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BASES AND SCIENTIFIC-TECHNICAL AND APPLIED ASPECTS OF PROCESSING OF RHYTHMOCARDIOSIGNALS

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Abstract. The known means and systems for description and determination of heart rate rhythmic are analyzed. The new mathematical model of rhythmocardiograms as periodically correlated stochastic sequence is on the first applied. Expressions of estimations of rhythmocardiogram characteristics are obtained and digital methods of their evaluation in the biomedical systems are developed. Methods of digital processing of rhythmocardiograms are developed and verification of the results had been made.

Keywords: electrocardiosignal; rhythmocardiosignal; heart rate; periodically-correlated stochastic sequence; stationary components; power spectral density; confidence.

Introduction. Cardiac rhythm (heart rhythm) is increasingly used in functional prognostic diagnosis of the psychoemotional and biophysiological state of the human body due to the nature (semantics) of its informativity. Information on cardiac rhythm contains a rhythmocardio signal - a sequence of values of RR-intervals of the electrocardiogram. Since the R-wave signals of the cardiac signal are associated with cardiac contractions, and the latter caused by the electrical impulses of the source is the bundle of His, controlled by the unconscious reactions of the body to external (internal) stimuli (through the autonomic nervous system), then their informative state of the organism (psychoemotional, biophysiological, Etc.) is very significant. This explains the role and importance of studying the rhythm of the heart, evaluating its characteristics, which has recently received considerable attention. The value of automatic (without human participation) definition (analysis, monitoring, etc.) of the characteristics of rhythmics, in particular its variability, variability, grows. The analysis of heart rate variability (HRV) concerns the technology of studying and evaluating the vegetative regulation of physiological functions. At the same time, it is necessary to ensure simultaneously sufficient reliability of the results of the analysis of rhythmics and the economic and technical effectiveness of equipment for automatic processing of the rhythmocardiosignal. However, the stochastic character, non-stationarity of the rhythmocardio signal causes difficulties in ensuring this requirement. In modern systems of rhythm monitoring this difficulty is bypassed by the complication of the apparatus.

To clarify the reasons for the inconsistency between the need to simultaneously provide sufficient reliability of the results of the analysis of rhythmics and the economic and technical efficiency of equipment in the automatic processing of the rhythmocardio signal, the biophysical, medical and technical aspects of it are primarily established.

Materials and Methods. Widespread use in the diagnosis of analysis of HRV characteristics led to the construction of a strict definition of variability. In the works of Baevsky RM, Zhematyi DI, Mironov VA, Mironova T.F. And others, three main characteristics of heart rhythm are distinguished: the spread of the RR-intervals in the ECG range studied, the variability of the RR-intervals in the transition from one cardiocycle to the other, and the nature of the periodicity of the change in the heart rate (HR) for a selected period of time. In his works (see [1]) Baevsky RM Means HRV as follows: First, HRV is the spread of the values of RR-intervals in the time interval under study $\Delta\xi^{i}_{RR}(t), i=\overline{1,\infty}$, $t\in[0,T)$; Secondly, HRV is the variability of the time interval between two adjacent cardiac contractions recorded during the transition from contraction to contraction $\xi^{i}_{RR}(t), i=\overline{1,\infty}$. Thirdly, HRV is the vibration of the heart rate around its mean value in the time interval under study. According to the first two definitions, HRV analysis is a time domain analysis, and according to the third one, it is analysis in the spectral range.

First of all, these definitions do not take into account all cases of the appearance of HRV. For a better understanding of the issue, let us first designate what is rhythm, variability, variability of rhythm.

Rhythmics - ECS selected (according to Einthoven) [2] in its morphological features, carries information on the phases of the heart, which is of a cyclic nature. In particular, the R-tooth all the time repeats cyclically (ECS is normal), if the cycle-to-cycle time does not change, then the cyclic repetitions are rhythmic.

Due to the influence of external (climate, human factors) and internal factors (the functioning of the human body systems), rhythmic work of the heart is not possible. The duration of each RR-interval varies. Adequate mathematical model for most practical (medical) problems of the magnitude of the rhythm is a random variable, in particular, with a normal distribution (Gaussian) distribution probability its values [3,4]. Therefore, to determine the rate used parameters of this distribution: mean and variance, that is to say that the heart is working rhythmically, if these parameters are not changed at different times. When the state of the body (functional tests), the value of these parameters (rate) can vary but for healthy organism it always returns to its previous state (the nature of this process is its adaptation fitness of the organism) [5].

