Software for statistical processing and modeling of a set of synchronously registered cardio signals of different physical nature

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Abstract
It has been developed the software complex, that allows to perform mutual statistical processing of synchronously registered cardiosignals on the basis of the vector model of the cyclic rhythmically connected stochastic processes.
The developed software provides the ability to form a discrete rhythm function, depending on the number of cycles and zones of the cardio signal to be modeled. The developed set of programs allows to perform statistical processing of synchronously registered cardiosignals of different physical nature and to obtain estimates of mathematical expectation, dispersion, autocorrelation and mutual correlation functions taking into account the rhythm function and the period. The software also allows you to simulate cardio signals, using the loaded input data of the cardiosignal, rhythm functions, the number of cycles and zones of the signal to be modeled.

Keywords 1
Synchronously registered cardiosignals, statistic processing methods, software complex

1. Introduction

Cardiovascular diseases in the world are a serious problem. The medical-social burden of the circulatory system diseases, especially exacerbated by the rapid spread of COVID-19 and is that they significantly affect the duration and life quality, the loss economic potential indicators of countries. That is why the fight against diseases of the circulatory system at the present stage is a priority problem of modern medicine [1, 2]. Therefore, the development of modern technologies for instrumental diagnosis of the cardiovascular system (CVS) pathology in the early disease stages, monitoring the effectiveness of preventive and curative measures, as well as monitoring the vital functions of the body in critical conditions is an urgent problem of modern medicine and technology [3, 4].

A promising direction to overcome this problem is to improve existing methods of instrumental diagnosis of CVS by developing new diagnostic and prognostic features based on the choosing adequate mathematical analysis methods of synchronously registered signals. To date, a significant number of functional methods for studying the state of the CVS, which uses the synchronous registration of several identical or different in origin cardiosignals. One of the main ones is the synchronous registration of the electrocardiogram (ECG) in different leads [5] and in standardized formats [6].

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When monitoring the vital functions of the body, which occurs during the provision of emergency and urgent medical care, synchronously recorded key indicators of the body: ECG, curves of arterial and central venous pressure, external respiration, oxygen and carbon dioxide in the blood and others, depending on specific clinical situation and capabilities of the applied equipment [7, 8]. Mechanical devices to support blood circulation in advanced heart failure are considered in the work [9].

However, and in this situation the diagnostic analysis is conducted on each signal in particular which is compared with age norm or magnitude which is defined and corrected by the doctor. An urgent problem today is the improvement of existing methods of instrumental diagnosis of the cardiovascular system by developing a software package for the analysis of cardio signals.

A smart system for monitoring and predicting heart disease, which is based on in-depth training, is presented in the work [10]. The article [11] presents cardio diagnostic systems that use artificial intelligence and machine learning, as it concerns the health of the cardiovascular system. Cyclic analysis between meteorological rhythms of respiratory and cardiovascular diseases is considered in [12]. Diseases of the circulatory system under the influence of ionizing radiation are considered in this work [13].

Algorithms and methods of cardiac signal processing are created on the basis of their adequate mathematical models. Thus, it can be stated that today the methods of compatible automated processing of the set of synchronously registered cardiosignals (SRCS) have not received significant development. This is due to the insufficient level of development of unifying ideas in the construction of mathematical models of different types of cardiosignals and diversity of methods for their processing. The development of other highly informative diagnostic methods also had a significant impact. However, it can be stated that the development of optimal ways to analyze SRCS or vital parameters of the organism with access to new integrated indicators and empirical confirmation of their higher diagnostic value, compared to existing ones, can raise to a new level the nature of diagnostic process and health management treatment.

Despite significant advances in mathematical modeling of cyclic heart signals, their existing models do not take into account the following facts. For example, new diagnostic features for cardio diagnostic systems based on the model of electrocardiographic signals in the form of a vector of cyclic random processes are considered in [14].

The above arguments indicate the relevance of software for statistical processing and modeling of cardiosignals based on a mathematical model in the form of a vector of synchronously registered cardio signals for the needs of automated cardiodiagnostics.

The effectiveness of modern cardiodiagnostic systems largely depends on the hardware and software components on which they are based. The use of various processing methods included in the software significantly expands the functionality and increases the reliability of human heart diagnosis [15]. While the methods are based on mathematical models that establish the possibility and specifics of processing. In particular, the simultaneous processing of cardiosignals of different physical nature can be performed only if their mathematical models are in some way correlated and have a similar structure.

