Серцево-судинні захворювання продовжують залишатися основною причиною смертності. Згідно з офіційним джерелом, за останні три роки в Казахстані від ішемічної хвороби помирає в середньому 179200 осіб на рік. На цю недугу страждають 1 360 000 чоловік, тобто майже кожен дванадцятий казахстанець сьогодні страждає на ішемічну хворобу серця. В середньому 272000 чоловік щорічно надходять до лікарні з гострою серцевою недостатністю [1]. Щоб звести до мінімуму шкоду населенню і в медицині, необхідна своєчасна діагностика, що знижує вартість подальшого лікування.

У статті розглядається система неінвазивної діагностики серця, заснована на біофізичному підході. Система дозволяє заповнити існуючий розрив між електрофізіологією серця і найбільш поширеними методами аналізу електромагнітного поля серця в діагностичних цілях. Розроблена система неінвазивної діагностики серця використовує новітні досягнення в області інформаційних технологій, що дозволяє записувати, збирати, зберігати та обробляти кардіографічну інформацію.

Продукт дозволяє цілодобово відстежувати стан здоров`я людини з виявленням патологій і визначенням напрямів їх розвитку, а також з формуванням тривожних сигналів із зазначенням місцезнаходження пацієнта і миттєвим аналізом фізіологічних параметрів серця. Такий досвід може бути успішно використаний для персонального моніторингу здоров`я людини незалежно від його місця розташування.

Розроблений зразок вимірювальної системи визначення небезпечних аритмій серця в умовах вільної активності підвищує діагностичну ефективність медичних послуг за рахунок своєчасного визначення небезпечних аритмій серця.

Ключові слова: неінвазивна система кардіодіагностики, портативний кардіоаналізатор, завадостійка обробка електрокардіосигналу.

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DEVELOPMENT OF MEASURING SYSTEM FOR DETERMINING LIFE-THREATENING CARDIAC ARRHYTHMIAS IN A PATIENT'S FREE ACTIVITY

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1. Introduction

Modern systems of noninvasive cardiac diagnostics (SNCD) use the latest achievements of cardiology, biophysics, electrochemistry, physiology, electronics, computer science and mathematics to solve the problem of the diagnosis of the heart state and make a conclusion about the state of the patient's heart.

The extraction of diagnostic information from the electrocardiogram (ECG) signal is a serious scientific problem that requires large computational resources. Non-invasive determination of the electrophysiological characteristics of the heart is based on the solution of the inverse problem of electrocardiography. Fig. 1 shows the structure of cardiovascular diseases (CVD).

It is possible to timely receive diagnostic information based on the solution of the ECG inverse problem by organizing cloud processing of cardiological information (CI).

The use of portable computing devices, for example, smartphones, in the process of monitoring electrocardiographic parameters of the heart helps to increase the efficiency of diagnosis of electrocardiographic information.

Thus, the development and improvement of portable systems for the timely determination of dangerous cardiac arrhythmias in conditions of free activity is an urgent scientific and technical task.

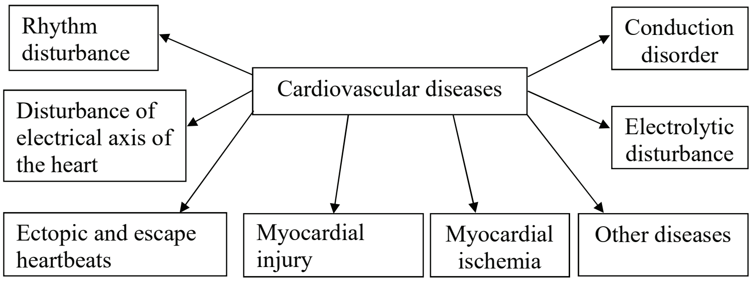


Fig. 1. Structure of cardiovascular diseases

2. Literature review and problem statement

From foreign portable devices for recording and processing an electrocardiogram, we can select a heart rate monitor "Smart Device for the Determination of Heart Rate Variability in Real Time". This is a modern device used to measure heart rate [2]. The device is designed for quick and accurate verification of heart function and ECG recording.

The device is attached to any appliance on the IOS or Android platform. It turns on automatically and communicates with the application on the mobile phone wirelessly.

With all the advantages – ease of use and accessibility for users, the device has significant disadvantages. First of all, this is a short ECG recording time, which does not allow a complete diagnosis of the condition of the heart.

Of the available devices, we can distinguish the development of Russian scientists "Cardiovid" – a system of remote ECG monitoring [3].

Cardiovid is a remote ECG monitoring system. Real-time continuous monitoring can be carried out both at home and at work [4].

ECG data is transmitted from the sensor to the mobile phone via Bluetooth. In turn, the phone transmits data over the mobile network to the server, which stores the data. The data can be processed in two ways: using a web browser for analysis purposes or with the monitoring mode on the computer in real time. In a web browser, a specialist can examine and analyze carefully stored ECG data. A report on the results of the analysis can be sent to the patient's email immediately after it. The monitoring mode allows you to control multiple patients at the same time. The patient's heart rate can be seen in the viewing mode, and alarm notifications will indicate problems detected in the patients or on the device and help to take action.

Ordinary people at home intend this appliance for use. However, it does not imply an offline determination of risks in real time, a conclusion on the state of the heart can be obtained only after registration is completed.

One of the promising developments is the mobile Portable ECG based on wireless sensor network, developed by Turkish scientists [5].

The device under development is intended for daily recording of an electrocardiogram and heart rate throughout the real life cycle (for example, when passing a health path in a sanatorium). The device using the GPS/GLONASS positioning system determines the patient's location. Using telemetry, a doctor timely receives data on the physical condition of his patient and his location (data can be received constantly or in case of critical situations).

The disadvantages of the device include insufficient ergonomics and the inability to use in a domestic environment without the participation of a doctor. Also, there is not enough information about the methods of analysis of the recorded data.

One of the well-known Russian systems for recording and transmitting physiological parameters over the radio channel is the Poly-Spectrum-Radio system of Neurosoft [6].