If the rhythm is increased (or decreased), then the arrhythmia (eg., tachycardia, bradycardia). Sequences of RR-intervals are nonstationary nature (evolutionary) random process [6,7]. If the non-stationarity has a repeating oscillatory character, then the rhythm is called the variable [8,9].

Thus, HRV is a nonstationary random process of oscillatory character. In this case, the value of RR-intervals can be tied to a certain periodic (rhythmic) sequence of moments of time (in this case, the mathematical expectation is equal to a certain value). In the definition, it is advisable to enter numerical values for the parameters of the sequence of RR-intervals. In view of the foregoing, there arises the task of improving the mathematical model of rhythmocardiogram, which takes into account the nonstationarity of the variability of cardiac rhythm for increasing the reliability of the result of evaluating its characteristics.

The improvement of the HRV model, taking into account its nonstationarity, is necessary in order to allow the adaptation of a well-known or to develop a new corresponding, consistent, mathematical apparatus of analysis that is essential in the study and processing of rhythmocardiosignal [10].

By analogy, when constructing a mathematical model, stochastic oscillations and, the rhythm of natural processes, are used. Their properties are expressed by means of the energy theory of stochastic signals (Dragan J., Dragan A., Sikora L., Yavorsky B., Yavorsky I., Harry L. Hurd, Gardner W.A., Kallianpur G.).

The main cardiac rhythm describes a periodically correlated process (PCSP) and it is considered that it is a polyimpus type in which the same-name cardiac signals will be in-phase with respect to cardiac cycles. These applied accumulation method, which is one-phase method known periodicity statistics correlated processes:

$$\varphi_{\xi}^{N}(t_0, T) = \frac{1}{N} \sum_{k=\overline{1,N}} \varphi_{\xi}(t_0 + kT),$$

where is $\varphi(\cdot)$ a function of the RKG values; t_0 - the initial phase of the selection of the electrocardiogram; $t_0 \in [0, T)$; T - the period of correlation - the parameter of this model, $\xi(\cdot)$ - PCSP, N - note the number of RR-intervals.

Results. New expressions for assessing the characteristics of rhythmocardiogram were obtained, which allowed calculation of the parameters of digital processing and obtaining estimation methods with the predicted probability of evaluation results within the framework of the improved model. A spectral-correlation method for obtaining informative characteristics of the RCG is developed based on the use of in-phase and component analysis methods.

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It is established that the in-phase method of analysis of the RCG is effective for the long-term uniformity of the RCG statistics, and the component method for short-term stability, that is, it is sensitive to rapid changes.

The component method is based on the fact that the characteristics of the RCS (mathematical expectation and mean covariance) are periodic functions of time, and therefore are expressed by analogy with Fourier series in terms of the relation:

$$m(t) = \sum_{k\in Z} \hat{m}_k \, e^{\left(ik\frac{2\pi}{T}t\right)}, \quad t \in [0, T)$$

$$b(t,u) = \sum_{k\in Z} \hat{B}_k(u) e^{\left(ik\frac{2\pi}{T}t\right)}, \quad t \in [0, T)$$

where is m_k, $B_k(u)$ — components of the mathematical expectation and the correlation function of the RCG.

Estimates of their bias, dispersion, and correlation functions were obtained for such statistics of the RCG. It was found that unbiased (zero-shift) estimates with minimal variance and uncorrelated values would be effective. The properties of the estimates depend on the chosen evaluation rule (which determines the form of the function of the observed valuesand the length of the implementation of the analyzed segment.

The correlation analysis of the RCG is applied, in which, in addition to calculating the covariance estimates $\hat{b}(t,u)$, the correlation components $\hat{B}_k(u)$ are estimated. Evaluation of the correlation components (a known mathematical expectation of such an estimate is unbiased) statistics is:

$$\hat{B}_k(u) = M_t\left\{\xi(t+u)\overline{\xi(t)}e^{-ik\frac{2\pi}{T}t}\right\}, k \in Z,$$

where is $M_t\langle\bullet\rangle$ — the averaging symbol over the entire numerical axis is the parameter range t.

