Methods of Processing Cyclic Signals in Automated Cardiodiagnostic Complexes

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Abstract. The paper proposes the automated processing of an electrocardiogram based on the use of its mathematical model in the form of a cyclic random process. On the basis of the offered mathematical model the methods of processing of an electrocardio signal, in particular, methods of segmentation (identification of its segmental structure), methods of estimation of a rhythmic structure and methods of statistical processing are developed. We propose a complex system of new methods of processing electrocardiograms can be used as components of specialized software in cardiodiagnostic complexes in diagnostics of the human heart condition. The results obtained by the developed methods are used to obtain diagnostic features in the form of coefficients of orthogonal decompositions of normalized statistical estimates in cardiodiagnostic complexes for functional diagnostics of the human heart condition and based on this analysis; proposed software can automatically distinguish cardiac signals with rhythm disturbance pathologies from the normal range.

Keywords: electrocardiogram, cyclic random process, methods of segmentation, evaluation of the rhythm structure, statistical processing methods, diagnostic features.

1 Introduction

In many fields of science, there are various oscillatory phenomena and cyclic signals, examples of such signals are electrocardiosignals (ECS), cyclic processes of reliefs formations surface caused by mechanical effects on it, economic cyclic processes, signals describing astronomical phenomena and others. Their existence determines the relevance of their analysis of processing and modeling in different subject areas.

The problems of analysis of cyclic signals, in particular electrocardiograms (ECG), raise the question of evaluating their morphological and rhythmic characteristics. Two approaches are used for their analysis and modeling - deterministic and stochastic for the choice of their mathematical model. Mathematical models in the deterministic approach are quite simplified and do not allow to take into account the stochastic nature of biological signals. The stochastic approach uses different mathematical models [1-6]. Mathematical models are adequate, which, in addition to stochasticity, allow us to take into account both the morphological characteristics and the rhythm characteristics of real cyclic signals, in particular ECG. In the mathematical model presented in [6], the rhythm of a cyclic signal is taken into account by a continuous rhythm function and its morphological characteristics are taken into account due to its segmental structure. To evaluate the continuous rhythm function, it is necessary to obtain a discrete rhythmic structure. Such a structure can be obtained by applying its segmentation methods to ECS. They allow dividing into parts in the test signal characteristic segments: cycles, zones [7-17]. By determining the segmental structure, it is possible to evaluate the rhythmic structure, a characteristic that is related to the continuous rhythm function. Receiving continuous rhythm function, methods of statistical processing of cyclic ECS are applied. On the basis of his statistical estimates, his informative diagnostic features are analyzed. The obtained diagnostic features allow evaluating the diagnostic state of the patient's heart, for this purpose the diagnostic spaces are created. Taking into account both morphological characteristics on the basis of created diagnostic spaces and rhythmic characteristics on the basis of the estimated rhythm function, the procedure of diagnosis in automated cardio-diagnostic complexes can be performed. The elimination of such diagnostic complexes for processing cyclic signals, in particular, ECG, is an urgent scientific-technical task.

2 Literature review

The paper [6] describes a mathematical model of oscillatory phenomena and signals in the form of a cyclic function, which generalizes the concept of periodic and almost periodic functions for deterministic and stochastic mathematical models, in particular, introduces the concept of continuous and discrete cyclic random processes with a zonal-time structure. In papers [6, 19, 20] it was shown that the cyclic rhythmic structure of any cyclic function is fully described by the rhythm function, which determines the law of change of time intervals between single-phase values of the cyclic function. In automated systems for digital processing of cyclic signals, in particular, electrocardiodiagnostics systems, the methods of sampling [19], statistical processing [6] and computer modeling of cyclic signal [6] are used, which can be applied only if a certain rhythm function is determined. However, in most cyclic signal analysis tasks, their rhythm function is unknown, and it is therefore necessary to evaluate it in advance. In papers [20, 21], methods for estimating the rhythm function based on piecewise linear and piecewise quadratic interpolations of discrete rhythmic structure are described. As in most practical cases, nothing is known a priori about the regularities of changing the rhythmic structure values within the segment-zones, so the use of different approaches to evaluating the rhythmic structure is correct.

The research goal of this paper is to propose a system of interconnected, new methods of processing electrocardiograms that can be used as components of specialized software in cardiodiagnostic complexes in diagnostics of the human heart condition.