2. Analysis of recent researches

A stochastic approach to their simulation is mainly used in the direction of cardiac signal processing. Thus, for this purpose, use the mathematical models of cyclostationary signals [16-18], modeling diagnostic features [19-20], analytical approaches for myocardial fibrillation signals [21], modeling the pulse signal by wave-shape function [22]. An interesting approach to the description of cardio signals is the mathematical model presented in [23]. It allows to take into account both morphological features of cardiac signals and their rhythmic structure. It is important that this mathematical model takes into account the common rhythm of synchronously recorded cyclic cardio signals of different physical nature, which do not allow to implement other mathematical models using a stochastic approach. In order to be able to apply the proposed mathematical model, a necessary condition is the availability of information about the characteristic elements of cardio signals (cycles and zones, such as zones P, Q, R, S, T - electrocardiogram). It is possible to obtain tau information about the characteristic elements of cyclic cardiac signals by applying their segmentation methods, for example, the methods presented in [24], other methods of analysis of cardio signals are presented in [25-27].

3. Objectives

The work is devoted to the creation and application of software for statistical processing and modeling of synchronously registered cardiac signals as components of cardio diagnostic systems.

The importance of these studies lies in the possibility of using a common rhythm in the modelling and static processing of different in nature cyclic signals but formed by a single source.

4. Method

According to paper [22], we give a definition of the vector of cyclic rhythmically connected stochastic processes.

Definition 1. If there is a function such as $T(t,n)$, which satisfies the conditions of the rhythm function that finitely measurable vectors $\{\xi_{i_1}(\omega,t_1),\xi_{i_2}(\omega,t_2),...,\xi_{i_k}(\omega,t_k)\}$ and $\{\xi_{i_1}(\omega,t_1+T(t_1,n)),\xi_{i_2}(\omega,t_2+T(t_2,n)),...,\xi_{i_k}(\omega,t_k+T(t_k,n))\}$ $n\in\mathbf{Z},i_1,...,i_k=\overline{1,N}$, where $\{t_1,...,t_k\}$- multiple separability of the vector $\mathbf{\Theta}_N(\omega,t)$, for all the integers $k\geq 1$ are stochastic equivalent in the broadest sense, we will call the vector $\mathbf{\Theta}_N(\omega,t)$ of cyclic stochastic processes $\left\{\xi_i(\omega,t),\, i=\overline{1,N},\, \omega\in\mathbf{\Omega},\, t\in\mathbf{W}\right\}$ as the vector of strictly rhythmically connected stochastic processes and the processes as strictly rhythmically connected.

Area of definition $\mathbf{W}$ vector of cyclic rhythmically connected stochastic processes can be as ordered discretely $\mathbf{W}=\mathbf{R}=\{t_{ml}\in\mathbf{R},m\in\mathbf{Z},l=\overline{1,L}\}$ or continuous $\mathbf{W}=\mathbf{R}$ set of real numbers. In the case of discrete domain definition $\mathbf{W}=\mathbf{D}$ for its elements if $m_2>m_1$, or if $m_2=m_1$, a $l_2>l_1$, in other cases $t_{m_1l_1}>t_{m_2l_2}; m_1,m_2\in\mathbf{Z}$, $l_1,l_2\in\overline{1,L}$ there is a type of linear ordering: $t_{m_1l_1}<t_{m_2l_2}$. Moreover $0<t_{m,l+1}-t_{m,l}<\infty$.

The rhythm function $T(t,n)$ determines the law of changing the time intervals between the single-phase values of the vector of cyclic rhythmically connected stochastic processes. The function of the rhythm satisfies such conditions according to the theorem which is proved in the paper:

$$\text{a) } T(t,n)>0,\text{ if } n>0\ (T(t,1)<\infty);$$
$$\text{b) } T(t,n)=0,\text{ if } n=0;$$
$$\text{c) } T(t,n)<0,\text{ if } n<0,\ t\in\mathbf{W}; \quad (1)$$

for any $t_1\in\mathbf{W}$ and $t_2\in\mathbf{W}$, for which $t_1<t_2$, for function $T(t,n)$ should be performed a strict inequality:

$$T(t_1,n)+t_1<T(t_2,n)+t_2,\ \forall n\in\mathbf{Z}; \quad (2)$$

function $T(t,n)$ is the smallest modulo ($|T(t,n)|\leq|T_\gamma(t,n)|$) among all such functions $\{T_\gamma(t,n),\gamma\in\mathbf{\Gamma}\}$, which satisfy (1) and (2).

In the partial case, if the rhythm function is $T(t,n)=n\quad T\ (T>0,n\in\mathbf{Z})$, we will call the vector $\mathbf{\Theta}_N(\omega,t)$ as the vector T - periodically connected stochastic processes.