The obtained relationships indicate the properties of statistics of mathematical expectation, parametric covariance of the RCG and their components, determining the nature of the approximation of estimates to the estimated quantities, depending on the methods of finding them. In addition, component

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estimations of mathematical expectation and correlation functions of the RCG have advantages over those that are formed on the basis of samples over the correlation period with a small number of correlation components of the probability characteristics.

For verification, test sequences (test RCGs) are used. Examples of test RCGs generated by software using the developed algorithms are shown in Fig. 1 (a - within the framework of the model, stationary sequence, b - within the framework of the model, PCSP). The results of spectral analysis of test RCGs are presented.

The use of parametric methods and nonparametric methods, modified for application to random sequences, including PCSP (in-phase, component, filter methods for estimating spectral components) for spectral analysis of the RCG is investigated.

For a comparative analysis of the results obtained by combining test RCGs and spectral analysis methods, a system of indicators regulated in the relevant normative documents is used - the probability p_F of error, the probability p_D of a possible result, the threshold for choosing a probability decision v (eg, MI 187-86, 188-86. Methodical instructions. GSI. Reliability and requirements for verification methods of measuring instruments. - Moscow: Publishing Standards, 1987. - 39 p.)

Methods for the modification of standard such indices for computation of them by the components of the power spectral density of periodically correlated random sequences-an improved mathematical model of the RKG or a power spectral density-stationary model.

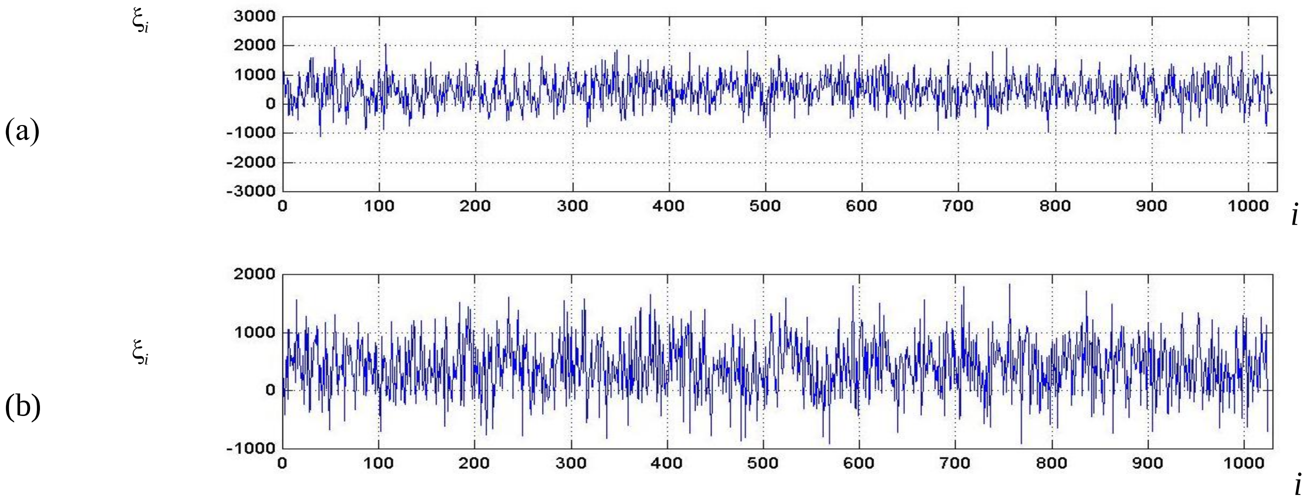

Fig. 1.

The adequacy of digital methods of processing rhythmocardiograms is established by the value of this probability.

To determine the reliability p_D of the estimation of the power spectral density (PSD) of the test signal, a threshold v was first found (test statistics for choosing the solution for the adequacy of the model). The probabilities p_F are chosen from a number of values $(0.001;\ 0.01;\ 0.1)$. Threshold

$$v = \sqrt{\sigma_0}\Phi^{-1}(1 - p_F) + m_0,$$

where is $m_0 = \sum m_{PSD} / N$, $\sigma_0 = \sum \sigma_{PSD}^2 / N$ – respectively, the mathematical expectation and the average deviation of the averaged value of the power spectral density of the stationary test RCG ("training" experiment). Here Φ^{-1} denotes the probability integral, a function inverse to $\Phi(x)$, which is realized by the function MATLAB norminv (inverse of the normal cumulative distribution function).