3. Method and results

3.1 Structure of cardiodiagnostic software

A block diagram of the related methods for ECG research is shown in Fig 1.

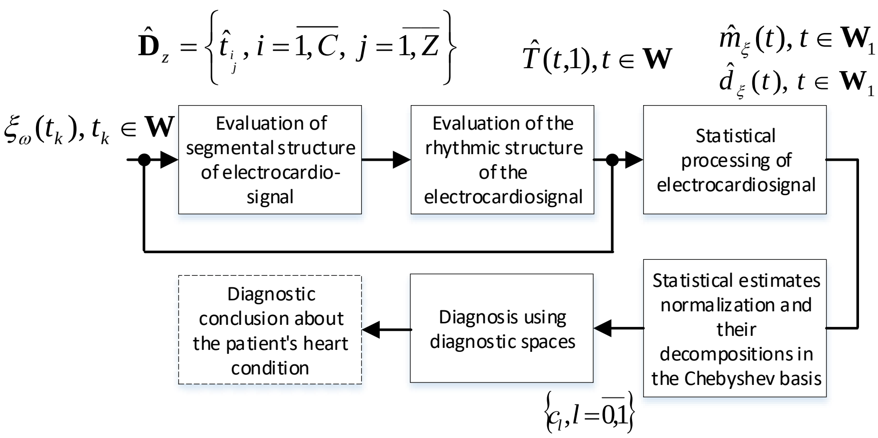


Fig. 1. Structure of cardiodiagnostic software.

Consider the methods of processing the ECS that are included in this block diagram and can form components of specialized software of cardio-diagnostic complexes.

3.2 Mathematical model of electrocardio signal

In paper [6], the definition of a cyclic random process according to it is a separable random process $\xi(\omega,t), \omega \in \mathbf{\Omega}, t \in \mathbf{R}$, is called a cyclic random process of a continuous argument if there is such a function $T(t,n)$, which satisfies the conditions of the rhythm function [6], that finite-dimensional vectors ($\xi(\omega,t_1)$, $\xi(\omega,t_2)$,…, $\xi(\omega,t_k)$) and ($\xi(\omega,t_1+T(t_1,n))$, $\xi(\omega,t_2+T(t_2,n))$) ,..., $\xi(\omega,t_k+T(t_k,n))$), $n \in \mathbf{Z}$, where $\{t_1, t_2,...,t_k\}$ - multiple separability of process $\xi(\omega,t), \omega \in \mathbf{\Omega}, t \in \mathbf{R}$, for all the integers $k \in \mathbf{N}$ are stochastically equivalent in the broadest sense.

In this definition $T(t,n)$ it is a the rhythm function of the cyclic process it defines the law of time changing intervals between the single-phase values, the basic properties of this function are described in paper [6].

In order to be able to conduct morphological analysis of the ECS and to evaluate its rhythm function, it is necessary to take into account in the mathematical model the segment-zone structure of its realizations.

Therefore, we present a mathematical model of cyclic ECS, in the form that takes into account its segment-zone structure in this form

$$\xi_\omega(t) = \sum_{i=1}^{C}\sum_{j=1}^{Z} f_{i_j}(t),\ t \in \mathbf{W}\ , \tag{1}$$

where Z – the number of segments-zones in the segment-cycle of the cyclic signal. $\mathbf{W}$ – area of definition of cyclic ECG, and range of values, for the case of a stochastic approach is the Hilbert space of random variable, that are given on one probabilistic space $(\xi_\omega(t) \in \mathbf{\Psi} = \mathbf{L}_2(\mathbf{\Omega}, \mathbf{P}))$. In design (1), the segments-zones of cyclic signal are related to segments-cycles and are determined by indicator functions, that is

$$f_{i_j}(t) = \xi_\omega(t) \cdot I_{\mathbf{W}_{i_j}}(t) = f_i(t) \cdot I_{\mathbf{W}_{i_j}}(t),\ i = \overline{1, C},\ j = \overline{1, Z},\ t \in \mathbf{W}\ . \tag{2}$$

