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DEVELOPMENT OF AN ATRIOVENTRICULAR BLOCK PREDICTION OF METHOD FOR PORTABLE HEART MONITORING SYSTEM

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The object of the study is a portable system that allows real-time monitoring of the state of the heart for the timely provision of medical care. The task of detecting atrioventricular (AV) blocks in the conditions of free motor activity of the patient is being solved. To develop a method for detecting AV block, models of the electrical activity of the heart were used to take into account the spatiotemporal organization of the process of spreading excitation, analyze the dynamics of the behavior of the cardiovascular systems (CVS) for any value of the period of atrial excitation, and assess the degree of fitness of the CVS. The proposed method made it possible to determine the heart rate (HR) at which the development of AV block is possible. AV block of the III degree – heart rate 304 bpm; AV block of the II degree with the loss of half of the impulses – heart rate 260 bpm; AV block II degree with loss of individual impulses – heart rate 234 bpm; AV block of the 1st degree – heart rate 200 bpm. Prediction of AV block allows assessing the degree of "training" of the patient's heart. The obtained quantitative results are consistent with the heart rate values known to modern health care. The developed method was implemented on the basis of a portable ECG monitoring system previously developed by the authors. Tests of the portable ECG monitoring system indicate an increase in the sensitivity and specificity of diagnosing cardiac arrhythmia and confirm the achievement of the goal of this study: improving the efficiency of diagnostics and expanding the functionality of the portable ECG monitoring system

***Keywords:** holter monitor, automatic conclusion, cardiovascular system, cardiovascular disease, life-threatening arrhythmia*

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1. Introduction

Modern medicine has become one of the leading branches of scientific and applied activity, the most important task of which is the timely prevention and reduction of the risks of diseases based on the development of new effective methods for early diagnosis of the onset of pathologies.

In developed countries, the main factor in mortality of the population is associated with diseases of the cardiovascular system (CVS) [1]. A decrease in CVD mortality is possible if pathologies are detected at the beginning of their development. In this regard, the timeliness and availability of diagnostics of heart diseases is one of the most urgent tasks of modern health care.

The improvement of technologies determined the development of miniature devices for recording human physiological parameters, which, together with mobile computing devices, can organize continuous monitoring of the electrocardiosignal (ECS) and control of the electrophysiological characteristics (EPC) of the heart during daily activities outside the clinic.

The task of monitoring the ECG is to identify and prevent the development of heart disease through non-invasive monitoring of its EPC when registering the pacemaker, assessing diagnostic indicators and obtaining a preliminary diagnosis of the presence or possible development of the disease if the indicators deviate from their normal values.

Modern decision support tools at various stages of providing cardiac care implement an algorithmic approach to processing and analyzing recorded data, according to which all processes in the heart occur according to strict rules, and in order to obtain diagnostic information about its condition, it is necessary to perform a series of sequential transformations of the pacemaker. This approach does not take into account the probabilistic regularities due to the state of the heart tissues when observing electrical activity and the propagation of autowaves.

Therefore, to improve the efficiency of diagnosing heart diseases, it is important to develop a probabilistic-information concept for monitoring the EPC of the heart, aimed at identifying statistical patterns in the processing of ECS and studying electrical activity using stochastic models.

Existing methods do not provide prompt diagnosis of the condition in conditions of free physical activity. The identification of new symptoms of the disease during the development of a probabilistic approach expands the possibilities of non-invasive diagnostic methods based on the results of ECG examination. For modern medicine, the direction of developing methods and means of non-invasive diagnostics that do not injure the patient during examination and provide objective quantitative data on the development of pathologies of the disease is relevant. Among these areas, the problem of modeling the EPC of the heart should be singled out.

2. Literature review and problem statement

AV blocks can threaten a person's life, so their timely detection is an important condition for life support. It is currently believed that the genesis of arrhythmias is due to structural and functional disorders in the work of the heart. Arrhythmias are a typical form of heart pathology, characterized by a violation of the frequency and periodicity of the generation of excitation impulses.

