) and maximum (Max) are presented for some continuous variables. The obtained estimations were considered statistically significant if $P < 0.05$. For a statistical analysis the software package Statistica 6.0 (StatSoft Inc., Tulsa, Oklahoma, USA) was used.

We apply the Shapiro–Wilk test to check whether the data are approximately normally distributed. Since some data occur to be non-normal, further analysis was carried out using non-parametric statistical methods. For pairwise comparison of variables within the group of subjects we used the Wilcoxon test.

Results

All healthy subjects had baseline characteristics (mean HR, BP, and breathing rate) typical to a rest condition (table 2). The baseline TP was similar for all PPG spectra ($P > 0.05$ for all pairs: PPGV(ear)–PPGV(R), PPGV(ear)–PPGV(L), and PPGV(R)–PPGV(L) calculated by Wilcoxon test) (table 2). LF%, HF%, and LF/HF in HR were significantly different from the corresponding parameters in each PPGV ($P < 0.001$ for all pairs) (figures 2 and 3). In particular, LF% and LF/HF were smaller and HF% was greater in HRV. In all studied PPGV spectra, LF% and HF% were similar ($P > 0.05$ for all pairs) (figures 2 and 3), but LF/HF was greater in PPGV(ear) ($P < 0.001$ for pairs PPGV(ear)–PPGV(R) and PPGV(ear)–PPGV(L)) (table 2). Index *S* of synchronization between the LF oscillations in HRV and LF oscillations in each studied PPGV has similar baseline level ($P > 0.05$ for each pair) (figure 4).

During the head-up tilt test a significant increase of mean HR was observed (table 2). TP increased under the tilt test in each PPGV, but not in HRV (table 2). LF/HF increased in HRV and decreased in PPGV(ear) during the tilt test, while LF/HF in each of finger PPGV was constant (table 2). Note that in each studied PPGV, LF% was much greater than HF% ($P < 0.001$) (see figures 2 and 3) in all stages of tilt test, leading to high values of LF/HF in PPGV (table 2).

The placing of a subject in a vertical position was associated with significant increase of LF% in HRV (figure 2), decrease of HF% in HRV (figure 3), and increase of HF% in the left finger PPGV (figure 3). LF% was similar ($P > 0.05$) in each PPGV during all stages of the tilt test (figure 2).

Before and after the head-up tilt test, the levels of synchronization between the LF oscillations in HRV and LF oscillations in each PPGV were similar ($P > 0.05$) (figure 4). Overturn in a vertical position was associated with a statistically significant increase of index *S* for each studied pair of oscillations (figure 4). The most pronounced increase of *S* was observed for the pair HRV–PPGV(ear).

Spectra of PPGV(R) and PPGV(L) exhibit high coherence in 0.005–0.5 Hz band in the most of the studied healthy subjects in a horizontal body position and in a fewer number of subjects in a vertical body position (figure 5). The coherence between PPGV(ear) and PPGV from the fingers was low in the most of subjects in both body positions (figure 5). Index *S* of synchronization between the LF oscillations in PPGV calculated for PPG signals recorded from the fingers and the earlobe was close to 100%.

Discussion

For studying cardiovascular control, many different methods are used, such as HRV analysis (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996), blood pressure variability (BPV) analysis (Parati *et al* 1995), assessment of synchronization of different oscillations in CVS (Prokhorov *et al* 2003, Karavaev *et al* 2009, Kirilina *et al* 2009, Kiselev and Gridnev 2011, Orini *et al* 2011, Liao and Jan 2012, Zhang *et al* 2015), analysis of variability of peripheral blood flow (Hilsted 1991, Nishihara *et al* 2003, Koryakov 2012, Zhang *et al* 2015), etc.

Table 2. HR, breathing, BP, LF/HF, and TP of HRV spectrum, PPGV(ear), PPGV(R), and PPGV(L) at rest and under the passive head-up tilt test in healthy subjects.

