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Synchronization and coherence of the low-frequency components of the signals of the cardiovascular system in newborns

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ABSTRACT

In this work, we analyzed the signals of heart rate variability and leg's photoplethysmograms of newborns. A series of experiments included 10 conditionally healthy subjects; each recording was carried out for 15 minutes during feeding. We used methods of spectral analysis and methods of nonlinear dynamics. This work shows some features of the autonomic nervous regulation of the cardiovascular system in newborns, an assessment of the degree of synchronization and the coupling of the loops for regulating heart rate variability and vascular tone using methods for calculating cross-spectrum, the coherence coefficient and the total percentage of phase synchronization.

Keywords: newborns, cardiovascular system, RR variability, synchronization, coherence, sympathetic regulation

1. INTRODUCTION

The development of methods for the functional diagnosis of the state of the cardiovascular system (CVS) allows one to identify deviations in the functioning of the body systems in the early stages, before any morphological changes in organs and tissues in adults, newborns, and children occur [1-8]. Non-invasive methods for the analysis of CVS are especially relevant for work with newborns. However, the development of applied analysis methods is often complicated by the lack of a clear understanding of the physiological mechanisms of the heart and blood vessels of this category of patients. The available modest amount of knowledge in this area indicates, first of all, a significant difference in the regulation of the loops of CVS in adults and newborns [9-24]. This work aimed to obtain more fundamental information about the nature of the interaction of the loops of the autonomic regulation of heart rhythm and vascular tone of newborns using spectral analysis and nonlinear dynamics.

2. MATERIAL AND METHODS

2.1 Subjects

The experimental group included 10 newborns (, chosen based on a healthy case history of their mothers and a normal birth. The identification of illnesses of any kind was reasons for disqualification). Experimental signals from newborns were recorded on the third day after birth. Signals were recorded during feeding, which made it possible to obtain data while awake. All parents were informed about the nature and objectives of the study and provided consent before participation. A series of experiments was conducted at the Perinatal Center (Saratov, Russia).

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2.2 Signal recording

Heart rate variability (HRV) is very useful and easily recorded phenomenon that can be analyzed in research as well as in clinical practice. Usefulness and accessibility of the HRV examination in neonatology are based on the fact that cardiac chronotropic regulation for a newborn is crucial; and that time series of the RR variability [25] can be easily obtained by ECG devices or by special (HRV) systems.

In the framework of this work, simultaneous recording of signals with a sampling frequency of 250 Hz was carried out by a standard certified recorder: the psychophysiological telemetric device "Reactor-T" (Medicom-MTD, Taganrog). The analyzed experimental signals were signals of electrical activity of the heart (ECG) and photoplethysmograms of blood vessels (PPG) of the newborn. This device made it possible to set the following settings for the bandwidth of the recorded signals: the ECG registration range was from 5 to 8000 mV, the cut-off frequency of the HPF during registration of all signals was 0.016 Hz. An infrared PPG sensor of reflected light was placed on the heel of the subject. The length of each experimental record was 15 minutes.

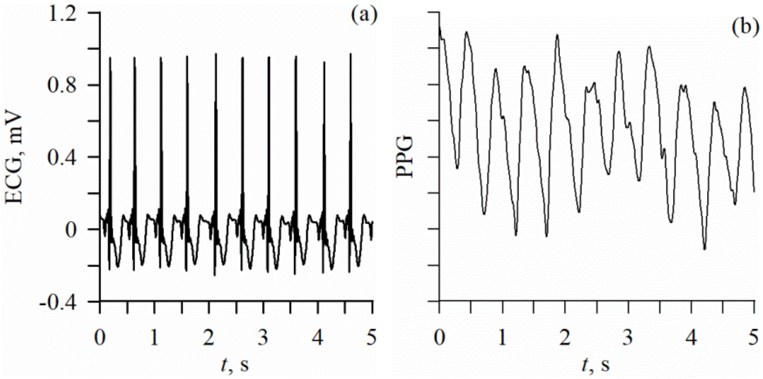

Figure 1. The examples of simultaneous experimental records of newborn A (duration 5 second): (a) – ECG, (b) – leg’s PPG.