Sinoatrial dysfunction is dysfunction of the sinus node or atria that interferes with the formation of impulses or their conduction. Arrhythmias caused by sinoatrial dysfunction include atrioventricular heart block. It is characterized by abnormal coordination between atrial and ventricular contractions resulting in:

– to prolongation of the interval between atrial and ventricular contractions (AV block of the 1st degree);

– to an increase in the number of atrial contractions in relation to the number of ventricular contractions occurring due to blocked conduction of some of the atrial beats (AV block II degree);

– to a complete lack of coordination between atrial and ventricular rhythms (AV block of the III degree).

As summarized in a systematic review [2] on the critical assessment and comparison of existing cardiovascular risk factor assessment tools, the defining features of the onset of lethal arrhythmias are:

– myocardial infarction, ventricular hypertrophy and dilatation, inflammation and edema of myocardial tissue;

– "classic" risk factors (RFs), such as age, diabetes mellitus, gender, smoking, family analysis of cardiovascular diseases (CVD), arterial hypertension (AH).

These signs, according to many researchers, form the anatomical basis for the occurrence of arrhythmias with various mechanisms.

Atrioventricular block (AVB) is a poorly defined clinical condition characterized by an abrupt and sudden change in atrioventricular conduction to complete heart block, leading to syncope and possible sudden cardiac death [3]. Although it is a dangerous condition, the correct diagnosis of AVB is often overlooked due to its unpredictability and, in some cases, the absence of clear signs of atrioventricular conduction disturbance during normal conduction.

Currently, there is the only method in the world for detecting AV block using Holter monitoring, the development of which began in 1961 [4]. Nowadays, thanks to the development of computer technologies, Holter monitoring has found widespread use in clinical practice. For example, in [5], a Holter system for monitoring the state of the heart based on the Zigbee method was developed, which has a measuring and recording device. In another work [6], a method for detecting peaks for Holter devices using self-organizing operational neural networks is presented. Also, Holter has a number of other names: outpatient ECS monitoring, long-term ECS monitoring, 24-hour ECS monitoring.

Holter monitoring – continuous recording of the ECS on the media in the conditions of the patient's free activity, followed by offline decoding on special decoders. Holter monitoring is as follows. For a certain period of time – several hours, a day or several days – the subject wears a portable device in which a continuously recorded electrocardiogram is accumulated. After the study, the portable device is removed from the patient, the electrocardiogram contained in it is pumped into a stationary device, in which the accumulated information is analyzed in an accelerated time mode. When using the Holter, it is not possible to monitor the state of the heart in real time (it is possible only after wearing the device for a day or more), and after processing the record on a computer, the doctor of functional diagnostics must give a conclusion about the rhythm, its violations. And when diagnosing AV block, it is difficult to determine the disease manually, where the doctor may miss or not notice changes in ECG curves. Currently, systems for monitoring the ECG and physiological characteristics of human life have become a routine technique in cardiology clinics and diagnostic centers.

In [7], a method for non-invasive electrophysiological study of the heart was proposed, based on the registration of multiple leads or the method of ECG mapping of the heart, which is one of the most informative methods for studying ECS. The use of twelve-channel recorders to detect rhythm disturbances is not appropriate: the study becomes less comfortable, but the presence of leads does not provide additional information about heart rhythm disturbances. The use of a twelve-channel monitor is justified only when it becomes necessary to assess the dynamics of the ST segment and associate cardiac arrhythmias with episodes of myocardial ischemia. In our case, the detection of myocardial infarction is not provided. In the study [8], a method is presented that allows recording an electrocardiosignal (ECS) and measuring the potentials generated by the heart, registering frontal and left-sided fluorographic images of the patient's heart, determining the geometric parameters of the patient's heart from the images, synthesizing a computer model of the patient's heart, determining the potentials generated by the heart on patient's torso, determine the dipole moments and potentials of the epicardium φ at the reference points of the computer model of the patient's heart, simulate the propagation of an excitation wave in the epicardium, synthesize a model ECS, compare the model ECS with the registered ECS, correct the calculated parameters of the model of propagation of an excitation wave in the epicardium by changing the parameters when determining moment distributions of the main electrophysiological characteristics on the surface of the heart and visualize the electrophysiological characteristics of the heart on a three-dimensional model of the heart by means of computer graphics in the most convenient way for acceptance of the form. While an ECG and chest x-ray may well provide insight into a person's systolic function and indicate whether or not an echo study is needed, it is expensive and requires trained personnel and therefore may not be available in primary care settings. And most importantly, there is no way to determine the arrhythmia of the heart in real time.