In Fig. 2 shows the graphs of the ensemble of the power spectral density of the stationary test sequence, and the thresholds (statistics) for choosing the correctness of the PSD estimation by the Neumann-Pearson criterion.

The thresholds were determined for given probabilities of incorrectness of the ensemble estimate of the estimates of the power spectral density of the realizations of the RCG (64 implementations of 128 values). In this case, the adequacy of the application of the normal probability distribution function of the RKG values is established.

The probability p_D of a probable estimate of the power spectral density of a non-stationary test RCG:

$$p_D = \Phi[v - (m_1 + \sigma_1)],$$

where is m_1, σ_1 — respectively, the averaged values of the expectation and variance of the spectral estimates RCG (e.g. PKSP).

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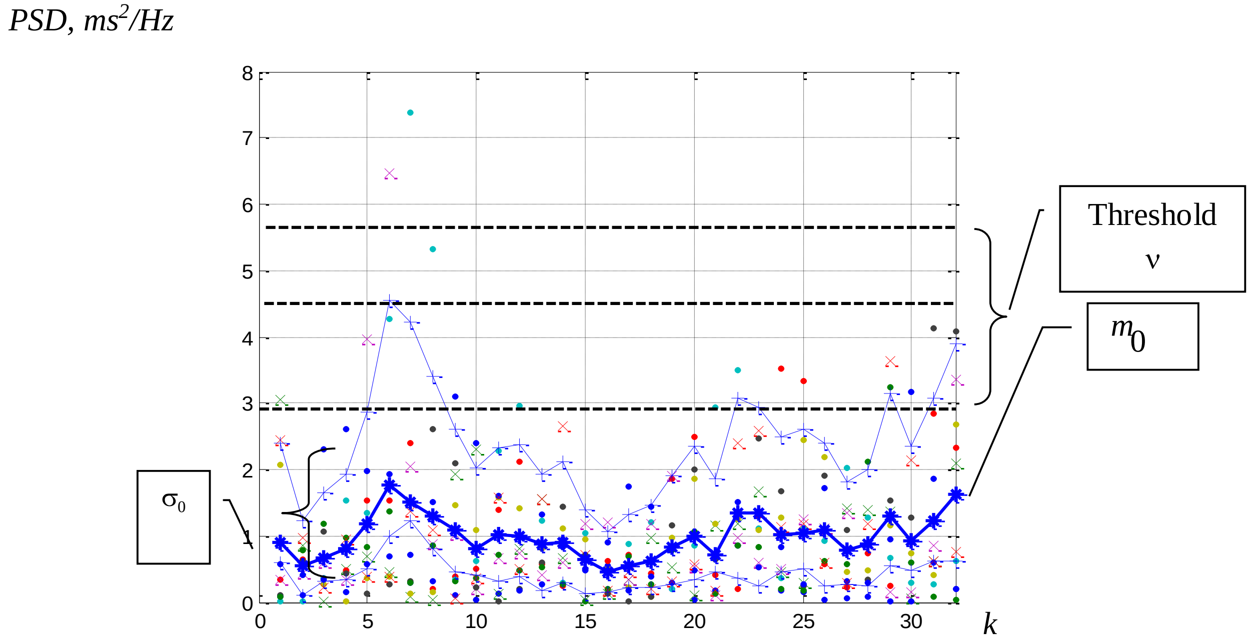

Fig.2

For the nonstationary RCG, these estimates are calculated taking into account the component structure:

$$m_1 = \frac{1}{kl}\sum_k \sum_l m_{kl} \,,$$

$$\sigma_1 = \frac{1}{(k-1)l}\sum_k \sum_l \sigma_{kl} \,,$$

where is k, l – indexes that determine the number of components and harmonics.

In Fig. 3 shows the graphs of the spectral components.