The system is designed to record and transmit over the radio channel at a frequency of 900 MHz physiological signals (ECG and respiratory rhythm) from a person or animal. The recorded signals are displayed in real time on the screen of a personal computer located at a distance of up to 300 meters from the transmitter and stored in the memory of the transmitter and computer. The system allows the registration of signals from several people or animals at the same time. Having the ability to store the transmitted signal in the transmitter's memory helps to avoid data loss in the event of a radio communication violation.

The receiver receives signals and transmits them via a USB cable to a computer. A program is installed on the computer that displays all the registered signals in real time on the monitor. The program can save all the data in the computer memory and analyze them using the Poly-Spectrum-Rhythm, Poly-Spectrum-Ergo, Poly-Spectrum-Sport modules [6].

Another example of the Russian development is the device of the Mediatek company Astrocard – Telemetry 3G [7].

The Astrokard – Telemetry 3G ECG telemetry registration complex is designed for wireless remote continuous monitoring of the electrocardiogram in real time for a long time (from 20 hours or more). The complex provides 3-lead ECG monitoring and subsequent retrospective analysis of them using holter programs. During monitoring, the patient can freely move within the coverage area of mobile networks.

Thanks to the use of digital signal transmission and processing, the original method of highlighting QRS-complexes and correction of the contour offset, high and stable quality of ECG recording is achieved. The appearance of the device is shown in Fig. 2.

Fig. 2. ECG sensor of the ASTROKARD TELEMETRY 3G complex

Each cardiac diagnostic system incorporates an ECG recording device, the physical dimensions of which allow the system to be classified as stationary or portable. Modern stationary systems have high-quality ECG recordings, a wide range of diagnostic capabilities. Portable systems are more variable in their parameters, functions and capabilities (Table 1).

The presented portable systems have a different set of functions. In addition to its purpose, ECG registration, many cardiographs automatically decrypt the ECG. Based on the analysis of the signal, some systems issue a diagnostic report. Despite the possibilities of automatic analysis and conclusion, a user with a portable cardiograph is not always able to objectively assess his health condition, possible threats to his life and decide on calling an ambulance. In this regard, it is justified to endow portable cardiographs with the function of calling an ambulance in a critical condition of the patient. Based on the analysis of existing systems, it can be concluded that there is no emergency call function for ambulances.

A common drawback of the systems considered is the lack of the ability to quickly obtain the latest ECG recordings of the patient in emergency situations. Storage of the archive of records on the server is a necessary but not sufficient condition for the implementation of such an opportunity. A number of systems allow you to store ECG records on the server of a medical advisory organization. However, as a rule, this data is a one-time treatment for advice on the current condition of the patient. Obtaining access to the latest current electrocardiographic records of the patient in emergency situations is not provided, since the provision of emergency and emergency care is a medical service of a different level. However, for diagnostic purposes, it would be extremely important to provide the doctor with the latest cardiogram of the patient upon admission to the hospital.

The most effective medical care scheme is possible if the patient's ECG records archive contains both home-acquired records and ECG records recorded in the hospital. This means that there is a two-way exchange of the MIS server of medical institutions with the server of the cardiac diagnostic system.

Ensuring high noise immunity of such systems is one of the main problems of modern non-invasive cardiac diagnostics. Increasing the level of external electromagnetic interference, increasing the degree of integration of electronic components leads to the fact that the selection of the ECG becomes a difficult task. This task is particularly difficult for non-invasive cardiac diagnostic systems operating in conditions of free activity of the patient, when the intensity and variability of interference has a significant disinformation effect.

Traditionally, linear frequency filtering methods are widely used for ECG pretreatment, which is associated with the presence of a formed theory and the rather simple synthesis of linear filters [8, 9].

Digital low-pass filters are implemented relatively simply, while to create digital high-pass filters, either a non-recursive scheme with a large number of coefficients or a recursive scheme with strict requirements for rounding errors in calculations is used.

The main disadvantage of classical frequency filters is the distortion of the useful signal, which is unacceptable for most modern electrocardiographic tasks. The distortions are mainly associated with a decrease in the amplitudes of the Q, R, S teeth, the expansion of QRS complexes, and the displacement of the ST segment.

Japanese scientists in their ECG devices to suppress noise used the median filtering algorithm (median filter), for filtering impulse noise, smoothing signals, and isolating low-frequency noise [10]. The central count in the sliding window is replaced by the median (the average position report in the ranked row), removing the anomalous counts regardless of their amplitude values.

The disadvantages of median filters are the complexity of the mathematical analysis of signals, insufficient suppression of Gaussian noise, with an increase in the size of the filter window, blurring of sharp changes in the signal occurs [11].

The use of non-linear Kalman filters for suppressing interference in an ECG was considered in [12]. Classic Kalman filters are based on time-discrete linear dynamic systems. Since biological processes are nonlinear, Kalman filters are not effective enough to suppress interference in an ECS.

In conclusion, it should be noted that none of the methods considered provides effective suppression of all types of interference.

When choosing promising methods that provide increased noise immunity, one should give preference to methods for suppressing interference, which preserve the shape of informative ECG sections. It is advisable to filter out high-frequency noise with non-linear filters and compensate for low-frequency ones.

All this allows us to argue that it is advisable to study modern systems of non-invasive cardiac diagnostics and noise-resistant processing of cardiosignals, which allows determining current directions in the development of non-invasive cardiac diagnostics systems.

Table 1

Comparative analysis of portable cardiac diagnostic systems [2–7]

Title		Astro-card® Teleme-try 3G	Cardiovid	Smart Device for the Determination of Heart Rate Variability in Real Time	Portable ECG based on wireless sensor network, developed by Turkish scientists	Poly-Spectrum-Radio-1
System functions	Automatic decoding of an ECG	+	+	+	+	+
	Automatically generated conclusion	+	+	+	–	+
	Ambulance call	–	–	–	–	-
Place of storage of ECG records	Local	–	+	+	–	+
	On a remote server	+	+	+	+	–
Ability to integrate with MIS		-	+	–	–	–
Getting the latest ECG recordings		-	–	–	–	–

3. The aim and objectives of the study

The aim of the study is the development of an information-measuring system for monitoring and determining life-threatening cardiac arrhythmias in a patient's free activity.