Let us consider the properties of some probabilistic characteristics of the vector $\mathbf{\Theta}_N(\omega,t)$ cyclic rhythmically connected stochastic processes. So, for its compatible k - measurable distribution function takes place equation:

$$F_{k_{\xi_{i_1}\dots\xi_{k_1}}}(x_1,\dots,x_k;t_1,\dots,t_k)=$$
$$=F_{k_{\xi_{i_1}\dots\xi_{k_1}}}(x_1,\dots,x_k;t_1+T(t_1,n),\dots,t_k+T(t_k,n)),n\in\mathbf{Z},i_1,\dots,i_k=\overline{1,N},t_1,\dots,t_k\in\mathbf{W} \qquad (3)$$

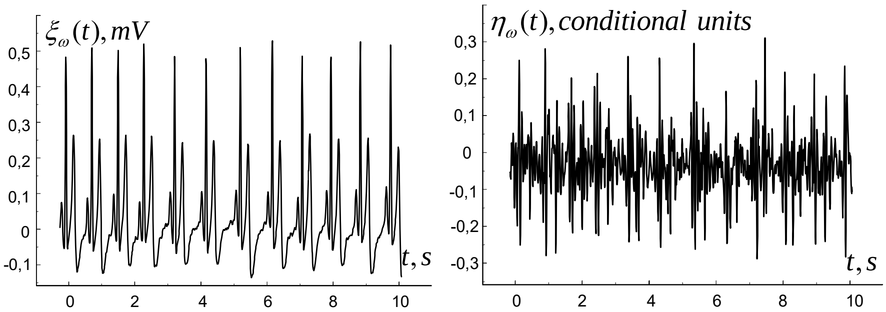
Combined central moments function of order $p=\sum_{j=1}^{k}R_j$:

$$\begin{aligned} r_{p_{\xi_{i_1}\dots\xi_{i_k}}}(t_1,\dots,t_k) &= \mathbf{M}\{(\xi_{i_1}(\omega,t_1)-m_{\xi_{i_1}}(t_1))^{R_1}\cdot\ldots\cdot(\xi_{i_p}(\omega,t_k)-m_{\xi_{i_k}}(t_k))^{R_k}\}= \\ &= r_{p_{\xi_{i_1}\dots\xi_{i_k}}}(t_1+T(t_1,n),\dots,t_k+T(t_k,n)),t_1,t_2,\dots,t_k\in\mathbf{W},i_1,\dots,i_k=\overline{1,N},n\in\mathbf{Z}. \end{aligned} \qquad (4)$$

5. Results and Discussion

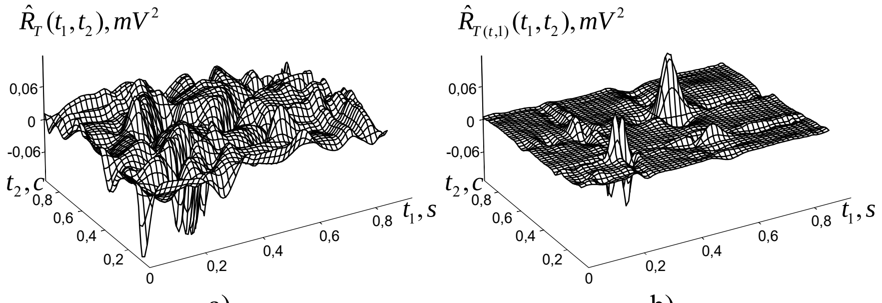
It was made the series of experiments on processing of the cardiaosignals of the same and different physical origin which were investigated for the purpose of approving of the greater effectiveness of the simultaneous processing of synchronously registered cardiosignals (SRCS) based on the model of the vector of cyclic rhythmically connected stochastic processes in comparison with the well-known method of their processing.

As the example it is shown on the Figure 1 the realizations of SRCS electrocardiosignal (ECS) and phonocardiosignal (PCS) and on the figures 2-4 are represented the results of a comparative analysis.



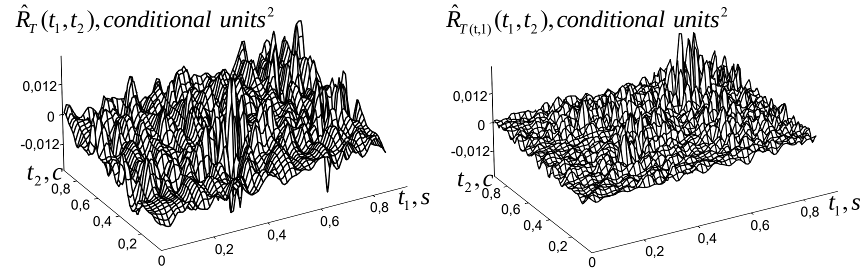
a) b)

Figure 1: The realizations of SRCS: (a) electrocardiogram, (b) phonocardiogram.