The use of spectral components for nonstationary sequences made it possible to obtain probable estimates of them, since in this case the spectra of the nonstationary sequence are concentrated on different stationary components, which are determined by the time structure of its spectrum and analysis, and the spectra of the stationary RCG are a partial case of them. Thus it is confirmed that the digital methods of processing the RCG for the determination of HRV characteristics directly from the results of the RCG analysis are informative, in contrast to the methods of processing within the framework of the stationary model.

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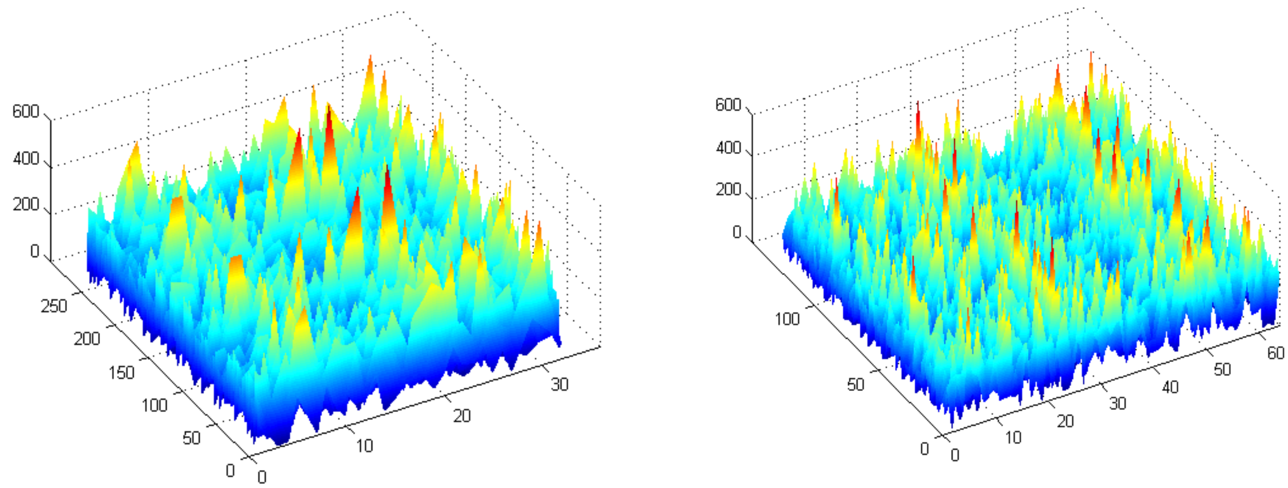
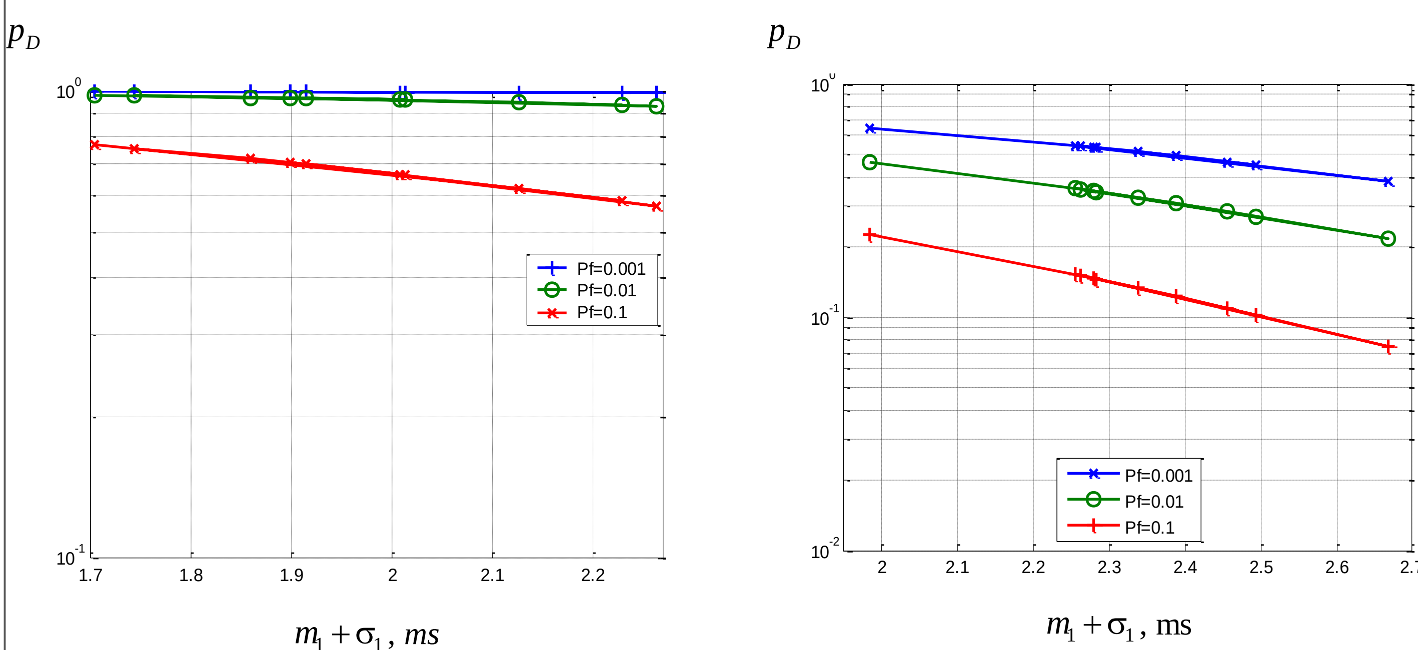