Parameter	Horizontal positions of subject's body	Vertical positions of subject's body	*P*-level
Mean HR (beats min^{-1})	60 (56, 65)	80 (75, 89)	**<0.001**
Breathing (per min)	17 (15, 18)	17 (15, 20)	0.580
SPB (mmHg)	117 (110, 125)	115 (110, 120)	0.098
DPB (mmHg)	70 (69, 75)	76 (70, 84)	**0.048**
TP in HRV spectrum (ms^2)	1338 (898, 4237)	1744 (803, 3553)	0.428
TP in PPGV(ear) spectrum (cu)	0.374 (0.297, 0.475)	0.478 (0.441, 0.521)	**<0.001**
TP in PPGV(R) spectrum (cu)	0.311 (0.151, 0.397)	0.419 (0.357, 0.458)	**<0.001**
TP in PPGV(L) spectrum (cu)	0.358 (0.275, 0.404)	0.418 (0.380, 0.442)	**0.004**
LF/HF in HRV spectrum	0.8 (0.5, 1.3)	3.0 (1.7, 6.3)	**<0.001**
LF/HF in PPGV(ear) spectrum	13.5 (5.2, 21.5)	10.7 (4.7, 18.8)	**0.026**
LF/HF in PPGV(R) spectrum	6.6 (4.4, 11.1)	5.8 (3.5, 10.3)	0.894
LF/HF in PPGV(L) spectrum	8.2 (5.5, 11.2)	4.7 (3.2, 9.2)	0.082

Note: Data are presented as Me (Q1, Q3). SPB is a systolic blood pressure; DPB is a diastolic blood pressure.

The set of spectral and statistical HRV indices having physiological interpretation is well known (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996, Cohen and Taylor 2002, Malpas 2002, Pagani *et al* 2012). However, the HRV indices can assess cardiac autonomic regulation, but not peripheral blood flow. In recent years, LF oscillations in CVS having the frequency in the range of 0.04–0.15 Hz attract a special attention. These oscillations often named as 0.1 Hz oscillations are revealed in HRV and BPV (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). They are associated with both the cardiovascular baroreflex and central control (deBoer *et al* 1987, Cooley *et al* 1998, Gridnev *et al* 2006).

We assume that the analysis of PPGV for PPG signals recorded from the earlobe and fingers substantially enhances the possibilities of conventional methods for monitoring and autonomic control of cardiovascular activity. It is explained by the fact that PPGV characterizes not only the variability of peripheral blood flow, but reflects BPV and its oscillations synchronize with oscillations in HRV. In addition, taking into account the relationship between the PRV and HRV, we can conclude that PPG is a complicated signal having potentially a wide application in medicine.

It is known that both oscillations in microcirculatory bed and blood filling of digital arteries make a substantial contribution to PPG signal (Rhee *et al* 1999). González *et al* (2014) reported that systolic blood volume oscillations assessed by PPG have dynamic changes similar, but not identical, to oscillations in BPV and HRV. But oscillations in

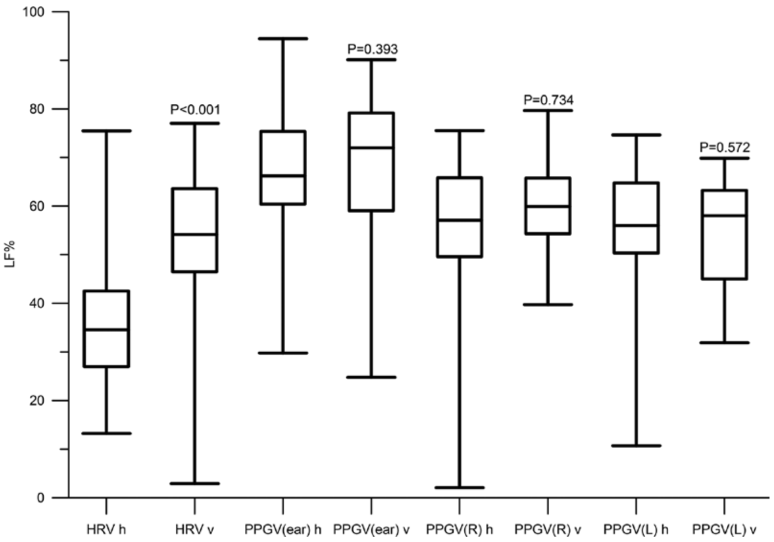

Figure 2. Dynamics of LF% calculated from power spectra of HRV, PPGV(ear), PPGV(R), and PPGV(L) during the passive head-up tilt test in healthy subjects. Data are presented as a box–whisker plot (Min, Q1, Me, Q3, and Max). *P*-levels are presented for comparison with the corresponding values in a horizontal position of subject's body. Subscripts h and v indicate the horizontal and vertical positions of subject's body.