To achieve the aim, the following objectives are set:

– develop a portable cardio analyzer (Recorder);

– develop a method of noise-resistant processing of an electrocardiogram;

– create a system for diagnosing the state of the heart in conditions of free activity of the patient.

4. Development of a portable cardio analyzer (Recorder)

The portable cardio analyzer (PCA) is designed to diagnose the state of the heart in conditions of the patient's free activity. The device consists of an electrocardiogram recorder with external sticky electrodes, a microprocessor and a module for working with mobile networks [13].

The main task is to register electrocardiosignal (ECS) using a portable device for a long time with a normal lifestyle (free activity) of the patient and the prevention of cardiovascular diseases.

Due to the daily monitoring of the heart, it is possible to detect or prevent the development of the following diseases of the cardiovascular system:

– arrhythmia (cardiac arrhythmias);
– angina pectoris;
– coronary heart disease.

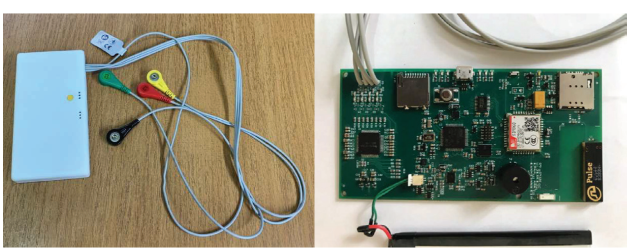
The principle work of the channel of the ECG device is based on the direct measurement of the electrical potential of the heart with the help of electrodes attached to the patient's body.

Structurally, the PCA consists of the main unit and a set of electrodes.

The main unit includes: input amplifiers of bioelectric potentials, control elements of the electrocardiograph operation modes, indicators of signals and modes of operation, filters, ADC, microcontroller, operational and flash memory, transceiver, power supply (small battery, DC/DC converters, power supervisor).

Using the ADS1298 chip and the BLE 4.1 radio module allows to reduce significantly the weight, size and power consumption of the portable electronic recorder. Restrictive circuits which are based on the diode assembly SP724 were used to protect against defibrillator pulses (patients may have implantable cardioverter-defibrillators) in the portable ECG signal recorder. The assembly is characterized by increased reliability and is capable of withstanding discharge up to 15 kV. A lithium-polymer battery with a voltage of 3.7 V and a capacity of 1600 mA/h was used as a power source ensuring continuous operation of the portable ECG signal recorder for 72 hours. DC-DC converter with increased efficiency TPS62237 (Texas Instruments) is used to power analog and digital elements with a voltage of 2–3.3 V. Battery charge provides charge controller BQ24202 (Texas Instruments).

The appearance of the main unit of the electrocardiogram is shown in Fig. 3.



a *b*

Fig. 3. Photo of a prototype portable cardio analyzer: *a* – appearance; *b* – board

Using PCA with a mobile device.

For transferring ECS from a portable recorder to a smartphone, for transferring wireless data, Bluetooth 4. 1 (Bluetooth Low Energy – BLE) developed by the Bluetooth Special Interest Group (Bluetooth SIG) in 2010 was used. Bluetooth 4. 1 allows devices to establish a connection in less than 5 ms and maintain it at a distance of up to 100 m. For this, advanced error correction is used, and the required level of security is provided by a 128-bit symmetric algorithm of block encryption. At the same time, a data transfer rate of 1 Mbps is provided with a data packet size of 8–27 bytes.

Reduced power consumption, obtained through a special operation algorithm (the transmitter is turned on only at the time of sending data), allows to use Bluetooth 4. 1 in devices with autonomous power.

The Bluetooth module of the portable recorder ECS goes into the Advertisement mode, after which it becomes available to other devices for detection. The Bluetooth module of the smartphone detects the portable recorder of ECS and stores information about it. The user of the smartphone (patient) at the start of the analysis of the CS connects with a portable recorder ECS, if it is already detected, or before the connection searches for the device, and the connection is established after its detection. In the process of registering an ECS, the mobile application periodically polls the server, and if it detects that new information is available, sends a corresponding request and reads new data from the server's attribute table. These operations are carried out through a set of special services, or services, on which the implementation of the Bluetooth 4. 1 protocol is based.

The main features of the device are:

– work in conditions of free activity;
– performing a preliminary ECG analysis;
– automatic diagnosis of life-threatening arrhythmias;
– call an ambulance;
– storing ECS entries locally and on a remote server;
– ability to integrate with the medical information system.

5. Development of a method of noise-resistant processing of an electrocardiogram

5. 1. Theoretical foundations of noise-resistant processing of electrocardiograms based on the Hilbert-Huang transform

Processing of electrocardiograms, with their complex structure and the presence of various interferences, is quite a challenge. ECS are non-linear non-stationary signals, have a special time-frequency structure, are characterized by the diversity and variability of amplitude-time parameters and pulse shape, as well as by the presence of interference of various types and origin. For an adequate analysis of such signals, a special approach is needed, which has the property of adaptability to each specific signal under study and ensures the localization of signals, both in time and frequency.

The basis of this approach is the formation of an adaptive basis, functionally dependent on the content of the signal itself (that is, taking into account the structure of the signal, the variability of its parameters, the presence of interference of various types and intensity). A priori given function, taken as a base function, no matter how complex it is, is not advisable to use for analyzing complex signals.

For the formation of an adaptive basis that corresponds to real changes in the signal over time, the points of extremum, discontinuities, kinks, and monotonous violations are of the greatest practical interest. The formation of basis functions by extremum points is the basis of the Hilbert – Huang transform (HHT), which includes two main stages: empirical mode decomposition (EMD) and the formation of the Hilbert spectrum from the obtained empirical modes (EM).