The most commonly used methods for analysis include frequency domain measures [25]. The clinical relevance of heart rate variability was first appreciated in 1965 when Hon and Lee noted that fetal distress was preceded by alterations in interbeat intervals before any appreciable change occurred in the heart rate itself [26]. Therefore, the first step in analyzing the obtained data was to obtain information on heart rate variability from the electrocardiogram signal according to the method for estimating the duration of the RR intervals of the experimental ECG’s series [25]. A new signal - a signal of a sequence of RR-intervals (RR variability), was interpolated using cubic β-splines.

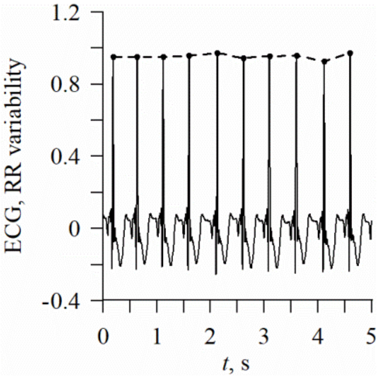

Figure 2. Examples of the plot of the experimental ECG signal (solid line) and the RR variability signal (dashed line). The curve for the RR variability is shifted up for presentation purposes.

3. RESULTS

The activity of the processes of autonomic regulation of CVS is reflected in the spectrum in the form of peaks at different frequencies. In the frequency domain, spectral analysis using Fast Fourier Transform enables to determine a spectral power in low frequency (LF) band reflecting the sympathetic activity in the standard frequency range LF: 0.04 −0.15 Hz, and power in high frequency band (HF: 0.15−0.4 Hz) determined mainly by the respiratory sinus arrhythmia mediated via parasympathetic nervous system, and peak heart rate: 1−2.5 Hz [25]. The presented frequency ranges LF and HF are introduced for the analysis of frequencies of adults and require adjustment when it comes to studies of newborns and infants [25, 13]. It is known that in children, the processes of autonomic regulation of cardiac and respiratory activity are reflected in the spectrum at other frequencies than is accepted in adults [13, 16, 27]. For example, the 0.1-Hz peak associated with sympathetic activity in adults, in infants, is observed below 0.1 Hz (Fig. 3) [24].

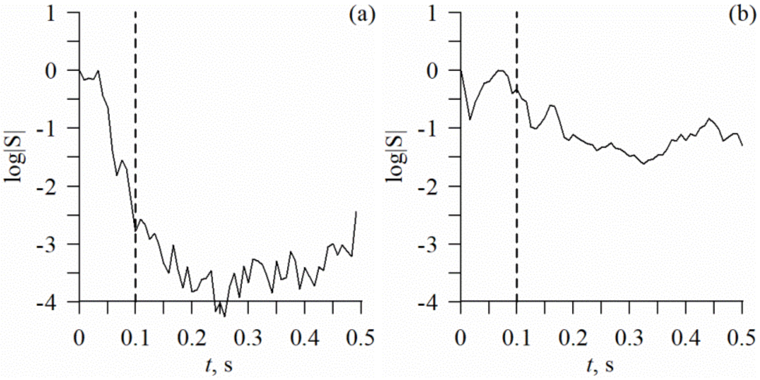

Figure 3. The logarithmic spectrum of the signals RR variability (a) and leg's PPG (b) for the subject A.

Standard linear HRV analysis by spectral analysis provides relevant information about periodic oscillations in heart rate. Standard linear HRV analysis by spectral analysis provides relevant information about periodic oscillations in heart rate. For all pairs of experimental RR variability and PPG signals, a coherence function with a critical significance level was calculated using the analysis of surrogate AFFT surrogates [28]. The presence of significant peaks in the LF range in the coherence function of a pair of signals indicates the presence of coherence between the low-frequency components in both signals.

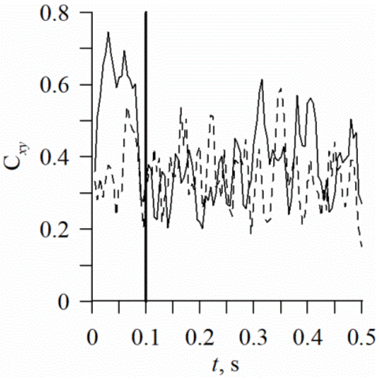

Figure 4. The cross-spectrum of PPG and RR variability signal for subject A. The dashed line indicates the significance level calculated using AAFT surrogates.