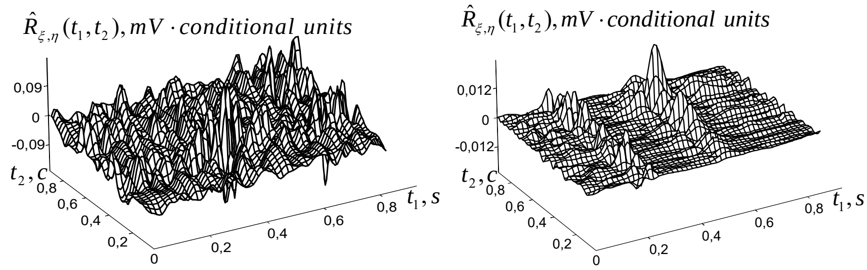
a) b)

Figure 2: The realization graphs of statistical estimations of the autocorrelation function of the ECS while its processing on the basis of: (a) the vector of periodically connected stochastic processes; (b) the vector of cyclic rhythmically connected stochastic processes.



a) b)

Figure 3: The realization graphs of statistical estimations of the autocorrelation function of PCS while its processing on the basis of: (a) the vector of periodically connected stochastic processes; (b) the vector of cyclic rhythmically connected stochastic processes.



a) b)

Figure 4: The realization graphs of statistical estimations of the mutual correlation function of the ECS and PCS while its processing on the basis of: (a) the vector of periodically connected stochastic processes; (b) the vector of cyclic rhythmically connected stochastic processes.

It was set in the result of the comparative analysis of the statistical processing of sets of SRCS which was made that the method of statistical processing of the analyzed cardiosignals on the basis of the vector of cyclic rhythmically connected stochastic processes significantly reduces the negative effect of "blurring" of statistical estimations of mutual correlation functions as a part of set of synchronous cyclic signals of a heart that is strongly-pronounced in results of statistical processing of the cardiac signals which were investigated on the basis of the vector of periodically connected stochastic processes. It is proved by the fact that the new method of compatible statistical processing takes into account the variability of the SRCS rhythm, in contrast to the well-known methods.

5.1 Software operating principle

It was developed the software complex which allows to perform SRCS statistical processing and its structural scheme is shown in Figure 5.

In this complex was implemented: block of SRCS formation, SRCS filtering block, trend removal block, SRCS segmentation block, block for determining the SRCS rhythm function, statistical analysis block of the rhythm function, valuation block of statistical estimates of SRCS, statistical analysis block of SRCS, dimension minimization block of the vector of informative features, diagnostic block.

The exported synchronously registered cardio signals were used from PhysioNet in accordance with the article [28] in the SRCS implementation generation unit. Pre-processing units are designed to filter and extract trends from SRCS. The segmentation unit is used to obtain the time-time structure of SRCS to determine their rhythmic functions. Blocks of statistical processing are intended for the normalization of statistical estimations, the analysis of investigated cardiac signals. The block of minimization of dimensionality of a vector of informative signs is necessary for minimization of their quantity representing norm or a certain pathology of the cardiovascular system. The diagnostic unit allows you to diagnose the cardiovascular system using SRCS (Fig. 5).

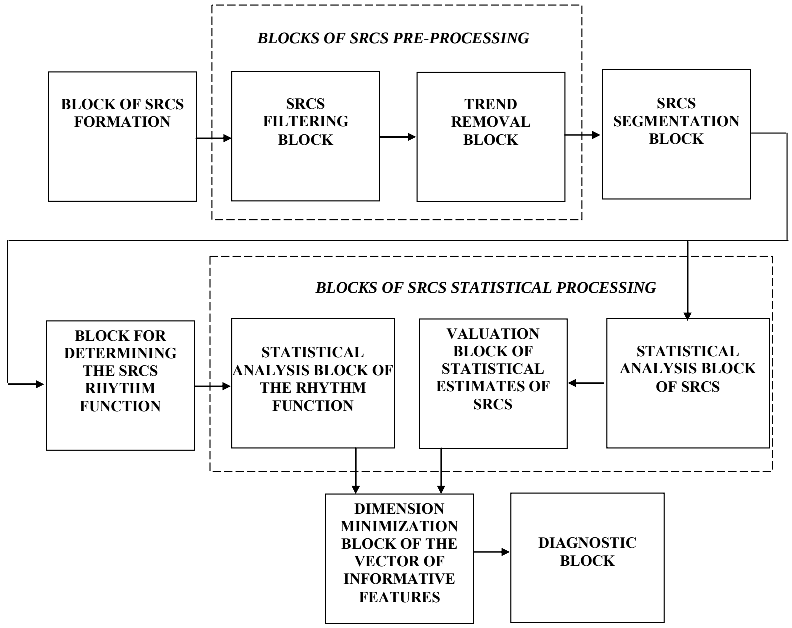


Figure 5: Software complex for statistical processing of synchronously registered cardiosignals.

For the compatible statistical processing of SRCS (electrical, magnetic, acoustic nature) the module “Compatible statistical processing of SRCS” is used, the structural-functional scheme of which is shown in fig. 6.