In [9], the system of Maxwell's differential equations is used to determine the electrophysiological characteristics of the heart. The task of electrocardiography is to determine the electrophysiological characteristics of the heart based on the solution of the system of Maxwell differential equations for a medium in which geometric relationships are conditionally set between the area of current generators in the shape of a heart and the surface points where the potential is measured. In the known method [10], the verification of their determination is based on the conceptual model of the electrical activity of the heart (EAH). A distinctive feature of the EAS conceptual model is the simplicity of the formal mathematical description of the phenomenon concept, which makes it possible to single out the qualitative properties of an object without revealing its internal structure. The use of conceptual models is aimed at describing the change in an individual property of an object without describing its internal structure. This approach does not allow revealing the reasons for the change in electrophysiological characteristics.

All of the above methods of mapping the ECG of the heart allows to obtain maximum information about the features of the electric field of the heart at any time of depolarization and repolarization of the heart ventricles, however, it requires the participation of a highly qualified specialist in the diagnosis, the use of expensive equipment and a significant investment of time for one study. According to the authors, the disadvantages of the known methods of non-invasive electrophysiological study of the heart are: the impossibility of using in mass preventive examinations (screening) of the heart due to the registration of multiple electrocardiographic signals.

All this suggests that it is appropriate to conduct a study on the development of a portable ECG monitoring system for diagnosing AV block.

3. The aim and objectives of the study

The aim of the study is to expanding the functionality of a portable ECG monitoring system by developing a method for predicting atrioventricular block based on a model of the electrical activity of the heart.

To achieve this aim, the following objectives were implemented:

– substantiation of the model of the electrical activity of the heart;

– development of the algorithm for determines the degree of fitness of the cardiovascular system;

– implementation of the developed method in a portable ECG monitoring system.

4. Materials and methods

4. 1. Model of the electrical activity of the heart

The study of the electrical activity of the heart (EAH) according to the signals of standard electrocardiographic leads remains one of the fundamental problems of theoretical and practical electrocardiography. EAH modeling is of great importance, since diagnostic signs are extracted both directly from the analysis of the patient's cardiographic information, and from the analysis of indirect parameters determined on the basis of a model of electrical processes in the myocardium. The use of EAH modeling results is a condition for increasing the efficiency of CVS diagnostics. It is known that the Noble model most fully describes the processes of propagation of excitation in the heart, but its use requires significant computational resources. The need for significant computing resources is due to a detailed description of the ionic mechanisms of interaction in the myocardial cell.

For the purposes of functional diagnostics, it is necessary to find a compromise between the completeness of the description of the processes of propagation of excitation in the heart, the cost and efficiency of the implementation of these processes. It is quite obvious that at present the last two criteria make it impossible to use the Noble model for the purpose of functional diagnostics for a complete description of the processes of propagation of excitation in the heart. It is proposed to use a generalized model of the electrical activity of the heart (GMEAH), which includes a model of the propagation of excitation in the heart muscle, and a model of the equivalent electrical generator of the heart (EEGH). Fig. 1 shows the structure of the functional components of the CVS, based on physiological data and consisting of the EAH system, the contractile system and the hemodynamic system.