In this case, the indicator functions that distinguish the segments-zones are defined as follows:

$$I_{\mathbf{W}_{i_j}}(t) = \begin{cases} 1,\ t \in \mathbf{W}_{i_j}\ , \\ 0,\ t \notin \mathbf{W}_{i_j}\ . \end{cases}, \tag{3}$$

where $\mathbf{W}_{i_j}$ – the area of definition of the indicator function, which in the case of a continuous cyclic signal, that is $\mathbf{W} = \mathbf{R}$, is equal to the half interval

$$\mathbf{W}_{i_j} = \left[t_{i_j}, t_{i_{j+1}} \right),\ i = \overline{1, C},\ j = \overline{1, Z}\ , \tag{4}$$

and in the case of a discrete signal, that is $\mathbf{W} = \mathbf{D}$, is equal to a discrete set of samples

$$\mathbf{W}_{i_j} = \left\{ t_{i_{j,l}}, l = \overline{1, L_j} \right\},\ L = \sum_{j=1}^{Z} L_j,\ i = \overline{1, C},\ j = \overline{1, Z}\ , \tag{5}$$

where L_j – the number of discrete samples of the investigated ECS on j-th area corresponding to its segment-cycle.

Segment-zone structure is taken into account by multiple time frames $\{t_{i_j}\}$ or $\left\{ t_{i_{j,l}}, l = \overline{1, L_j} \right\}$, $i = \overline{1, C},\ j = \overline{1, Z}$. In this construction of the mathematical model (1), the rhythm of the cyclic ECS due to the continuous rhythm function is taken into account $T(t, n)$, that is,

$$I_{\mathbf{W}_{i_j}}(t) = I_{\mathbf{W}_{{i+n}_j}}(t + T(t, n)),\ i = \overline{1, C},\ j = \overline{1, Z}, n \in \mathbf{Z}, t \in \mathbf{W}\ . \tag{6}$$

In order to evaluate the rhythm function $T(t,n)$ it is necessary to determine the segment structure of the ECS, that is to find $\hat{\mathbf{D}}_z = \{t_{\substack{i\\j}}, i=\overline{1,C}, j=\overline{1,Z}\}$, which is the set of time points that correspond to the boundaries of the segments-zones of the ECS. In medical practice in the processing of ECS distinguish segments-zones, which are usually designated – P, Q, R, S, T.

3.3 Methods for determining the segment-zone structure of ECS (segment structure evaluation)

Taking into account the justified mathematical model of the ECS, the statement of the problem of segmentation of a cyclic signal with a segmen-zone structure consist in the need to find an unknown set of time j-th segments-zone in the corresponding i-th segments-cycles $\mathbf{D}_z = \left\{t_{\substack{i\\j}}, i=\overline{1,C},\ j=\overline{1,Z}\right\}$, which is similar to finding a partition $\mathbf{W}_{\mathbf{W}}^{z} = \left\{\mathbf{W}_{\substack{i\\j}}, i=\overline{1,C},\ j=\overline{1,Z}\right\}$ areas of determination of ECS. It is thus necessary that for a certain set of moments of time $\mathbf{D}_z = \left\{t_{\substack{i\\j}}, i=\overline{1,C},\ j=\overline{1,Z}\right\}$ the conditions of biection of the established samples-zones were fulfilled, their ordering was faithful, that is, isomorphism with respect to the order of the samples (7), that correspond to the segments-zones , as well as the equality of attributes of the samples segments-zones (8), that is:

$$t_{\substack{i\\j}} \leftrightarrow t_{\substack{i+1\\j}}, \ldots;\ t_{\substack{i\\j+1}} > t_{\substack{i\\j}},\ t \in \mathbf{W}, i=\overline{1,C}, j=\overline{1,Z}, \tag{7}$$

$$p(f(t_{\substack{i\\j}})) = p(f(t_{\substack{i+1\\j}})) \to \mathbf{A},\ t \in \mathbf{W}, i=\overline{1,C}, j=\overline{1,Z}\,. \tag{8}$$

Similarly, within the framework of the mathematical model, the formulation of the segmentation problem of a cyclic ECS with a segment-zone structure is formulated, taking into account its phases. It is about finding an unknown set of time samples j-th segments-zone in i-th segments-cycles $\mathbf{D}_z = \left\{t_{\substack{i\\j}}, i=\overline{1,C},\ j=\overline{1,Z}\right\}$, which is similar to finding a set of single-phase values $\mathbf{A}_{\varphi_\alpha}$, that correspond to the boundaries of these segments-zone , that is

$$\mathbf{A}_{\varphi_\alpha} = \left\{ f\left(t^{\alpha}_{\substack{i\\j}}\right) : t^{\alpha}_{\substack{i\\j_1}} \leftrightarrow t^{\alpha}_{\substack{i\\j}},\ j_1 = const, i, j \in \mathbf{Z} \right\}. \tag{9}$$

The characteristics of the mathematical model mentioned in the statement of the segmentation problem [6], namely the attribute and the phase are important, they are used in ECS segmentation methods.