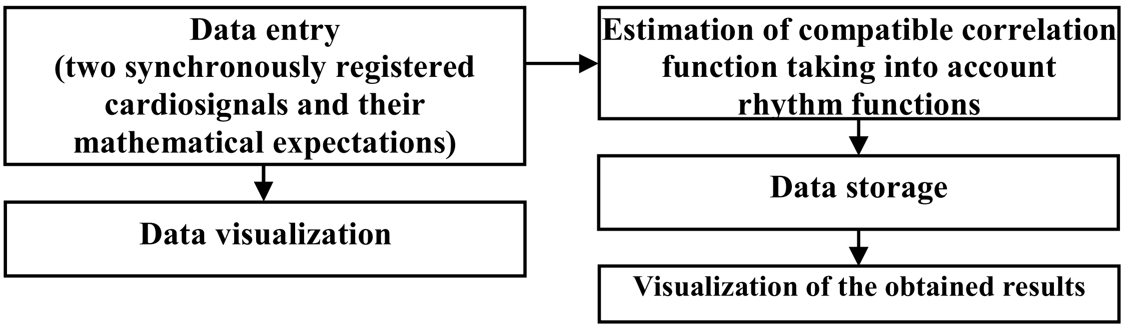


Figure 6: Structural-functional module scheme of the program "Compatible statistical processing SRCS".

The input data for compatible statistical processing are oversampled values of signals and their estimates of mathematical expectation. The result of joint statistical processing is a cross-correlation function obtained taking into account the rhythm function (Fig. 6).

To simulate cardiosignals, a simulation unit SRCS was developed taking into account the rhythm function, the structural-functional scheme of which is shown in Fig. 7.

In order to simulate cardio signals taking into account the rhythm function, it is first necessary to open the input data of the cardio signal and rhythm function, set the number of cycles and signal zones, load the input cycle (Fig. 7).

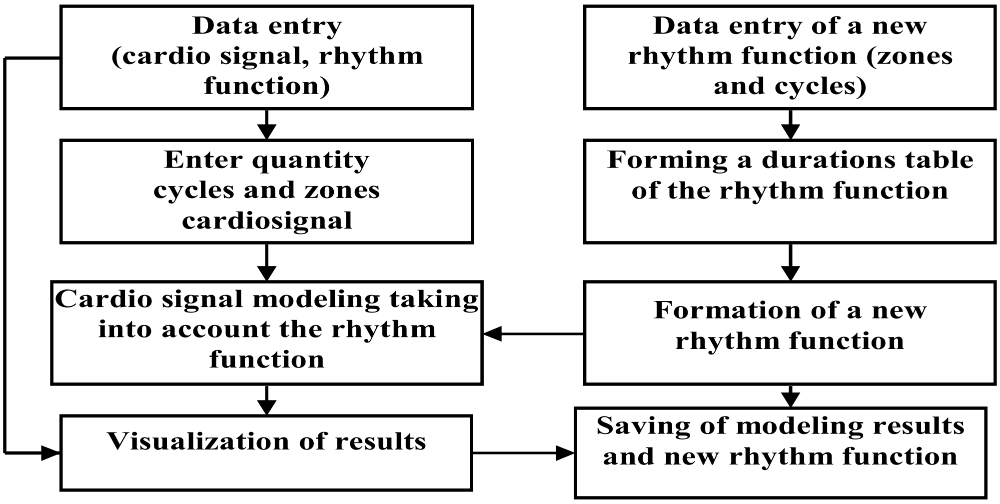
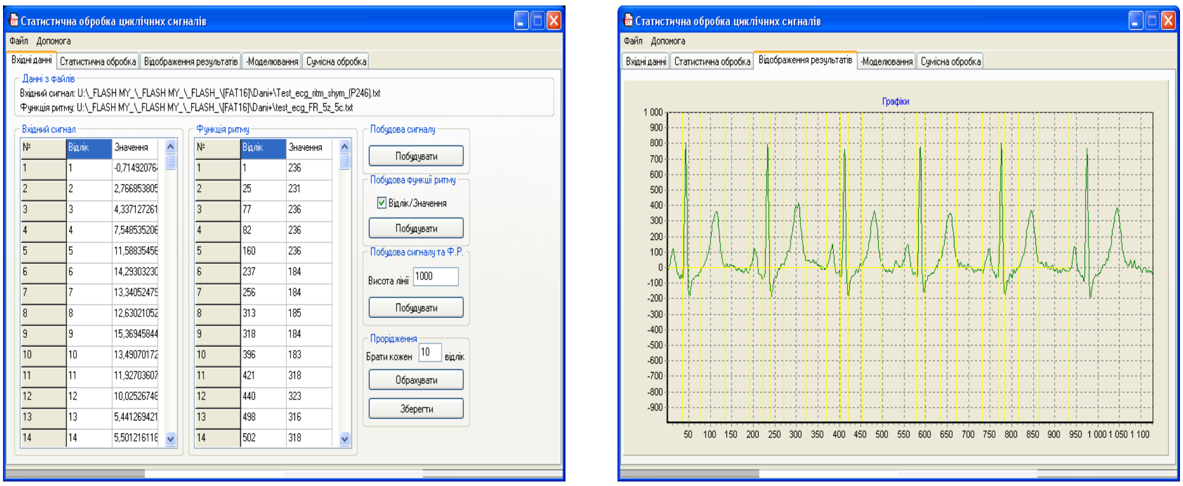


Figure 7: Structural-functional scheme of the SRCS simulation unit taking into account the rhythm function.