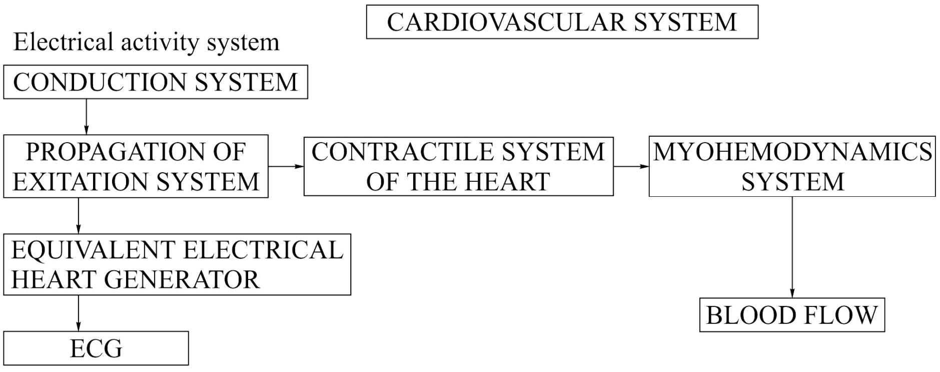


Fig. 1. Functional components of the cardiovascular system

The EAH system consists of the cardiac conduction system (CCS), the cardiac excitation propagation system (EPS), and the equivalent cardiac electrical generator (ECEG).

A distinctive feature of GMEAH is that each level of the process of propagation of excitation in the heart corresponds to its own level of description. Thus, to describe the processes of propagation of excitation in the CCS, the Noble model is used [11], and to describe the processes of propagation of excitation in the heart, a transition is made to another level of description – autowave. In this case, the Noble ion-membrane model serves as a kind of "generator thread" or generator of initial conditions for the autowave model. There are many variants of violation of the propagation of excitation in the CCS, which are recorded using ECG [12–14]. The essence of conduction disorders is reduced to a complete –

or partial block of the conduction pathways. In this case, it is considered that the shape of the pulse of propagation of excitation in the CCS corresponds to the data of an electrophysiological study.

The shape of the transmembrane action potential (TMAP) of the His bundle, calculated according to the Noble model, is shown in Fig. 2 and is identical to the shape of the TMAP of the His bundle, obtained as a result of an electrophysiological study.

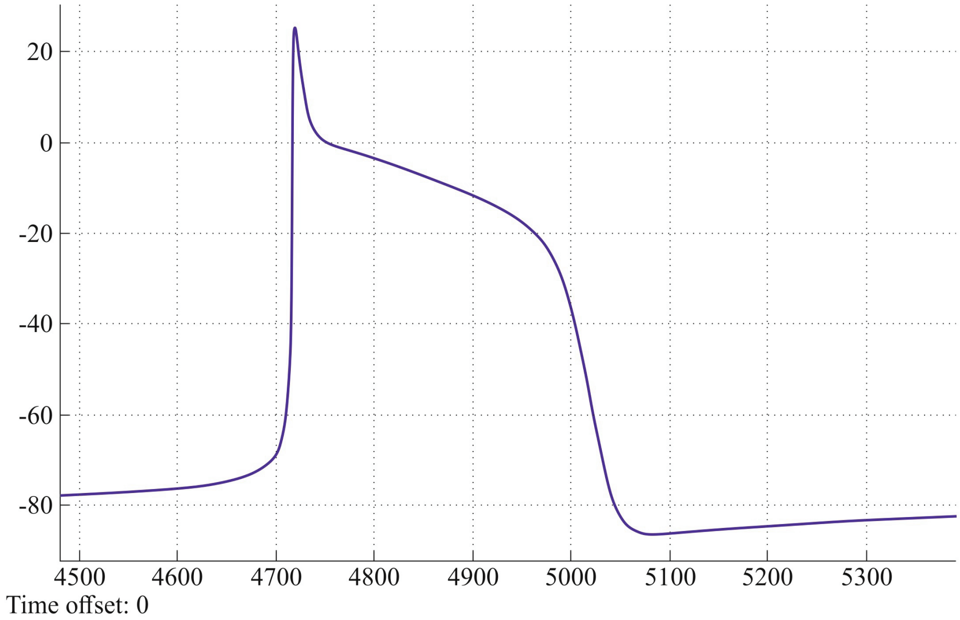


Fig. 2. The shape of the transmembrane action potential of the His bundle, calculated according to the Noble model