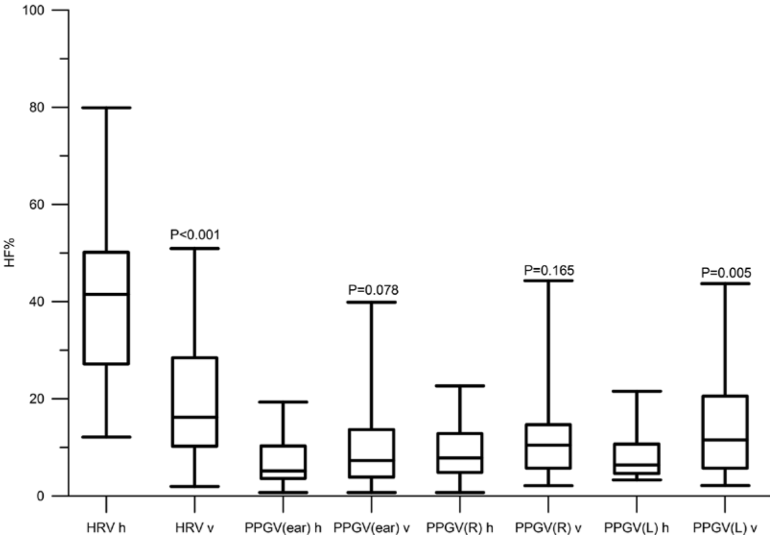

Figure 3. Dynamics of HF% calculated from power spectra of HRV, PPGV(ear), PPGV(R), and PPGV(L) during the passive head-up tilt test in healthy subjects. Data are presented as a box–whisker plot (Min, Q1, Me, Q3, and Max). *P*-levels are presented for comparison with the corresponding values in a horizontal position of subject's body. Subscripts h and v indicate the horizontal and vertical positions of subject's body.

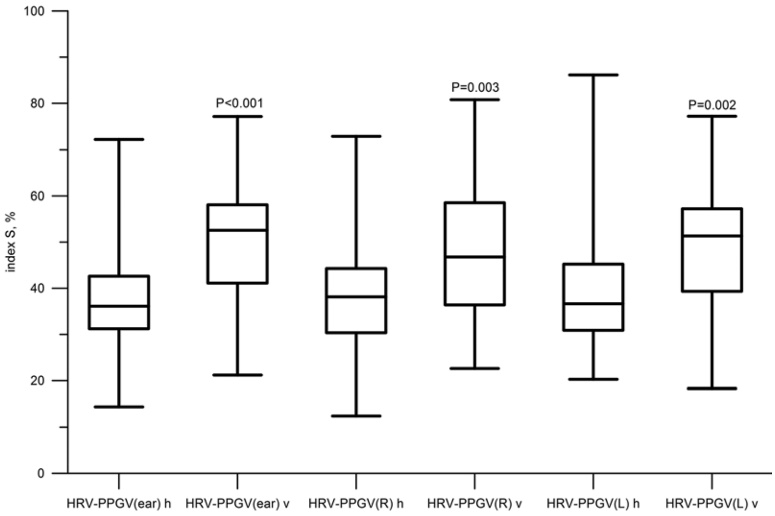

Figure 4. Dynamics of index *S* of synchronization between the LF oscillations in the indicated pairs of signals (HR and PPGV(ear), HR and PPGV(L), and HR and PPGV(R)) during the passive head-up tilt test. Data are presented as a box-whisker plot (Min, Q1, Me, Q3, and Max). *P*-levels are presented for comparison with the corresponding *S* values in a horizontal position of subject's body. Subscripts h and v indicate the horizontal and vertical positions of subject's body.