The idea of EMD technology is that the signal at each level of decomposition is represented as two components. The first component is another extracted EM, rapidly oscillating, detailing, responsible for the transmission of high frequencies, reflecting local features and fine details of the signal. The second component (the remainder after the extraction of the next EM) is slowly oscillating, approximating and responsible for the transmission of low frequencies. The residue is subject to further decomposition (if it has at least one extremum of each type).

The main advantage of EMD is high adaptability, due to the fact that the basic functions used to decompose a signal are constructed directly from the signal itself, which allows to take into account all its local features, internal structure, and the presence of various interferences. In addition to adaptability, EMD has other properties that are important for practical applications:

– locality, i. e. the possibility of taking into account local features of the signal;

– orthogonality, providing signal recovery with a certain accuracy;

– completeness guaranteeing the finiteness of the number of basis functions for a finite signal duration.

When analyzing signals using HHT, it is assumed that an arbitrary signal can be represented as a superposition of certain oscillatory processes – empirical modes. Empirical modes are monocomponent components of the signal, but instead of a constant amplitude and frequency, as in a simple harmonic, they have a time-varying amplitude and frequency.

The oscillatory nature of each EM allows it to be mapped into a complex region using the Hilbert Transform (HT). The result is an analytical spectrum to which you can apply a two-dimensional transform, which allows you to use the information contained in the real and imaginary parts of this spectrum.

Studies conducted in recent years have proved that HHT is a unique technology of time-frequency analysis of nonlinear and non-stationary data, based on an adaptive basis and frequency determination through the Hilbert transform. At the same time, there is no need for fictitious harmonics to represent nonlinear processes, as in any of the methods with a priori given basis. In addition, HHT has no fundamental limitations on the resolution in time or frequency associated with performing convolution, since the frequency in this transformation is determined by differentiation, and not by convolution.

HHT has proven its effectiveness in various applications, including medical applications. The use of HHT for processing and analysis of ECS provides:

– suppression of narrow-band interference, based on the separation in space of features of information on interference and a useful signal;

– suppression of broadband interference, based on non-linear threshold processing;

– separation of various processes (for example, fetal ECS-on the background of the mother ECS);

– detection and classification of informative signal areas (complexes, waves, segments) and measurement of their parameters;

– implementation of the transformation, as a result of which the ECS is represented as a 3-D surface in the coordinate system "amplitude-time-frequency" or "energy-time-frequency", in connection with which, it becomes possible to identify new diagnostic features based on hidden modulations and areas of energy concentrations.

The above features of the Hilbert – Huang transform and its capabilities for the adaptive time-frequency representation of the ECS make it possible to adopt HHT as the second direction for increasing the efficiency of noise-resistant processing.

The Hilbert-Huang transform is the decomposition of a signal into empirical modes, followed by applying the Hilbert transform to them. The Hilbert transform allows the initial narrowband signal to be decomposed into two components: amplitude and phase. Note that a signal is called narrowband if the width of its spectrum is significantly less than the average frequency.

$$\Delta\omega = |\omega_1 - \omega_2| = \frac{\omega_1 + \omega_2}{2}, \quad (1)$$

where ω_1, ω_2 – upper and lower cutoff frequencies. Such signals with limited spectrum can be analytically presented using HT.

Unfortunately, the main problem of such a transformation is that the instantaneous frequency obtained using HTs for real signals may have frequency components that have no physical meaning. Attempts to solve this problem on the basis of the Fourier method and the theory of filters did not give a positive result. Success was achieved only when Huang and his colleagues developed the technology of empirical mode decomposition.

The basis of the classical EMD algorithm is the construction of smooth envelopes based on the maxima and minima of the signal, finding the average of these envelopes and its further subtraction from the input signal. Envelopes are constructed using cubic spline interpolation or another smoothing method. The result of these actions is the first approximation to the first empirical mode. To fully isolate EM, it is necessary to again find the maxima and minima of the found estimate of EM, and repeat all previously described actions. This iterative process, called screening, continues until the specified criterion for stopping it is reached. As a result of the screening process, the first empirical mode will be obtained. Further, in order to find the next EM, it is necessary to subtract the already found EM from the original signal and repeat the described actions again. This continues until all EMs are found. The search for the next EM stops when there are no more than two extremes in the remainder.

The Hilbert-Huang transform, in addition to EMD, includes the algorithm for generating the Hilbert spectrum using the empirical modes obtained.

There are a number of publications, devoted to the development of noise suppression algorithms in the ECS based on HHT. The basis of these algorithms is the decomposition of the ECS into empirical modes (EMD), the processing of EM and the subsequent restoration of the signal. Simpler and less efficient algorithms use the removal of some "interfering" empirical modes. Studies have shown that for real ECS spectra of the useful signal and interference significantly overlap, and the interference is distributed over a significant part of the frequency range and is present over many EM. Consequently, algorithms based on the removal of individual EM, in principle, cannot ensure high efficiency of interference suppression.

More efficient algorithms for suppressing high-frequency interference use nonlinear threshold processing (thresholding), borrowed from wavelet filtering, and to eliminate low-frequency interference, their compensation based on the reconstruction of low-frequency noise and its subsequent subtraction from the input signal. Various modifications of these algorithms have insufficient effectiveness of interference suppression in the ECS due to the lack of adaptation to the signal-interference environment and the use of Gaussian interference models and their components at different levels of decomposition.

To improve the effectiveness of noise suppression, a method of noise-resistant processing of the ECS based on the Hilbert-Huang transform was proposed.

The energy density surface, built on the basis of the Hilbert-Huang transform, characterizes the distribution of the instantaneous signal energy at each point of the time-frequency plane. Such a presentation provides more opportunities for effective interference suppression in the ECS and opens up the possibility of extracting new diagnostic features of electrocardiograms.

Adaptive processing of the probe implements a different approach to the elimination of high-frequency and low-frequency interference.