5.2 Software design

In Fig. 8 the general view of program interfaces for data input (cardiosignals, rhythm functions) and their visualization is given.

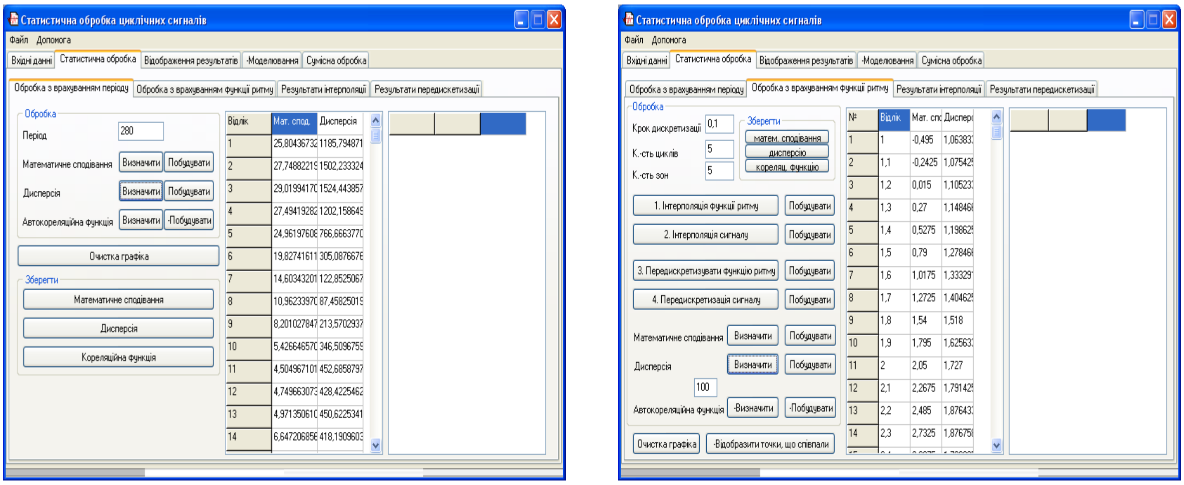


a) b)

Figure 8: General view of the program interfaces for data entry (a) and their visualization (b).

Two methods were used in the program for statistical processing of SRCS: the method of averaging the values of signal realization taking into account the period and the method of averaging the values of signal realization taking into account the rhythm function. An example of the program interface for statistical processing taking into account the period is shown in Fig. 9.

The method of averaging the values of signal realization taking into account the rhythm function, in comparison with known methods, significantly reduces the negative effect of "blurring" of statistical estimates of probabilistic characteristics of SRCS, which allows to increase the accuracy, reliability and informative of complex automated diagnosis of the human cardiovascular system by synchronous cyclic heart signals (Fig. 9).



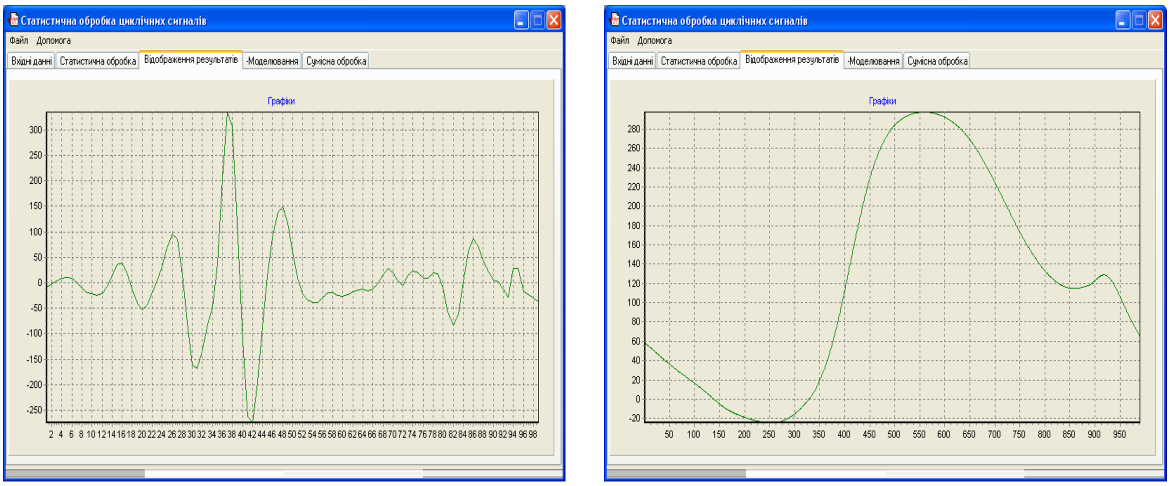
a) b)

Figure 9: General view of the program interfaces for statistical processing through period (a) and taking into account the rhythm function (b).