PPG and BPV may reflect similar vascular regulatory mechanisms (Millasseau *et al* 2000). Quality translation of HR to PPG signal is a disputable question (Heathers 2013, Schäfer and Vagedes 2013). Many authors use PPG as the main approach to studying the central and peripheral nervous systems (Phama *et al* 2013) and cardiovascular regulation (Chen *et al* 2015).

HRV and BPV exhibit LF oscillations that are associated with both cardiovascular baroreflex and central control (deBoer *et al* 1987, Cooley *et al* 1998, Gridnev *et al* 2006). LF oscillations have also been identified in PPGV (Kiselev *et al* 2007, Karavaev *et al* 2009). In our previous studies, LF oscillations in HRV and PPGV were found out to be synchronized between themselves in healthy subjects during the most of time (Kiselev *et al* 2007, Karavaev *et al* 2009). We believe that synchronization of LF oscillations is a criterion of adequate cardiovascular autonomic control, ensuring the functional interaction of CVS parts (heart and peripheral vessels). Previously we have shown that the quality of synchronization of LF oscillations in HRV and PPGV is the main factor for cardiovascular risk assessment (Kiselev *et al* 2012a) and control of drug therapy in patients with some cardiovascular diseases (Kiselev *et al* 2012b, 2014).

However, the origin of LF oscillations in PPGV remains insufficiently understood. The main hypothesis on the origin of components of LF oscillations in PPGV are the following: baroreflex control of central BP, since the oscillations in blood supply in digital arteries contribute significantly to the PPG signal in fingers (Higgins and Fronek 1986, Rhee *et al* 1999), vascular sympathetic nerve activity (Robinson *et al* 1994, Bernardi *et al* 1996, Larsen *et al* 1997), vasomotions (vascular endothelial activity, skin temperature regulation, and myogenic autoregulation of blood flow) (Söderström *et al* 2003, Bandrivskyy *et al* 2004, Anschutz and Schubert 2005, Bernjak *et al* 2008, Krupatkin 2009), passive peripheral blood flow fluctuations caused by the elastic properties of blood vessels (arteries and veins) in response to the interactions between the oscillations in BP, systolic blood flow, and HR (Grinevich *et al* 2014).