5. 2. Justification of the use of a truncated EMD algorithm for interference suppression in an ECS

The main problem in the implementation of the developed ECS-based processing algorithms for HHT in the non-invasive ECG-diagnostics system is the considerable computational complexity of the classical EMD algorithm (due to the iterative screening procedure) and the procedure for generating the probe. Computational complexity does not allow to use these algorithms for processing ECS in real time in portable NECS devices.

To create noise suppression algorithms in real time, a modified truncated algorithm of EMD was developed, and the formation and processing of probes were replaced with adaptive EM processing.

The basis of the classical EMD algorithm [15, 16] is the construction of smooth envelopes based on the maxima and minima of the signal, finding the average of these envelopes and its further subtraction from the input signal. As a result of these actions, the first approximation to the first empirical mode is found (estimation of EM). To fully isolate EM, it is necessary to again find the maxima and minima of the found estimate of EM, and repeat all previously described actions. This iterative process, called screening, continues until the specified criterion for stopping it is reached. As a result of the screening process, the first empirical mode will be obtained. Further, in order to find the next EM, it is necessary to subtract the already found EM from the original signal and repeat the described actions again. This continues until all EMs are found. The search for the next EM stops when there are no more than two extremes in the remainder.

To improve the performance of the EMD algorithm, it was proposed to exclude the screening procedure from it [17, 18]. In this case, the first approximations to the corresponding empirical modes will be considered as empirical modes of the input signal.

5. 3. Evaluation of interference levels based on detection of informative sites in empirical modes

During the segmentation of empirical modes, it becomes possible to isolate non-informative sections that correspond to ECS TP – intervals and contain only interference. Forming an estimate of interference in the absence of a useful signal in these areas using a robust Q-estimate improves the accuracy of the estimate of interference and, accordingly, the pore value of p.

The basis of EM segmentation is the detection algorithms of QRS complexes, which may well be developed on the basis of empirical mode decomposition, which has the ability to take into account the local features of the ECS. The prospect of using EMD for detecting QRS complexes, ECS, has been confirmed by a number of publications.

The decomposition of fragments of various real ECS (with noises of various types and intensities) showed that the greatest part of the energy of QRS complexes is contained in the first three EMs. Moreover, these EMs are symmetric with respect to zero, so their processing is somewhat simpler compared to the detection of QRS complexes in an ECS.

From this, it follows that for the detection of QRS complexes in the ECS, it is necessary to use either all three EMs, or 1–2 most informative. Empirical modes ECS in the general case are non-stationary non-Gaussian signals, therefore, for detection of bursts corresponding to QRS complexes in EM, non-parametric methods that are invariant to the laws of the distribution of sample values turn out to be most acceptable. In most cases, these procedures involve the ranking of the values of the samples (the transition to the rank scale of measurement of the trait) and are called ranking criteria.

All parts of the EM, except for those found informative, are considered non-informative. The robust scale estimate is calculated on them (the noise estimate is specified). The advantage of the algorithm is the high accuracy of the estimate. In addition, with no additional cost and with high accuracy another task of processing the ECS is solved – the detection of informative sites, this makes it possible to obtain reference points for the reconstruction of low-frequency noise (drift of an isoline).

5. 4. Experiments and results of FIR and EMD

The first method of noise-resistant processing of the ECS that will be considered in this work is the FIR filter.

FIR filters are not recursive, which means that only current and delayed input values are used to calculate the output of the filter.

$$\begin{aligned} y[n] &= b_0 x[n] + \\ &+ b_1 x[n-1] + \cdots + b_N x[N] = \\ &= \sum_{i=0}^{N} b_i \times x[n+i], \end{aligned} \qquad (2)$$

where $x[n]$ is the input signal; $y[n]$ is the output signal; N is the filter order; b_i is the value of the impulse response, also a coefficient of the filter [29].

In the difference equation, there is only an equation in front of x, and the filter circuit also has no feedback. The scheme for counting discrete convolution is very similar to the scheme of an FIR filter; the vector of input samples is formed using a delay line or registers; the signal sample is multiplied by the pulse characteristic count in multipliers. The impulse response of the FIR filter is the vector of coefficients in front of x. FIR filters are very stable, that is, even with a very large level of the input signal, when it is turned off after a while the output signal is guaranteed to fade out. This is a direct consequence of the fact that FIR filters do not have feedback. The main disadvantage of FIR filters in comparison with IIR filters when implementing is more hardware and computational costs. In the hardware implementation of FIR filters, multipliers, adders, delay lines, multiplexers are used.

In this work, FIR filters were used to eliminate interference (noise) in electrocardiosignals (ECS). The filter is implemented using the signal processing toolbox, which includes: analysis, synthesis, quantization and implementation of filters. Using these tools we find the coefficients, that is, the counts of the impulse response in the form of a vector column.

The main task of filtering is to get rid of low-frequency signals and highlight the QRS system. In the ECG, the most important thing is recognizing the QRS system for identifying the disease in a patient. When implementing noise-tolerant processing, the MATLAB platform is used. In Fig. 4, the upper part is low noise; the lower part – free from low-frequency signals, also clearly distinguished ST segmentation.

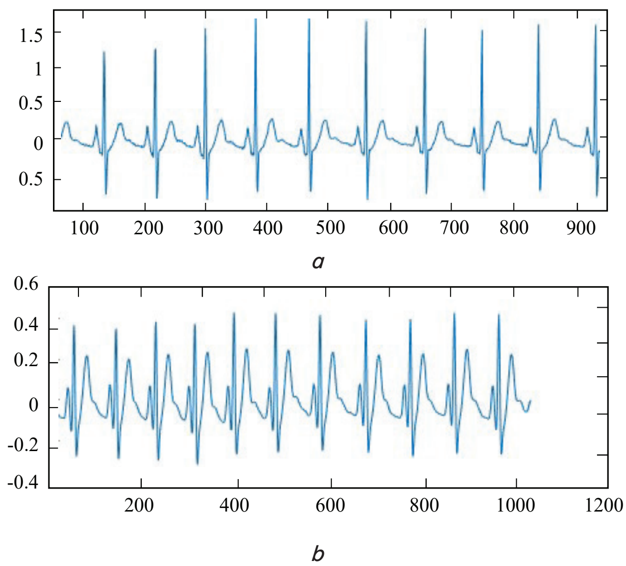


Fig. 4. Implementing noise-tolerant processing with MATLAB platform: *a* — low noise signal; *b* — free from low-frequency signals

In FIR filters, Fast Fourier Transform is applied; also when determining the coefficients, you can immediately apply FIR filters. After we determine the low-frequency interval, using convolution after removing the noise, we restore the original signal. Fig. 5 shows the elimination of low-frequency signals in the time domain.