During statistical processing, taking into account the rhythm function, it is necessary to specify additional parameters, namely: the sampling step of the signal and rhythm function (required during resampling of signal and rhythm function), as well as the number of heartbeat cycles and the zones number (per cycle) of registered signal implementation. Performing consistent steps: rhythm function interpolation; signal interpolation; rhythm function resampling; signal oversampling we obtain the necessary data for statistical processing, taking into account the rhythm function.

In Fig. 9 shows that as a result of statistical processing we can obtain estimates of the following probabilistic characteristics: mathematical expectation, variance and autocorrelation function. All received data can be saved in text files if necessary.

The general view of the program interfaces for visualization of the estimation of the mathematical expectation of the phonocardiogram (a) and the integrated rheogram (b), by the method of statistical processing taking into account the rhythm function, is given in Fig. 10.

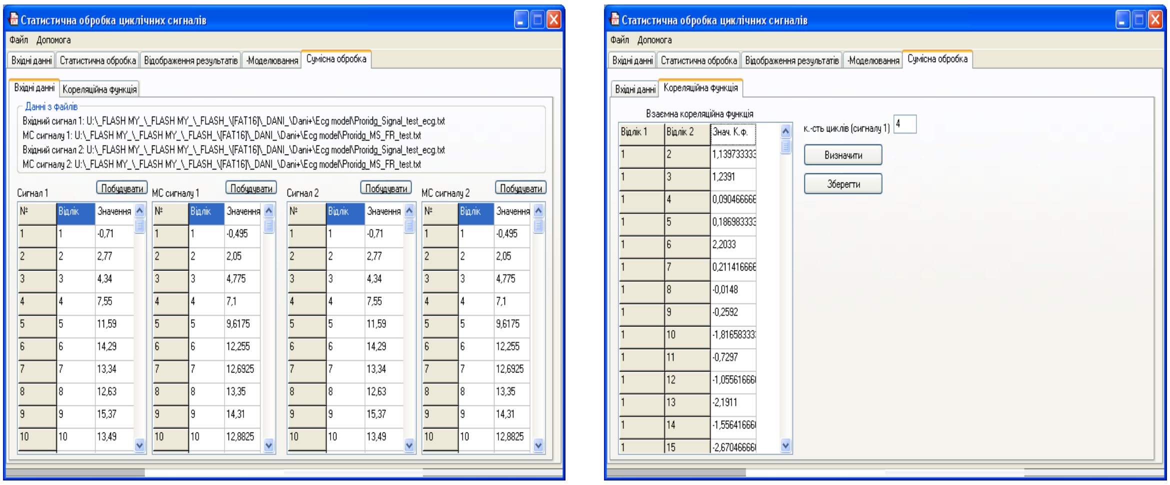


a) b)

Figure 10: General view of the program interfaces for estimation visualization of the mathematical expectation of the phonocardiogram (a) and the integrated rheogram (b).

The input data for compatible statistical processing are oversampled values of signals and their estimates of mathematical expectation. The result of compatible statistical processing is a mutual correlation function obtained taking into account the rhythm function.

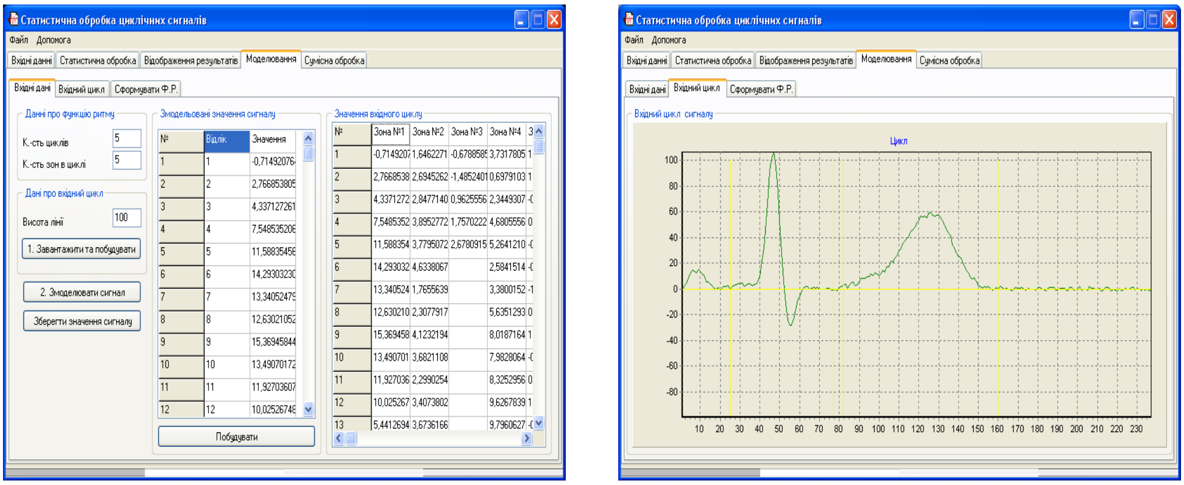
An example of the program interface for entering synchronously registered data (a) and their compatible processing (b) is shown in Fig. 11.