Changing Noble Model Parameters:

$$\frac{\partial V}{\partial t}=\Delta V-C^{-1}\begin{bmatrix}(V-E_k)\overline{g_k}\,n^4+\\+(V-E_{Na})\overline{g_{Na}}\,m^3h+(V-E_0)\overline{g_0}\end{bmatrix};$$

$$\frac{dn}{dt}=a_n(1-n)-\beta_n n; \qquad (1)$$

$$\frac{dm}{dt}=a_m(1-m)-\beta_m m;$$

$$\frac{dh}{dt}=a_h(1-h)-\beta_h h,$$

makes it possible to take into account the spatio-temporal organization of the excitation propagation process and to model the shape of TMAP in various anatomical regions of the CCS in accordance with physiological data.

In GMEAH, to simulate the propagation of excitation in the myocardium, the two-component Aliev-Panfilov model [15] is used, which is proposed for a simplified description of excitation waves in the heart muscle. The Aliev-Panfilov model is implemented in the form of equations of the "reaction-diffusion" type and contains two variables: a fast variable corresponding to TMAP, and a slow variable characterizing the properties of the medium:

$$\frac{\partial u}{\partial t}=-ku\cdot(u-a)\cdot(u-1)-uv+\Delta u;$$

$$\frac{\partial v}{\partial t}=-\left(\varepsilon_0+\frac{\mu_1 v}{u+\mu_2}\right)\cdot\left(v+ku\cdot(u-a-1)\right). \qquad (2)$$

In this case, the connections between myocardial cells – points of the autowave medium (heart muscle) – are described by diffusion terms of the equations, and the dynamics of an individual myocardial cell – by reactionary nonlinear terms of the equations.

In GMEAH, the modeling takes into account the spatial and temporal organization of the process of propagation of excitation, the form of TMAP in various anatomical parts of the heart, and the speed of passage of the excitation impulse through different parts of the heart. This is achieved by setting the appropriate parameters in the Noble and Aliev-Panfilov models based on the results of the analysis of cardiographic information.

The distribution of TMAP on the surface of the patient's heart model obtained as a result of modeling the process of excitation propagation is an EEGH and is a source of an electromagnetic field, the potential of which is modeled on the patient's body at the points of standard leads in the form of a model ECG. The theoretical basis of EEGH is Maxwell's differential equations for the potential of the electric field of stationary currents created by the heart in the body, as in a bulk conductor.

Thus, within the framework of GMEAH, simulation of the propagation of excitation in the heart is carried out. To verify the correctness of the GMEAH concept, it is necessary to study it when modeling the propagation of excitation in the heart muscle, synthesizing a model ECG, and predicting heart rhythms.

The values of the transmembrane action potential (TMAP) φ for each of the three possible states of the myocardial cell are shown in Fig. 3 [16].

Comparison of electrophysiological data and TMAP of the Wiener-Rosenblatt model in Fig. 3 shows that the following assumptions are made in the model:

– TMAP configuration is simplified and close to a right triangle;

– the entire R interval is considered absolutely refractory.

The Wiener-Rosenblatt model is described by the equation for the operation of a cellular automaton [17, 18]:

$$B(x_i,y_i,t)=\alpha(t)\cdot\sum_{i-j=1}B(x_j,y_j,t);$$

$$\alpha(t)=1-\frac{R-t_n}{R}, \qquad (3)$$

where α(t) is the value of myocardial cell refractoriness; R is the duration of the refractoriness interval; t_p is the duration of the rest interval.