The second method of noise-resistant processing of the ECS is using EMD based on the Hilbert-Huang transformation.

The basis of EMD technology is that the signal at each level of decomposition is divided into two components. The first component is the extracted EM, a fast oscillating one, which shows the transmission of high frequencies, local features and fine details of the signal. The second component (after the extraction of previous EM) is a slowly oscillating one, which shows, on the contrary, the transmission of low frequencies. The remains of the extracted signal are further decomposed until it has extremes of each type left.

The basis of the classical EMD algorithm is the construction of smooth envelopes along the maxima and minima of the signal, finding the average of these envelopes and its further subtraction from the input signal. As a result of these actions, the first approximation to the first empirical mode is found (estimation of EM). To fully isolate EM, it is necessary to again find the maxima and minima of the found estimate of EM, and repeat all previously described actions. This iterative process, called screening, continues until the specified criterion for stopping it is reached. As a result of the screening process, the first empirical mode will be obtained. Further, in order to find the next EM, it is necessary to subtract the already found EM from the original signal and repeat the described actions again. This continues until all EM are found. The search for the next EM stops when there are no more than two extremes in the remainder.

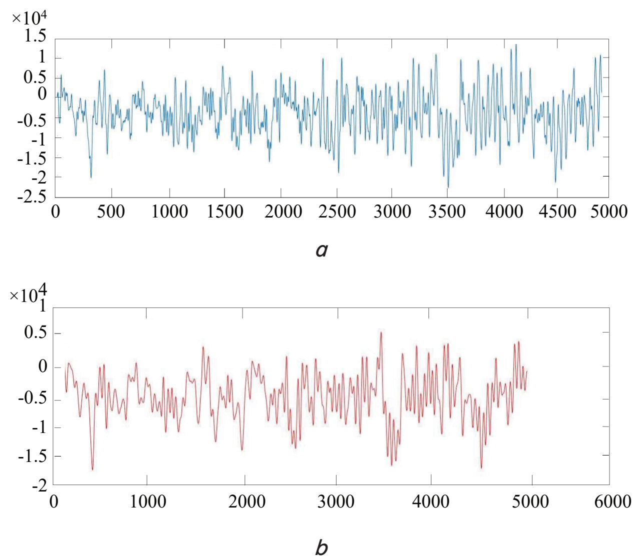


Fig. 5. Denoising process, time domain signal: a — noisier electrocardiogram; *b* —elimination of low-frequency signals in the time domain

To improve the performance of the EMD algorithm, it was proposed to exclude the screening procedure from it. In this case, the first approximations to the corresponding empirical modes will be considered as empirical modes of the input signal.

Another feature of the distribution of samples in the first three EMs is the concentration of interference samples in the vicinity of zero values, so that no more than 3–4 counts in a row have one character. Unlike interference, bursts corresponding to QRS complexes are characterized by at least five counts of one sign in a row. Thus, if during the formation of mono pulses, we get rid of several consecutive samples of different signs taken in a row, then the detection process will be much simpler.

It is advisable to carry out the formation of a mono-impulse corresponding to the QRS complex in three stages: the removal of readings from zero surroundings, taking of the module, and averaging in a sliding window. For the detection of monopulses, rank algorithms can be applied, for example, the binary discretization difference quantization (BKDR) algorithm. The collective decision on detection is made taking into account the informativeness of individual empirical modes. Empirical modes, in which informative sections are not found, contain only an interfering component and are excluded from the reconstruction. EM, in which informative sites are found with a certain frequency, are subject to NGOs and further reconstruction.

Thus, the developed algorithm for estimating interference in empirical modes based on the detection of informative plots contains the following steps.

Determination of the level of interference in EM by robust Q-scale estimation.

EM segmentation based on rank detection of informative sites with a threshold dependent on Q-score.

The decision on the detection of the ECS-informative sections is made on the basis of the detection of the informative sections in several EMs.

In the uninformative areas of the empirical modes, the estimate of the interference is refined and, thus, an estimate of the interference is formed in the absence of a useful signal for each cardiocycle and each EM.

According to the updated estimate of the interference for each cardiac cycle of each EM, a threshold value is calculated – *p*.

6. Creation of a system for diagnosing the state of the heart in conditions of free activity of the patient

SNCD developed by the authors is based on the use of multiple-link client-server architecture that allows to integrate subsystems of cardiac diagnostics, ambulance call service and personal portable cardiac analyzers by their interaction via the cloud service.

The modern organization of SNCD cloud service has such important properties as distribution, hardware scalability, high availability and security of communication channels and involves the provision of the following types of services to its users:

– storage-as-a-Service allows saving data in external storage, in the "cloud";

– database-as-a-Service provides the opportunity to work with databases as if the DBMS is installed on a local resource;

– information-as-a-Service lets remotely use any kind of information in real time;

– process-as-a-Service can link together multiple resources (such as services or data contained within one "cloud" or other available "clouds") to create a single CI processing process;

– application-as-a-Service or Software-as-a-Service enables each user to access it via the Internet.

Thus, the cloud processing of cardiological information is a promising direction of development of the system of non-invasive cardiac diagnostics, providing the extraction of diagnostic information from the ECG signal.

The organization of information exchange in SNCD is shown in Fig. 6.