(a) (b)

Fig.3

It is noted that in the case of a RCG with a minimum number of components, it is more expedient to use the component method of analysis, since the in-phase method gives a mixing of characteristics, which is not informative for this type of signal.



(a) (b)

Fig.4

Figure 4 shows typical graphs of the predicted probability of estimates of the spectral density of the HRV power.

If the processing was carried out by the proposed digital methods of processing the RCGs constructed in the framework of the nonstationary model, then the automaticity of this processing is achieved by taking into account the nonstationarity parameters in the model. In this case, if the chosen model of the PCSP, then the probability curves for estimating the power spectral density for the test stationary signal are 1.3 times worse (as in Fig. 4a) as compared to the results obtained in processing the non-stationary sequence as stationary (because, the stationary signal is a special case of the PCSP).

Discussion: Unlike the known methods of heart rate analysis with the assumption of its stationarity, it is justifiable to distribute second-order statistics to the analysis of the non-stationary RCG than to improve known expressions for estimating the characteristics of a non-stationary RCG, which allowed automatic recording of digital processing parameters, the generation of stationary components of a sequence of RR-intervals Obtaining methods for evaluating non-stationary RCG and increasing the likelihood of its results.

The results obtained for the computer model of the estimation of the power spectral density of the non-stationary rhythmocardiogram within the framework of the nonstationary model in comparison with the results in which only the stationary model is taken into account are important in the functional prognostic diagnosis of the psychoemotional and biophysiological state of the human body.

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REFERENCES:

1. Bayevsky RM Cybernetic analysis of the processes of controlling the heart rate. In: Actual problems of the physiology and pathology of blood circulation: Collection of scientific works dedicated to the memory of Academician VV Parin. Moscow: Medicine; 1976. - 161-175.
2. Murashko VV, Strutynskiy AV. Electrocardiography. Moscow: Medicine; 1991.
3. Venttsel' MD, Voskresenskiy AD. Statistical analysis of heart rate and hemodynamics in physiological studies. Moscow: Science; 1974.
4. Dragan YA Random processes with finite mean power. 2nd Vilnius. Conf. On the theory of probability and mathematical statistics: abstracts, 1977: V.1: 133-134.
5. Aksenov VV, Artamonov VN, Bayevsky RM. Rhythm of the heart of athletes. Moscow: Physical Education and Sports; 1986.
6. Bendat J, Pirsol A Measurement and analysis of random processes. Moscow: World; 1972.
7. Ogura H Spectral representation of a periodic nonstationary random process. IEEE trans. on. Inf. Th., 1971: IT-17, 2: 143-149.
8. Ryabykina GV Heart rate variability. Moscow: “Star’Ko”; 1998.
9. Goldkr R Regulation of rhythm and homeostasis in biology and medicine. Cybernetics and a living organism. 1964: 31-78.
10. Yavorska EB Determination of the reliability of the method of assessment of non-stationary heart rate variability. 7th International Youth Forum "Radioelectronics and Youth in XXI century": sat. materials of the forum. 2007: 274.