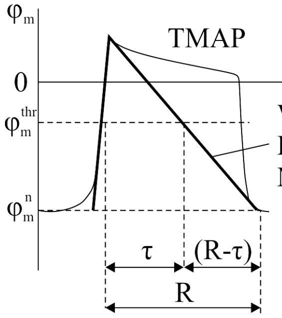


Fig. 3. Shape of transmembrane action potential in the Wiener-Rosenblatt model

The excitation wave in the Wiener-Rosenblatt model can be represented as a zone consisting of n cells in the refractory phase *R*, and moving through the region of resting cells at a constant speed *V*. The rate of excitation propagation is determined by the ratio introduced by Wiener:

$$V=\lambda/R. \qquad (4)$$

It follows from (3), (4) that in order for a myocardial cell to move to another state, it is necessary to know the states of the cell and its nearest neighbors. The use of the τ-model makes it possible to qualitatively describe the process of excitation propagation.

4. 2. The degree of fitness of the heart

An important diagnostic indicator of CVS is the degree of fitness. A strong external stimulus for a detrained cell introduces it into a pathological mode, that is, into a disease, and for a trained cell, this is normal intensive work. Fig. 4 shows a graph of the dependence of the degree of fitness on the strength of the stimulus.

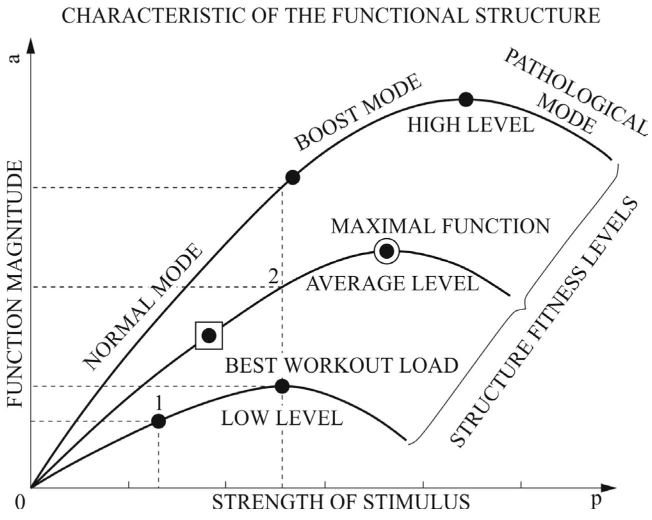


Fig. 4. Graph of the dependence of the degree of fitness on the strength of the stimulus

The lower point on the ordinate axis (point 1) corresponds to the amount of energy that the body at rest requires from the cell. For a detrained cell, this is almost the limit of the normal mode of functioning, and in order to get more energy from this cell, it must go into a forced mode of functioning. It follows from the graph in Fig. 5 that the "energy reserve" of the normal mode of a moderately trained cell compared to a detrained cell is three times, that of a highly trained cell is six times and the pathological mode of a detrained cell is the normal mode of operation of a highly trained cell.

5. Results of development of an atrioventricular block prediction algorithm for portable heart monitoring system

5. 1. Substantiation of the model of the electrical activity of the heart

The essence of the algorithm for studying the effect of physical activity on the occurrence of Wenckebach periodicals in GMEAH is as follows. Based on the morphological analysis of the ECG, the time of passage of the impulse in the corresponding section *t* is determined. To study AV block II, it is necessary to determine the intervals from the onset of atrial excitation to the onset of excitation in the atrioventricular node, from the onset of excitation in the atrioventricular node to the onset of activity in the His bundle. The time of passage of excitation through the conduction system of the atria is defined as two thirds of the ECG P wave, the time of passage of excitation along the AV node corresponds to the last third of the P wave plus the first half of the PQ segment of the ECG. According to the three-dimensional model of the heart, the geometric dimensions of the section of the conduction system *L* are determined. The speed of propagation of excitation is calculated by the formula:

$$V=L/t. \qquad (5)$$

Then, using the Wiener ratio (4) and the data of the morphological analysis of the ECG, the parameters of the model for the propagation of excitation in the CCS are determined. Since there can be several variants of the model parameter sets, an additional condition is necessary for an unambiguous interpretation of the simulation results, namely, that the excitation propagation velocity before and after exercise remains unchanged: $V_{rest}=V_{load}$. This condition is due to the fact that in the autowave paradigm, only the parameters of the excitation propagation medium determine the excitation propagation velocity, and this velocity does not depend on factors external to the excitation propagation medium. Since the speed of propagation of excitation does not depend on external factors, and the frequency of activation of the sinus node increases with an increase in the load on the heart, prerequisites arise for the emergence of Wenckebach's periodicals. This is illustrated by the time diagram shown in Fig. 5, which shows periodic stimulation by the sinus node of the heart muscle with a time interval *ts* between successive stimuli.

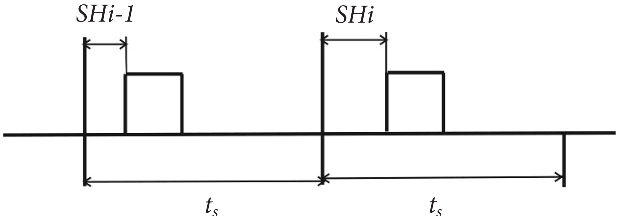


Fig. 5. Periodic stimulation (t_s intervals) by the sinus node of the heart muscle

An impulse from the sinus node (*Si*) causes excitation in the ventricles after some delay (SH_i). The duration of the interval SH_i is a function of the time from the end of the previous excitation to the moment the pulse Si is applied. In this case, the S-H interval corresponds to the time from the beginning of the impulse in the sinus node to the beginning of the response impulse in the cells of the *H* is bundle. Denoting the time interval between impulses of the sinus node through t_s, we have

$$SH_i = C\left(t_s - SH_{i-1}\right). \qquad (6)$$

Function *C* in the electrophysiology of the heart is called the recovery curve of the heart (RCH) [16]. To find the function *C*, it is necessary to obtain a sample of the successive change in the interval *S-H* from its previous value. Using the τ-model, the propagation of excitation is modeled and the values of the *S-H* interval are determined at different excitation frequencies of the sinus node. The obtained data can be approximated by an exponential function of the form.

$$SH = SH_{\min} + \alpha \cdot e^{-HS/\beta}, \qquad (7)$$

where α, β are positive constants.

In (7), the *H-S* interval can be expressed in terms of the previous *S-H* interval. Then the recovery curve can be represented as follows:

$$SH_i = SH_{\min} + \alpha \cdot e^{-\left(N \cdot t_s - SH_{i-1}/\beta\right)}, \qquad (8)$$

where *N* is the smallest integer such that

$$N \cdot t_s - SH_{i-1} > R.$$

By iterating expression (8), one can determine the dynamics of the behavior of the CVS for any value of the excitation frequency of the sinus node.

5. 2. Development of the algorithm for determines the degree of fitness of the cardiovascular system

The generalized model of the electrical activity of the heart (GMEAH) makes it possible to assess the degree of fitness of the cardiovascular system by predicting the heart rate under the influence of physical activity.

One of the main purposes of autowave models is the study of arrhythmias. Sinoatrial dysfunction is dysfunction of the sinus node or atria that interferes with the formation of impulses or their conduction. Arrhythmias caused by sinoatrial dysfunction include atrioventricular heart block. It is characterized by abnormal coordination between atrial and ventricular contractions resulting in:

– to prolongation of the interval between atrial and ventricular contractions (AV block of the 1st degree);

– to an increase in the number of atrial contractions in relation to the number of ventricular contractions occurring due to blocked conduction of some of the atrial beats (AV block II degree);

– to a complete lack of coordination between atrial and ventricular rhythms (AV block of the III degree).