In practice, in systems of digital processing of cyclic data, analysis of cyclic signals is carried out: ECS, cyclic signals of relief formations [18], economic cycles, solar activity cycles, etc. whose mathematical models are cyclical random processes. Different methods can be used to solve the segmentation task [7-17], however, they must first and foremost be consistent with the mathematical model of ECS. In this paper, the method of segmentation presented in the paper is used [17]. It allows you to determine the segment-zone structure $\mathbf{D}_Z = \left\{ t_{i_j},\ i = \overline{1, C},\ j = \overline{1, Z} \right\}$ and its parameters. The block diagram of the developed segmentation method is shown in Fig. 2.

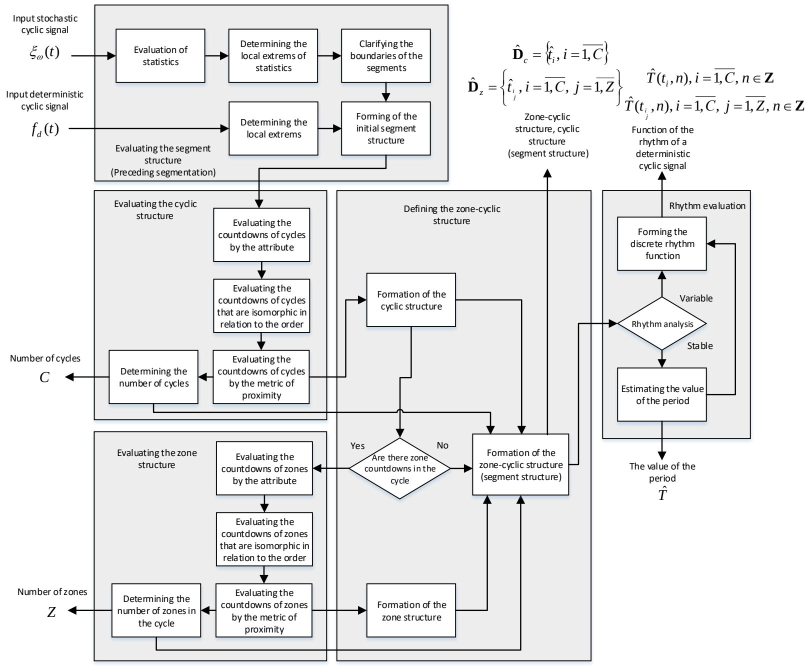


Fig. 2. Algorithmic support for the method of segmentation of stochastic cyclic signals

The results of the application of the developed method of segmentation of ECS are shown in Fig. 3.

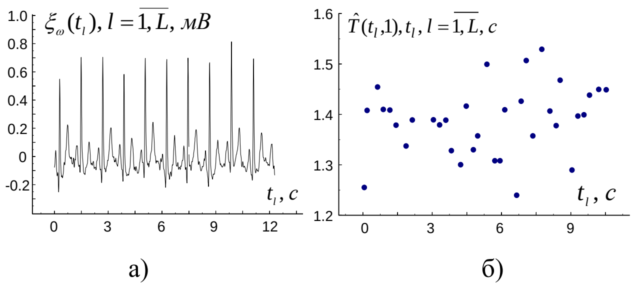


Fig. 3. Realization of cyclic ECS and its estimated rhythmic zone structure: a) realization of ECS (diagnosis is a conditionally healthy person); b) the discrete rhythmic zone structure of the ECS its samples correspond to the boundaries of the segments-zones (determined by the method of segmentation), and the values of the discrete rhythmic structure are defined by the formula (10).

The application of this method allows to evaluate the rhythm of cyclic ECS, which is important in the diagnosis, in particular allows to take into account pathologies that manifest in cardiac arrhythmias (tachycardia, bradycardia).

