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Dynamics of spectral indices of the heart rate variability and the photoplethysmogram and synchronization of the low-frequency oscillations in healthy subjects during the tilt test

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ABSTRACT

The spectral properties and synchronization of low-frequency (LF) oscillations during the tilt test were studied for the heart rate variability (HRV) and the finger photoplethysmogram (PPG) of healthy subjects. Dynamics of the LF oscillations in the PPG and synchronization strength between the HRV and the PPG were found to be inhomogeneous among healthy subjects, which suggest existence of individual differences in characteristics of adaptive reactions of the cardiovascular autonomic control.

Keywords: Tilt test, healthy subjects, heart rate variability, photoplethysmogram, spectral analysis, synchronization

1. INTRODUCTION

Different methods are used for fundamental investigation of the autonomic control of the cardiovascular system: analysis of the heart rate variability (HRV)[1], analysis of the blood pressure (BP) variability[2], detection of the synchronization between oscillating processes in the cardiovascular system[3,4]. Many fundamental and clinical studies[5] were dedicated to the investigation of synchronization between the low-frequency (LF) oscillations (with main frequency of about 0.1 Hz) in a number of biological signals from the cardiovascular system. Such oscillations can be extracted from the HRV [6,7], the BP [8] oscillations, the peripheral circulation and the microcirculation[9]. The origin of the LF oscillations in the HRV and the BP is relatively well-known (there are two main hypothesis: centrogenic[10] and baroreflectory [11]), but the origin of similar oscillations in the peripheral circulation is heavily debated. It is established that the LF oscillations in the HRV and the peripheral circulations can periodically synchronize with each other, providing functional cooperation between mechanisms of the autonomic control of those circulatory areas [5]. The original index S was already proposed for estimation of synchronization strength and demonstrated its potential importance for clinical applications[5].

The finger PPG is widely used for measurement of the peripheral circulation [12]. The PPG signal estimates the blood filling of finger tissues with vessels of various size and physiological purpose (finger arteries, arterioles, capillaries, veins and venules) [13,14]. The spectral power density of the PPG signal components is defined by oscillations of blood flow in those vessels. We could not find complex estimation of dynamics of the HRV spectral parameters, the PPG spectral parameters and value of the S index in available literature. Therefore we studied frequency spectra of the HRV, the PPG signals from symmetrical fingers and synchronization of the LF oscillations from these signals in healthy subjects during stages of the passive head-up tilt test.

2. MATERIAL AND METHODS

The study included 30 healthy volunteers (26 males and 4 females), age was 26.5 (25.0-29.0), the body mass index was 24.0 (22.0, 25.7) kg/m2 (data presented as the median with the lower and the upper quartiles). All volunteers didn't have the pre- and syncopal states in medical history and gave informed and voluntary consent to participate in the study.

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The study was approved by the Ethics Committee of Saratov State Medical University in Saratov, Russia, and informed consent was obtained from all participants. All procedures involving human participants were performed in accordance with the ethical standards of the institutional research committee and the Declaration of Helsinki and its later amendments.

All volunteers underwent 70º passive head-up tilt test with the spontaneous respiration. During the tilt test synchronous registration was conducted for the electrocardiogram (ECG), the respiration and the PPG of the distal phalanges of the both hands. Before the test subjects were laying in unstressed, awake state for at least 10 minutes.

The synchronous registrations were carried out for 3 minutes after the start of each state of the functional test (upright/supine), which were 10 minutes long. All studies were conducted in the same time of day (13:00–17:00). For the further analysis only recordings without the artifacts, the extrasystoles, the significant linear trend and the transition processes were used.

The following indices were evaluated during the HRV analysis 1: the mean heart rate, the spectral power density in the high frequency (HF) band (0.15-0.4 Hz) and the LF band (0.04-0.15 Hz) as a percentage from the total spectral power (hereafter referred as the HF% and the LF% respectively), and the LF/HF index. The similar indices were calculated for all of the PPG signals. Previously proposed method for estimation of the synchronization strength between the LF oscillations in the HRV and the PPG was also used. The reflectometrical PPG transducers were used to estimate the amplitude of the systolic wave (ASW), which characterizes pulse blood filling of the vessels. The measurements of the BP were carried out with the automatic shoulder tonometer «Omron i-C10».