In fact, in mental activity, a person spends 85 % of his time to search necessary information and only 15 % of time is spent

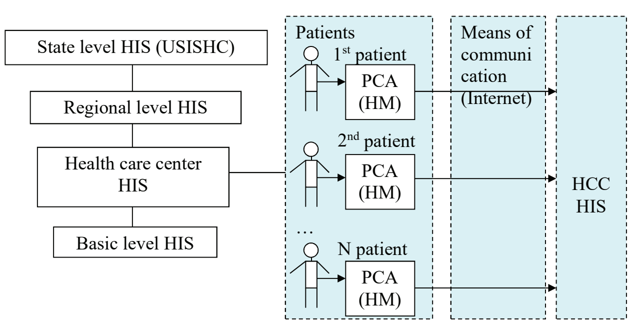


Fig. 6. Organization of information exchange in SNCD

on decision-making. This also applies to the doctor, so the main purpose of SNCD is information support, which involves:

– information support to medical personnel;

– information support of medical care;

– monitoring of the population's health level.

The database (DB) server is generally located in the health care center (HCC) hospital information system (HIS) and can only be accessed from an automated workplace with an Internet connection and access rights. Such organization of information exchange in the SNCD allows:

– supporting the unification of data formats and information exchange protocols. If HIS of different manufacturers are used, operational cooperation and electronic exchange of data between HIS become possible. As a result, it is possible to provide timely information about the patient to the attending physician;

– maintaining portable devices to register ECG signals, i.e. portable cardiac analyzer (PCA) is included in the structure of a distributed HCC database ("client" of HCC HIS). As a result, it is possible to monitor the state of the heart and automatically analyze ECG signals in conditions of a patient's free activity;

– meeting modern requirements on processing ECG signals and implementing the extraction of information parameters of ECG signals within the cardiocycle and the processing of ECG signals in a variety of ways to improve the accuracy of cardiac diagnostics in the analysis of the electrical activity of the heart. It is known that in the amplitude-time analysis of ECG signals, sensitivity of determining myocardial infarction is 75 %;

– implementing the full provision of data corresponding to the user's powers and excluding interference in case of simultaneous user access to patient data;

– reliably determining the start of ventricular repolarization of the heart;

– assessing the fitness degree of the heart based on the prediction of occurrence of AV-blockade;

– ensuring uninterrupted availability of information system resources;

– solving the problem of optimal medical care.

7. Research results

Analysis of Fig. 5 shows that the developed SNCD ensures:

– firstly, the assessment of the critical state of the heart in conditions of free motor activity of the patients at risk. Detection of life-threatening myocardial damage and arrhythmias is carried out by limited computing resources of a portable cardiac analyzer. The task of the health care system when identifying the critical state of the heart in conditions of the patient's free motor activity is emergency cardiac assistance within the "golden hour" of medicine. The authors developed a device for registration of ECG signals in conditions of the patient's free motor activity, which allows to prevent getting artifacts due to the break of electrodes on the registered ECG signal and to transmit information about the patient's condition in real time in case the critical state of the heart is detected;

– secondly, screening (mass and available) examination of the population with high efficiency (reliability) of diagnosis of diseases associated with the electrical activity of the heart.

One of such technologies is ECG mapping. Indications for ECG mapping:

– IHD (ischemic heart disease): angina, myocardial infarction, cardiosclerosis;

– heart disease;

– rheumatic heart disease;

– cardiac aging;

– pain in the heart area with no single triggering event;
– arrhythmia;
– tachycardia (palpitations).

Many researchers believe that "only a complete system of leads from the entire surface of the chest can provide the information necessary for the diagnosis of a wide range of cardiac pathology". It is obvious that for the implementation of the enlisted functional possibilities of SNCD, limited computing resources of a portable cardiac analyzer in conditions of the patient's free activity are not enough and appropriate computing resources, up to the use of cloud technologies are required.

The resource-intensive technologies of non-invasive cardiac diagnostics include modern detailed models of cardiac electrical activity (CEA) created by improving the Hodgkin–Huxley model, which is based on the processes of controlling the conductivity of membrane channel-forming proteins by changing the state of voltage-dependent particles. In this case, the formal control of the behavior of a single protein structure is given in the form of a system of differential equations modeling the state of voltage-dependent particles:

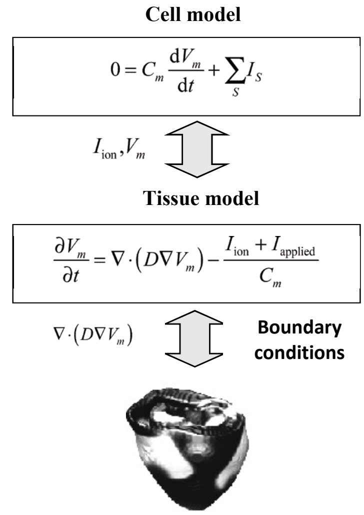


Fig. 8. Interrelation of detailed models of the ECG signal of the cell and autowave processes in heart tissues

$$j_m = C_m \frac{d\varphi}{dt} + \overline{g_{Na}} m^3 h(\varphi - E_{Na}) + \\ + g_k n^4 (\varphi - E_K) + g_L (\varphi - E_L), \quad (3)$$

where E_{Na}, E_K and E_L – equilibrium potentials for sodium, potassium and chlorine ions; m, n and h – gating variables, $\overline{g}_{Na}$, $\overline{g}_K$, $\overline{g}_L$, – maximum conductivity of membrane for sodium, potassium and chlorine ions.