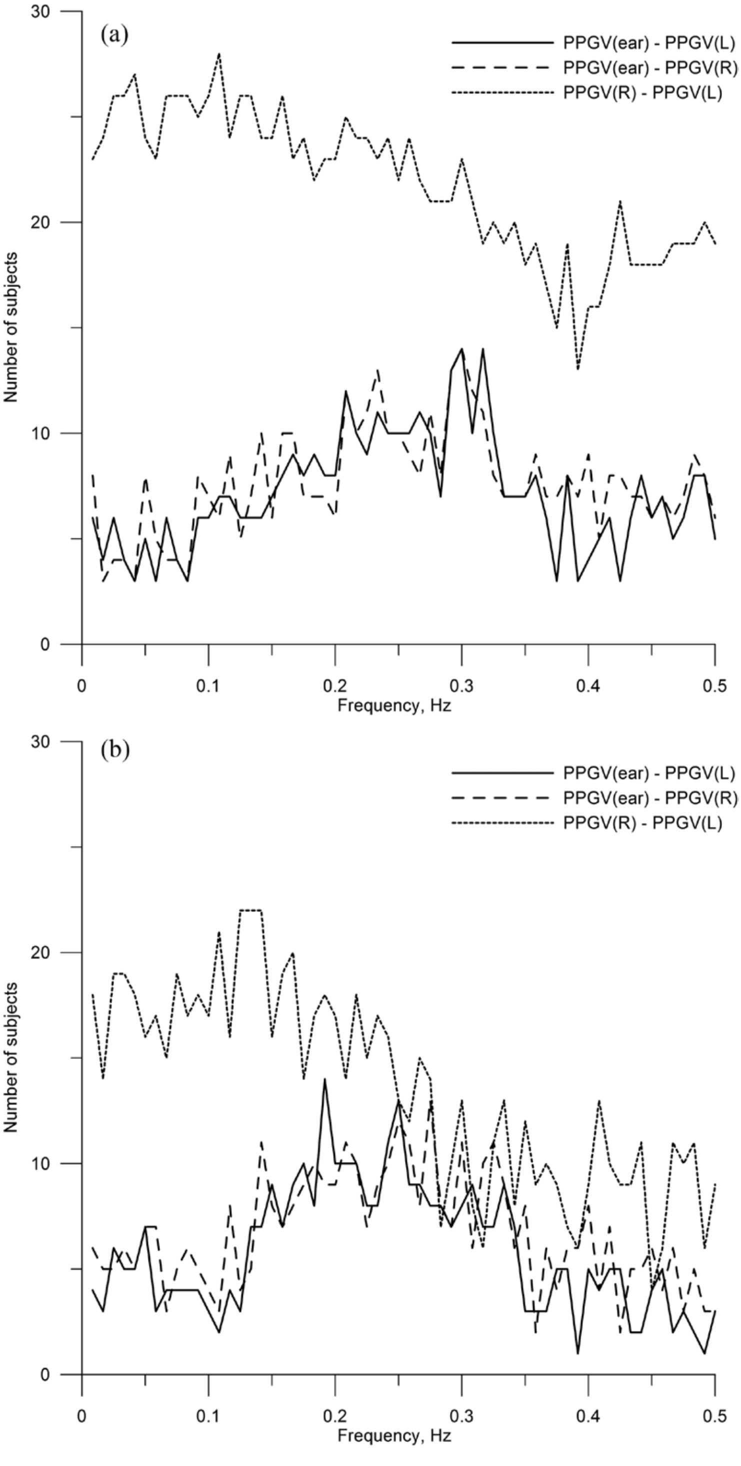

Figure 5. Number of healthy subjects with significant coherency between the indicated pairs of PPGVs in the frequency range from 0.005 to 0.50 Hz for the horizontal (a) and vertical (b) positions of subject's body.

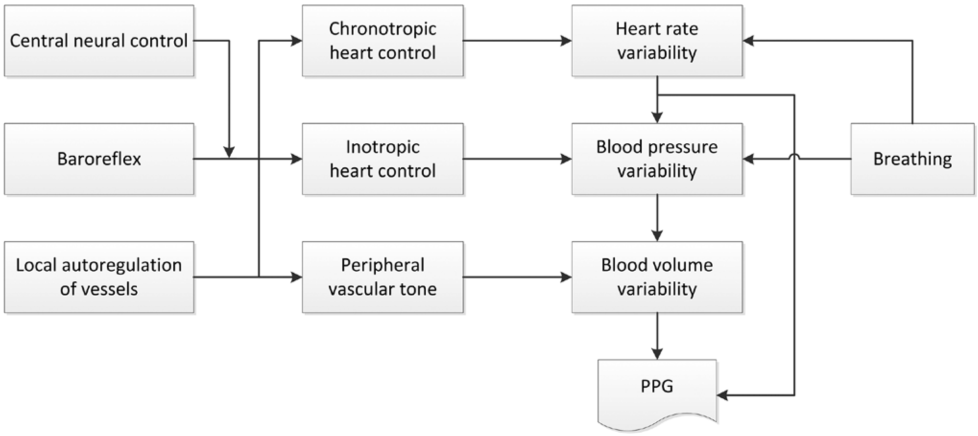

Figure 6. Generalized scheme of cardiovascular autonomic control system with marked position of PPG.

The frequency ranges of these processes overlap in part with the activity of 0.1 Hz baroreflex BP regulation that is a great problem for the interpretation of the origin of LF oscillations in PPGV.

Piepoli *et al* (1995) reported that LF power, together with other characteristics derived from the PPG waveform, can be used to classify the patients into the groups differing by systemic vascular resistance.