Statistical analysis of the results included testing of the numerical data correspondence to the normal distribution law using the Shapiro-Wilk test. It was concluded that not all indices correspond to the normal distribution law and further analysis was conducted with the non-parametric methods. Data presented as the median with the lower and upper quartiles – Me (LQ, UQ). Analysis of the dynamics of the indices was performed with the Wilcoxon test for paired samples and with the Mann–Whitney U test for non-paired samples. To study the correlation relationships the non-parametric Spearman test was used. The statistical reliability of the results was set to at least 95%. Statistical calculations were performed with the Statistica 6.1 (StatSoft, USA) software.

3. RESULTS

The tilt test did not result in the syncope in any of the volunteers. Table 1 shows the dynamics of the heart rate (HR), the respiration rate (RR), the BP level, the ASW, the spectral indices of the HRV and the PPG. The mean BP during the passive orthostasis risen by 6.3% ($p<0.05$), in comparison to the supine value, and the peripheral vascular resistance risen by 62.4% ($p<0.05$). The distal phalanges ASW lowered by (ΔASW) 60% in relation to the supine position, and the correlation analysis did not reveal any relationships between the ASW and the PPG spectral indices (LF%, LF/HF) during stages of the passive head-up tilt test.

Table 1. Dynamics of the heart rate, the respiration rate, the BP level, the ASW, the spectral indices of the HRV and the PPG in healthy subjects during the tilt test (n=30)

Index	Supine position	Passive orthostasis	p-level
SBP, mm Hg	117 (110, 125)	116 (108, 128)	0.512
DBP, mm Hg	70.0 (69.0, 75.0)	84.0 (78.0, 88.0)	<0.001
PD, mm Hg	45.0 (40.0, 50.0)	32.0 (26.0, 39.0)	<0.001
MBP, mm Hg	91.0 (87.0, 95.0)	97.0 (92.0, 105.0)	0.036
ASW-R, pm	3.7 (1.0, 4.4)	0.8 (0.5, 1.5)	<0.001
ASW-L, pm	4.3 (2.0, 5.8)	1.2 (0.7, 2.2)	<0.001
Mean RR, number per minute	17.4 (15.1, 18.1)	17.2 (15.4, 19.8)	0.430
Mean HR, bpm	60 (56, 65)	80 (75, 89)	<0.001
HRV HF%	41.4 (27.1, 50.1)	16.2 (10.2, 28.4)	<0.001

PPG-R HF%	7.8 (4.8, 12.8)	10.4 (5.7, 14.6)	0.177
PPG-L HF%	6.1 (4.6, 10.3)	11.5 (5.7, 20.5)	0.005
HRV LF%	34.5 (26.9, 42.5)	54.1 (46.4, 63.5)	<0.001
PPG-R LF%	57.0 (49.5, 65.8)	59.9 (54.3, 65.7)	0.734
PPG-L LF%	56.0 (50.3, 64.7)	58.0 (44.9, 63.2)	0.544
HRV LF/HF	0.8 (0.5, 1.3)	3.0 (1.7, 6.3)	<0.001
PPG-R LF/HF	6.9 (4.7, 11.7)	5.8 (3.5, 10.3)	0.599
PPG-L LF/HF	9.0 (5.9, 11.1)	5.9 (4.9, 6.3)	<0.001
S index (HRV- PPG-R), %	38.1 (30.3, 44.2)	46.7 (36.4, 58.5)	0.003
S index (HRV- PPG-L), %	36.6 (30.8, 45.2)	51.3 (39.3, 57.2)	0.002

Data presented as the median with the lower and upper quartiles – Me (LQ, UQ). SBP, systolic blood pressure; DBP, diastolic blood pressure; PD, pulse pressure; MBP, mean blood pressure; ASW-R, amplitude of systolic wave in right hand; ASW-L, amplitude of systolic wave in left hand; RR, respiration rate; HR, heart rate.

The HF% and the LF% were used to compare the PPG from different fingers (p>0.05; Table 1). The correlation coefficient between the HF% of the PPG from different fingers was estimated to be r=0.57 (p<0.001) and r=0.64 (p<0.001) for the supine and the upright positions respectively; for the LF% – r=0.86 (p<0.001) and r=0,56 (p=0.001), respectively. On stages of the tilt test no correlations were found between the LF% and the HF% of the finger PPG and similar indices of the HRV.