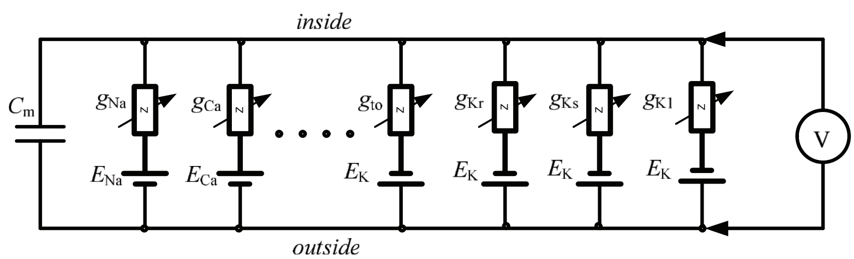


Fig. 7. Equivalent circuit diagram for a single excitable cell

The cells of the conduction system and the cardiomyocyte contain a greater amount of proteins forming electric current through the membrane. Fig. 7 shows an example of an electrical circuit for the electrophysiological model of a single heart cell, where g_{Na}, g_{Ca}, g_{to}, g_{Kr},g_{Ks}, g_{K1} are membrane conductivities formed by different proteins.

Boundary conditions imposed on solutions allow to obtain the distribution of excitation in the extension of anatomical models. The interrelation of detailed models of the ECG signal of the cell and autowave processes in heart tissues are given in Fig. 8.

When modeling the distribution of the transmembrane action potential (TMAP) in heart tissues, the heart model is assembled from equations that simulate the electrophysiology of a single heart cell, and the equations of extension of the transmembrane action potential in heart tissue.

Thus, autowave models of ECG signals are built at three levels: at the cell level, at the level of biological tissues (fibers) and at the level of the anatomical model of the object.

In the developed SNCD, as a result of solving the system of equations of the Aliyev-Panfilov model on a two-dimensional plane, the data describing the change in the distribution of TMAP on the heart surface in time are provided. To visualize the extension of excitation in the heart, a realistic image of the patient's heart model is used. TMAP distribution obtained as a result of the modelling is overlaid on the three-dimensional heart model. In the Aliyev-Panfilov model, actual TMAP and time can be obtained by the formulae:

$$E[\text{mV}]=100u-80,$$

$$t[\text{ms}]=12.9[\text{t.u}]. \quad (4)$$

These formulas are used to calculate the change in TMP at any point on the heart surface in time, as well as to determine the current time of modelling on the registered ECG signal.

According to the modelling results, the process of extension of excitation in the heart during the cardiocycle is clearly represented (Fig. 9).

Thus, according to the known information parameters of the patient's ECG signal, the distribution of potentials on the heart surface is determined. The areas of the heart surface where the potential behaves abnormally show the damaged myocardium. By the nature of myocardial damage, a diagnosis can be established.

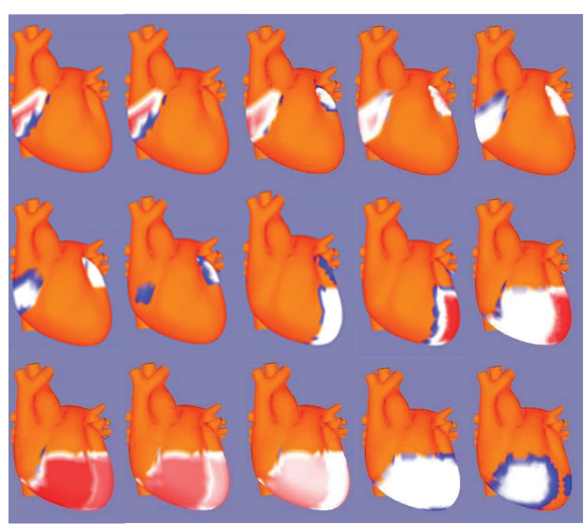


Fig. 9. Process of extension of excitation in the heart during the cardiocycle

7. Discussion of the results of the development of a cardiac diagnostic system

The non-invasive cardiac diagnostic system is an example of the practical implementation of the developed portable cardiac analyzer and the method of noise-resistant ECG processing for patients with free activity. The basis for the creation of a cardiac diagnostic system is modern information and communication technologies and patent-protected methods developed by the authors, algorithms, structural, circuit and software solutions.

The main features of the device in comparison with existing are:

– work in conditions of free activity;

– performing a preliminary ECG analysis;

– automatic diagnosis of life-threatening arrhythmias;

– call an ambulance;

– storing ECS entries locally and on a remote server;

– ability to integrate with the medical information system (section 4).

The introduction of a non-invasive cardiac diagnostic system in medical practice requires additional clinical trials and can serve as the basis for successful competition with leading foreign companies working in this field.

Currently, on the basis of the Satbayev University, ten sets of a portable cardiac analyzer have been designed and preclinical tests of the system are being conducted.

Study limitations. The main limitations of the electrocardiography method are:

– does not directly diagnose heart defects and tumors;

– does not reflect hemodynamics;

– does not reflect the presence of heart murmur.

Currently, the authors of the paper are trying to develop a method to display the hemodynamics of the heart.

8. Conclusions

1. A portable cardiac analyzer has been developed for recording the biopotential of the heart, which can be used as the basis for constructing a new cardiac diagnostic system in conditions of free activity of the patient.

2. Hilbert-Huang transform based interference suppression method is justified theoretically. To enable the implementation of Hilbert-Huang transform interference suppression algorithms in real-time systems, a truncated empirical mode decomposition algorithm has been developed. Based on the truncated empirical mode decomposition algorithm, procedures have been developed for suppressing interference in the ECG for use in portable devices of a non-invasive cardiac diagnostic system. Algorithms for estimating interference in individual empirical modes and an algorithm for detecting informative ECG sections based on Hilbert-Huang transform are developed.

3. A non-invasive cardiac diagnostic system has been developed that provides:

– high noise immunity, guaranteeing the reliability of automatic conclusions in conditions of free activity of patients;

– three-level ECG analysis: automatic express analysis of critical conditions (“Offline” mode), automatic differential analysis of critical conditions (“Smartphone-server” mode), detailed medical analysis using the workstation of a cardiologist (“Smartphone-server-doctor” mode);

– determining the location of the patient, providing emergency medical care in case of critical conditions;

– call an ambulance to the location of the patient in the event of a determination of critical conditions;

– input and editing of patient data.

Acknowledgements

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