The constancy of BP and moderate increase of HR under the tilt test indicate the presence of fast processes of cardiovascular adaptation with the increase of the sympathetic activity in studied healthy subjects. Marchi *et al* (2013) have shown the increase of power of LF oscillations in BPV and decrease of baroreflex sensitivity under the modified head-up tilt test in healthy adults. In our studies of healthy subjects, the proportion of sympathetic vascular activity (accessed by LF%) was constant in all PPG signals (from ear and fingers) during the tilt test. The power of HF oscillations (accessed by HF%) increased only in finger PPG as a response to the tilt test.

We revealed the increase of index *S* of synchronization between the LF oscillations in HRV and each PPGV during the tilt test. This fact may be an indication of activation of interaction between the different parts of CVS (heart and distal vessels) in order to ensure the adaptation of blood flow to the changes of body position.

According to some authors, the PPGV for ear PPG is more susceptible to central influences (passive effect of systemic BP and vascular sympathetic nerve activity) (Awad *et al* 2001, Desgranges *et al* 2011, Chan *et al* 2012) than PPGV for finger PPGs. In our study, the degree of LF synchronization for the pair PPGV(ear)–HRV exhibits the most significant increase during the tilt test that is generally consistent with the opinion of the above-mentioned authors. Note that the contribution of LF oscillations to the spectra of each PPGV, especially to PPGV from earlobe, was significantly higher than the contribution of HF oscillations (see LF/HF in table 2) that is not typical for the HRV spectrum.

Previously we have shown that the mechanisms of autonomic 0.1 Hz control of HR and BP are functionally independent (Karavaev *et al* 2013). Taking into account that oscillations in blood supply in digital arteries contribute significantly to the PPG signal in fingers (Higgins and Fronek 1986, Rhee *et al* 1999), it is possible to study the interaction between the chronotropic heart control (regulation of HR) and regulation of systemic BP (figure 6). It should be noted that the autonomic regulation of systemic BP includes inotropic heart control (regulation of cardiac output) and the regulation of peripheral vascular tone (figure 6). In all of these regulatory processes, the baroreflex may be involved.

But PPG from the ear may have distinctive characteristics because of the difference in the structure of the vascular bed in fingers and earlobes. Actually, the spectra of finger PPGV from different hands are highly coherent, but differ substantially from the spectrum of PPGV(ear).

Note that the impact of respiration on the spectra of each PPGV is comparatively small. On the contrary, the impact of respiration on the spectrum of HRV is very well pronounced and often greater than the impact of LF oscillations. In orthostasis, the TP of each PPGV increases as well as the impact of HF (respiratory) fluctuations with respect to the impact of LF fluctuations in finger PPGV. We assume that PPG(ear) is less vulnerable to external mechanical conducting of breathing influences (independently from body position) than PPGs from fingers. It may be explained by the smaller diameter of distal arteries in the area of PPG(ear) registration and the features of local vascular self-regulation. Some authors demonstrated the potential use of PPG(ear) waveform variability in critical care (Middleton *et al* 2011a).

At the present time it is difficult to assess the balance between the autonomic regulation of BP and local self-regulation of vessels in PPG signals recorded from fingers and earlobes. Moreover, the baroreflex control of vascular tone in different basins of the distal bed may have specific features which require additional investigation. We suggest that oscillatory indices of PPGV from earlobes, PPGV from fingers of both hands, and HRV complement each other for better evaluation of the cardiovascular dynamics and its autonomic control.

Conclusion

Under the tilt test, the PPG signals registered from the earlobe and fingers exhibit similar, but not identical, changes in their spectra, and similar degree of synchronization of LF oscillations with LF oscillations in HR. All studied PPGs are characterized by a low influence of respiration and high power of LF (of about 0.1 Hz) oscillations. The spectra of PPGV for PPG signals recorded from the fingers of the right and left hand are highly coherent. PPGV for earlobe PPG shows low coherence with PPGV for finger PPGs. We assume that joint analysis of frequency components of PPGV (for earlobe and finger PPGs of both hands) and HRV and assessment of their synchronization may provide additional useful information about cardiovascular autonomic control.

Study limitations

The main limitation of our study is a small number of included healthy subjects. The further studies in healthy subjects of different age and unhealthy patients will be desirable.

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