During the tilt-test increase of the LF/HF was registered for the HRV and decrease was registered for the PPG (Table 1) and the HL/LF rise for the HRV was caused by the significant HF increase and HF decrease. The LF/HF ratio for the PPG of different fingers was similar for all stages of the tilt test (p>0.05).

The S index between the LF oscillations in the HRV and the PPG was similar on stages of the tilt test (p>0.05). Transition to the uptight position was accompanied by the statistically significant increase in the synchronization of the LF-oscillations for each pair of studied oscillations (p<0.01) (Table 1).

During further analysis of the finger PPG groups of healthy volunteers were separated accordingly to the individual dynamics of the LF% index during the passive orthostasis (Table 2). For 16 subjects in the upright position synchronous increase in the LF% was observed (subgroup A), for 8 – synchronous decrease (subgroup B), and for 6 – multidirectional dynamics of the LF% was observed (subgroup C, not analyzed in the present study).

Increase in the HR was more pronounced in subgroup B (Table 2). Dynamics of the pulse blood filling in subgroups A and B was similar and had comparable values of the ΔASW on similar stages (Table 2). Similarly to combined group of healthy volunteers significant correlation relationships were not present for the A and B subgroups between the spectral indices of the PPG on stages of the tilt test.

Transition to upright position was accompanied with increase of the S index for both subgroups up to the average of ~ 50%. In subgroup B changes were statistically significant for all observed pairs of oscillations (Table 2).

The dynamics of the HF%, the LF% and the LF/HF in spectra of the HRV for both subgroups was comparable to dynamics of the similar indices in combined group of healthy subjects (Tables 1 and 2). In the finger PPG multidirectional dynamics of the LF% was registered: increase for subgroup A and decrease for subgroup B (Table 2).

Table 2. Dynamics of the respiration rate, the amplitude of systolic wave, the spectral indices of the HRV and the PPG during the tilt test in healthy subjects in dependence to individual dynamics of the LF oscillations in the finger PPGs

Index	Supine position	Passive orthostasis	p-level
	Subgroup «A», n=16		
ASW-R, pm	3.8 (3.3, 4.6)	0.8 (0.5, 2.4)	0.002
ASW -L, pm	5.0 (3.8, 6.2)	1.4 (1.0, 2.4)	<0.001
Mean HR, bpm	57.5 (51, 62.5)	77.5 (71.5, 86)	<0.001
Mean RR, number per minute	15 (13.7, 17.3)	15.5 (14.0, 19.0)	0.066
HRV HF%	41.4 (27.5, 47.6)	13.5 (7.2, 28.9)	0.015
PPG-R HF%	10.5 (6.3, 13.8)	8.3 (5.1, 11.0)	0.717
PPG-L HF%	5.7 (5.1, 11.2)	12.0 (6.4, 24.2)	0.120

HRV LF%	34.3 (22.1, 38.5)	48.6 (36.4, 64.8)	0.015
PPG-R LF%	54.5 (49.1, 63.2)	60.6 (54.6, 65.8)	0.178
PPG-L LF%	55.1 (50.5, 62.3)	60.8 (55.5, 67.1)	0.214
HRV LF/HF	0.8 (0.5, 1.2)	3.9 (1.4, 8.4)	<0.001
PPG-R LF/HF	6.3 (3.9, 9.8)	7.6 (5.6, 11.5)	0.301
PPG-L LF/HF	8.9 (4.7, 10.9)	5.2 (2.7, 10.7)	0.717
S index (HRV – PPG-R), %	40.5 (35.8, 45.9)	49.4 (37.2, 57.5)	0.196
S index (HRV – PPG-L), %	42.9 (32.5, 53.9)	53.3 (43.7, 59.8)	0.108
	Subgroup «B», n=8		
ASW-R, pm	1.7 (0.8, 4.2)	0.7 (0.6, 0.9)	0.025
ASW -L, pm	3.2 (1.5, 5.2)	1.3 (0.9, 1.8)	0.025
Mean HR, bpm	63.0 (57.0, 71.0)	95.5 (77.5, 100.5)*	0.011
Mean RR, number per minute	16.6 (15.2, 17.1)	15.5 (14.0, 19.0)	0.998
HRV HF%	31.3 (26.9, 49.5)	19.2 (9.8, 29.0)	0.017
PPG-R HF%	5.7 (4.3, 8.8)	13.1 (5.4, 17.2)	0.068
PPG-L HF%	6.5 (4.1, 7.5)	11.1 (4.9, 21.7)	0.011
HRV LF%	41.8 (32.4, 43.8)	57.5 (51.0, 67.9)	0.017
PPG-R LF%	64.8 (57.0, 71.3)*	56.5 (48.3, 62.7)	0.011
PPG-L LF%	63.8 (56.6, 66.7)	49.9 (39.9, 60.4)*	0.092
HRV LF/HF	1.2 (0.7, 1.6)	4.0 (1.7, 7.1)	0.011
PPG-R LF/HF	9.0 (7.6, 15.8)*	4.4 (2.6, 10.9)	0.068
PPG-L LF/HF	10.1 (8.2, 13.2)	4.6 (2.5, 9.8)	0.011
S index (HRV – PPG-R), %	33.6 (24.4, 38.1)*	48.2 (37.0, 62.2)	0.011
S index (HRV – PPG-L), %	34.7 (25.6, 36.6)*	47.4 (37.2, 53.4)	0.011