a) b)

Figure 11: General program interface view for entering synchronously registered data (a) and their compatible processing (b).

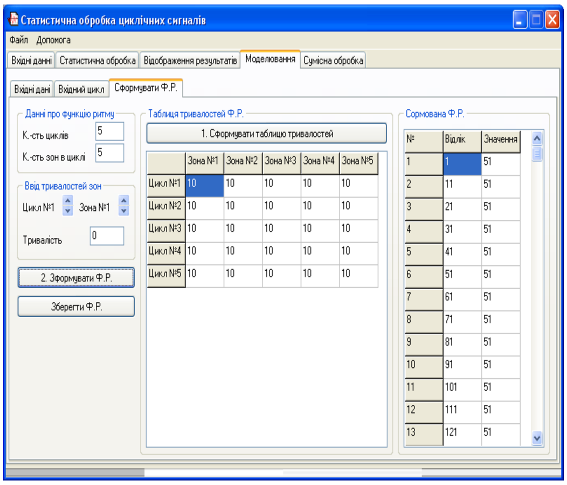
In order to simulate cardiosignals taking into account the rhythm function, it is first necessary to open the input data of the cardiosignal and rhythm function, set the number of cycles and signal zones, load the input cycle. The program interfaces are used for input data (Fig. 12 (a)) and for visualization of the input cycle (Fig. 12 (b)).



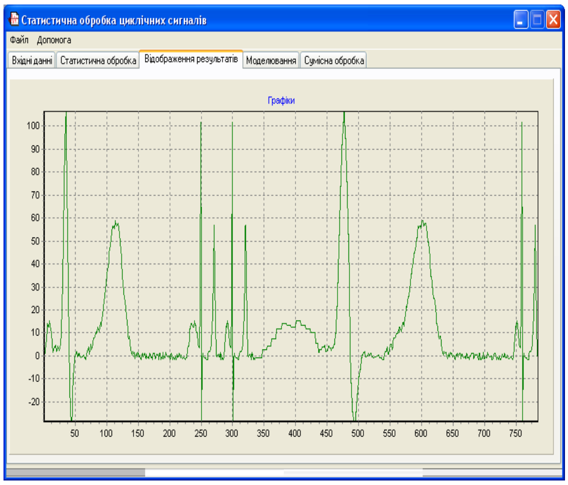
a) b)

Figure 12: General view of the interface of the program of input data input (a) and visualization of the input cycle (b).

The developed software provides the ability to form a discrete rhythm function, depending on the number of cycles and zones of the cardiosignal to be modeled. The program interfaces for forming the rhythm function and visualization of the modeled cardio signal are shown, respectively, in Fig. 13 (a, b).



a)



b)

Figure 13: General view of the program interface for forming the rhythm function (a) and the modeled cardiosignal generated by the rhythm function (b).

The developed set of programs makes it possible to perform statistical processing of SRCS of different physical nature and obtain estimates of mathematical expectation, dispersion, autocorrelation and mutual correlation functions (taking into account the rhythm function and taking into account the period). The software also allows you to simulate cardio signals. The developed software provides the ability to form a discrete rhythm function, depending on the number of cycles and zones of the cardio signal to be modeled.

6. Conclusions

A set of programs has been developed that allows for statistical processing of cardiac signals of different physical origin and to obtain estimates of mathematical expectation, variance, autocorrelation and cross-correlation (taking into account the function of rhythm and period). The software allows you to simulate the implementation of cardio signals of different physical nature, taking into account their constant rhythm (taking into account the period), variable (taking into account the rhythm function) and the common rhythm. The modeling method includes information obtained at the stage of statistical processing of cardiac signals, in particular, morphological features are taken into account on the basis of estimates of mathematical expectation and variance of cardiac cycle cycles.

The developed software provides the possibility of forming a discrete rhythm function depending on the number of cycles and zones of the simulated cardio signal.

This software can be used as a component of diagnostic systems of the human heart.

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