3.4 Methods for determining the rhythmic zone structure of the ECS (rhythmic structure estimation)

A discrete rhythmic structure for the case of a segment-zone structure of a discrete signal (see Fig. 3), when $\mathbf{W}=\mathbf{D}$ is defined as follows

$$\hat{T}(t_{i_j}, n) = t_{i_j+n} - t_{i_j},\ i=\overline{1,C},\ j=\overline{1,Z}, n\in\mathbf{Z}. \tag{10}$$

Having a rhythmic structure, it is necessary to evaluate it [6, 20, 21]. The formulation of the taks for the evaluation of the continuous rhythm function is given in paper [6, 20]. It is to determine the continuous rhythm function of a cyclic signal, that is, to determine such an interpolation function $\hat{T}(t,n),\ t\in\mathbf{W},\ n\in\mathbf{Z}$, which would pass through the discrete values of the rhythmic structure (discrete rhythm function) $\hat{T}(t_{i_j}, n), t_{i_j} \in\mathbf{W}, i=\overline{1,C},\ j=\overline{1,Z}, n\in\mathbf{Z}$ and would satisfy the conditions of the rhythm function $T(t,n)$, in particular, its derivative by argument, if any, should not be less than minus one [6, 20].

In practice, when creating cardio-diagnostic systems, it is taken into account that the processing of a cyclic signal, when a rhythmic structure is determined, will be if $n>0$, or rather by accepting $n=1$, conducting, for example, a statistical analysis taking into account of each subsequent cycle following one after the other, rather than selected cycles with a certain step, as is the case, for example, when $n=2$, respectively the first, third, fifth and so on cycles. Therefore, in the paper we will submit rhythmic structures, accepting $n=1$.

It is suggested to use the known method to evaluate the continuous rhythm function [20]. A block diagram of the method of estimating the rhythm function is shown in the figure 4.

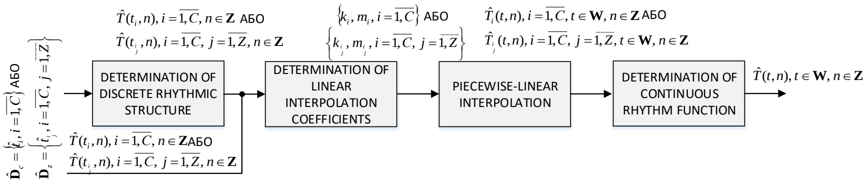


Fig. 4. Block diagram of a method of estimating the rhythm function of a cyclic electrocardiosignal by a piecewise-linear interpolation method

To estimate the continuous rhythm function, we use a piecewise-linear interpolant

$$\hat{T}_{i_j}(t,1) = k_{i_j} \cdot t + m_{i_j},\ i = \overline{1,C},\ j = \overline{1,Z},\ t \in \mathbf{W}. \tag{11}$$

The coefficients of the interpolate are determined by the formulas:

$$\begin{aligned} k_i &= \frac{\hat{T}(t_{i+1},1) - \hat{T}(t_i,1)}{t_{i+1} - t_i},\ i = \overline{1,C},\ j = \overline{1,Z-1},\ t_i \in \mathbf{W} \\ m_i &= \hat{T}(t_i,1) - \frac{\hat{T}(t_{i+1},1) - \hat{T}(t_i,1)}{t_{i+1} - t_i} \cdot t_{i+1},\ i = \overline{1,C},\ j = \overline{1,Z-1},\ t_i \in \mathbf{W}. \end{aligned}, \tag{12}$$

We use the formula to evaluate the rhythm function

$$\hat{T}(t,1) = \sum_{i=1}^{C} \sum_{j=1}^{Z} \hat{T}_{i_j}(t,1),\ t \in \mathbf{W}. \tag{13}$$

An example of the result of estimating a continuous rhythm function is given in the Figure 5.

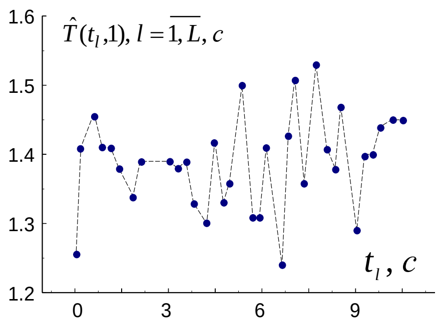


Fig. 5. The rhythm function was evaluated based on piecewise-linear interpolation.