* statistically significant difference from the similar indices in subgroup A. SBP, systolic blood pressure; DBP, diastolic blood pressure; PD, pulse pressure; MBP, mean blood pressure; ASW-R, amplitude of systolic wave in right hand; ASW-L, amplitude of systolic wave in left hand; RR, respiration rate; HR, heart rate.

4. DISCUSSION

The passive head-up tilt test causes dramatic outflow of the venous blood from the organs of the ribcage to the regions below the diaphragm. A number of reflexes activate to support hydrostatical response by increasing the sympathetic tone: increasing the HR, the myocardial contractility, increasing the peripheral vascular resistance. In our research the mean BP during the passive tilt test stayed within normal range and was accompanied with increase of the HR, at average by 35%, and 3-4 times decrease in the ASW in the peripheral vascular bed. The other parameters of the heart (contractility etc.) were not addressed in this study. It is established that the chronotropic response is defined by the sympathetic tone. During the tilt test the spectral power of the LF oscillations in the HRV increased by ~60% among all subjects. The physiological connection between this index and the HR is well established, the correlation coefficient (LF% vs HR) in present study showed moderate strength of relationship ($r=0.49$, $p<0.01$).

During the tilt test we expected evident increase of the LF% in the PPG signals. However for the combined volunteers group dynamics of the LF oscillations was rather modest and didn’t explain why the BP stayed sufficient for the normal perfusion during transition to the orthostasis. It appears that regulation of the vascular resistance on level of the distal vascular bed, estimated from dynamics of the LF% in the finger PPG, for tested subjects has significant differences during first ~10 minutes of the passive orthostasis. Assuming that the LF oscillations in the PPG signal reflect the sympathetic tone, than in 53% of cases the vascular resistance synchronously increased (subgroup A), in 27% of the cases synchronously decreased (subgroup B) and in in 20% – changes in symmetrical sections were opposite. In available literature we didn’t encounter the mentioning of such phenomenon. Subgroups A and B had following differences: 1) the LF% in the HR spectrum increased for both groups, and in the PPG spectrum it was the opposite; 2) the LF% in the HRV and the PPG was higher for subgroup B; 3) the HR in upright position was higher for subgroup B; 4) the S index in supine position was lower for subgroup B.

It appears the higher sympathetic tone means weaker functional interaction (characterized by the S index, which showed its relevance to cardiology [15, 16]) between the LF mechanisms of the autonomic control in studied sections of the cardiovascular system (the heart and the distal vascular bed). Assuming the LF oscillations in the PPG to be an index for the sympathetic activity, increase of the total peripheral vascular resistance among subgroup B during first minutes of the orthostatic stress was insufficient to support the necessary perfusion pressure. Therefore compensation was achieved by the high chronotropic activity of the sinoatrial node.

5. CONCLUSION

In this study we revealed inhomogeneity of healthy subjects in terms of dynamics of the LF oscillations in the HRV and degree of synchronization between the LF oscillations in the HRV and the PPG during the passive head-up tilt test which may suggest a presence of individual differences in characteristics of adaptive reactions of the cardiovascular autonomic control.

6. ACKNOWLEDGMENTS

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