We also calculated the distribution density of significant maximums in the frequency [0.04−0.15] Hz over the entire sample of experimental signals. We found significant coherence between the RR variability and PPG signal in the range of about 0.1 Hz in about 20% of the newborns studied.

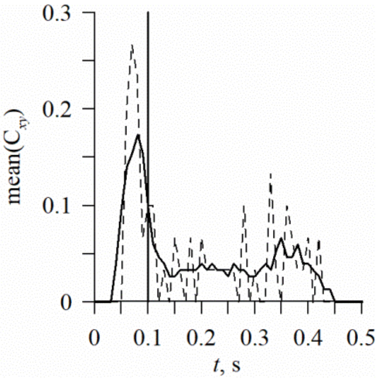

Figure 5. The distribution density of significant maximums in the frequency range [0.04.0.15] Hz over the entire sample of experimental signals. The solid line indicates the line smoothed in a sliding window.

The analysis is most useful when analyzing periodic oscillations, but in the complex control system output analysis, as in the case of human heart rate oscillations, where nonlinear components are also included. In this work, we analyzed the phase synchronization between the low-frequency components of the sympathetic autonomic regulation of CVS [7]. The method is based on the identification of signal phases using the Hilbert transform. Further, sections with a phase difference close to a constant value are recognized as phase synchronization intervals in a sliding window. A quantitative estimate of synchronization is the total percentage of phase synchronization (index *S*) − the ration of the sum of the lengths of all synchronous intervals to the total length of the time series, expressed as a percentage. In the study of healthy adults, the *S* index value was shown in the range from 40-50%, however, a sharp decrease in the indicator value was found in people who have an acute form of CVS pathologies (after myocardial infarction, etc.) [8]. In the analysis of adult subjects, a method for diagnosing synchronization among LF-frequency signal components has clinically proven itself. In this case, preliminary experimental signals are filtered by bandpass filters in the range [0.6–0.14] Hz, which allows one to distinguish only those components that are mainly associated with the influence of the sympathetic regulation loop. However, as noted above, in newborns and infants there is a shift in the frequency components of HRV. In this case, the search range for LF frequencies was also shifted to the lower frequency region: [0.04–0.1] Hz.

Table 1. The values of the total percentage for each subject, the statistical significance is indicated in parentheses.

Filtration band [0.04-0.1] Hz *S*, % (*p*)									
1	2	3	4	5	6	7	8	9	10
37,21 (0,71)	38,97 (0,32)	36,82 (0,86)	39,19 (0,34)	42,98 (0,36)	10,35 (0,99)	47,57 (0,31)	30,93 (0,84)	41,78 (0,60)	52,75 (0,26)

In addition to the method presented above, the interaction of low-frequency components was also analyzed by estimating the phase coherence coefficient − RO [29-30].

Table 2. The values of the RO coefficient for each of the subjects.

Filtration band [0.04-0.1] Hz *RO*									
1	2	3	4	5	6	7	8	9	10
0,12	0,13	0,11	0,26	0,07	0,11	0,11	0,26	0,19	0,16

The mean value of the phase synchronization coefficient was 37.85 ± 3.60 (mean + error of the mean). The mean value of the coherence coefficients was 0.15 ± 0.02. However, as can be seen in the table 2, the values of the coherence coefficient are extremely low, which may be due to the low sensitivity of this method and requires further research.

4. CONCLUSION

In the framework of this study, we recorded electrocardiogram and photoplethysmogram signals of 10 newborns. The received signals made it possible to study the features of sympathetic regulation of the heart and blood vessels of this category of subjects.

In the course of work, the features of the autonomic regulation of CVS in newborns were revealed. First of all, we are talking about the presence of a peak in the sympathetic activity of the processes of autonomic regulation at frequencies below 0.1 Hz. This result confirms the information of foreign and domestic researchers and leads to the idea that it is impossible to use methods for diagnosing the condition of adult CVS to study the condition of newborns with standard parameters: analysis frequencies, filtering frequencies, etc.

It is also worth noting the strong coherence in the analysis of the cross-spectrums of PPG and RR variability signals and a fairly high degree of phase synchronization of the sympathetic regulation loops of the heart rhythm and vascular tone of newborns. In the future, it is planned to increase the volume of the statistical sample, to study the degree of synchronization and the coupling of the loops of the autonomic regulation in healthy newborns and with severe pathologies of CVS.

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