3.5 Methods of statistical processing of ECS

Taking into account the mathematical model we will apply the developed methods of statistical processing presented in the paper [6]. The realizations of the statistical estimates of the probabilistic characteristics of the cyclic random process (ECS) are determined taking into account the estimated rhythm function, as follows statistical estimation of mathematical expectation of ECS:

$$\hat{m}_{\xi}(t) = \frac{1}{C} \cdot \sum_{n=0}^{C-1} \xi_{\omega}(t + T(t,n)),\ t \in \mathbf{W}_1 = [\tilde{t}_1, \tilde{t}_2). \tag{14}$$

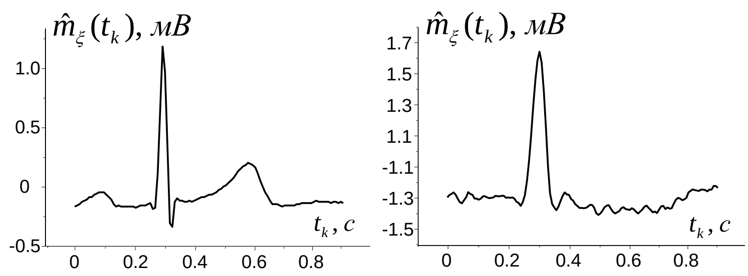
statistical evaluation of the dispersion of the ECS:

$$\hat{d}_{\xi}(t) = \frac{1}{C-1} \cdot \sum_{n=0}^{C-1} \left(\xi_{\omega}(t + T(t,n)) - \hat{m}_{\xi}(t + T(t,n))\right)^2,\ t \in \mathbf{W}_1 = [\tilde{t}_1, \tilde{t}_2). \tag{15}$$

where $\tilde{t}_1, \tilde{t}_2$ – the limits of the first cycle of the cyclic signal.

In paper [6], definitions and other probabilistic characteristics are described, in particular correlation and covariance functions, however, let us limit ourselves to these two characteristics because they are necessary for the next steps of processing the ECS.

The results of the obtained statistical estimates are shown in the figure 6.



а) б)

Fig. 6. Statistical estimation of electrocardiosignal cycles: a) statistical estimation of the mathematical expectation of the ECS cycle, a conditionally healthy person; b) statistical estimation of the mathematical expectation of the cycle of ECS, with the pathology of ischemia.

3.6 Methods for determining the diagnostic features of an ECS

In order to obtain informative diagnostic features of ECS, the paper [22] was proposed to use the decompositions of the obtained statistical estimates of the cycles of the ECS in the Chebyshev basis. The procedure of normalization of statistical estimates was used for the purpose of the one-type approach for estimation of the deduced diagnostic estimates, and only then we make their decomposition.

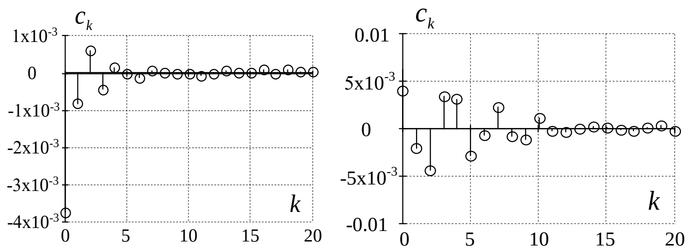


Fig. 7. Realization of statistical estimations of mathematical expectation of ECS and coefficients of their decomposition into the Chebyshev series: a) conditionally healthy person; b)in pathology of ischemia.

For normalization procedure we use formulas

$$\hat{m}_{н}(t) = \hat{m}_{\xi_1}(t \cdot \frac{T_1}{T_{н}}), t \in \mathbf{W}_{н}, \hat{d}_{н}(t) = \hat{d}_{\xi_1}(t \cdot \frac{T_1}{T_{н}}), t \in \mathbf{W}_{н} . \tag{16}$$

Herewith the area of definition of normalized statistical estimates is assumed equal to the area of definition of the first segment-cycle $\mathbf{W}_{н} = \mathbf{W}_1$, and the duration of the normalized cycle will be equal to the duration of the first cycle $T_{н} = \hat{T}_1$.

Examples of obtained statistical estimates of ECS are shown in the figure 7.

The obtained decompositions of statistical estimations allow build diagnostic spaces on the basis of the first two coefficients and to carry out diagnostics in automated diagnostic complexes.

4 Conclusions

This paper proposes consistent new methods of ECS processing, which together allow it to be processed for diagnostic purposes. They can be used as components of specialized software in cardio-diagnostic complexes in carrying out diagnostics of a human heart condition.

In the future researches, it is planned to build diagnostic spaces based on statistical estimates of ECS taking into account various pathological features of such cyclic signals and to implement automated diagnostic procedures based on the use of neural network algorithms.

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