From the point of view of modeling, II-degree block is of the greatest interest, since the possibilities of its implementation make it possible to simulate the mode of AV blocks of I and III degrees. This arrhythmia is known as the Wenckebach rhythm. The origin of II-degree AV block is associated with the lengthening of the absolute and relative refractory periods in the atrioventricular junction. With this block, conduction at the atrioventricular junction progressively worsens from contraction to contraction. This deterioration in atrioventricular conduction continues until the atrioventricular junction becomes unable to conduct another impulse to the ventricles. This leads to loss of contraction of the ventricles. On the ECG, a gradual deterioration in atrioventricular conduction is manifested in a progressive lengthening of the PQ interval from complex to complex. The initial PQ interval may be normal or prolonged. At the moment when the atrioventricular node becomes unable to conduct the next impulse to the ventricles, only the P wave is recorded on the ECG, due to atrial excitation, and the ventricular QRST complex falls out. There is a long pause. After a pause, the smallest PQ interval is observed. Then the cycle repeats. The number of ventricular contractions in II-degree block is always less than the number of P waves, since some of the atrial waves are blocked. With this block, they speak of atrioventricular block 3:2, 4:3, etc., indicating the number of atrial P waves in the numerator, and the number of QRS complexes in the denominator.

To predict the heart rate and determine the conditions for the occurrence of second-degree AV block, an algorithm has been developed that uses the proposed GMEAH. The scheme of the algorithm is shown in Fig. 6. The essence of the algorithm is to extrapolate the results of the ECG analysis, simulate the EAH and determine the degree of fitness of the cardiovascular system.

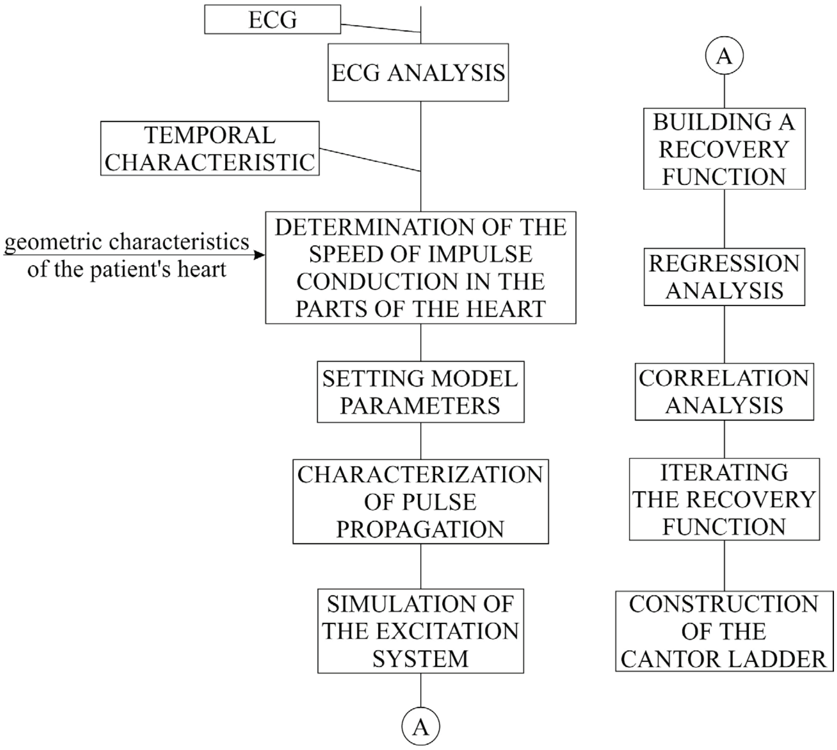


Fig. 6. Algorithm for determining the degree of fitness of the cardiovascular system

According to the algorithm, based on the results of the ECG analysis, the time counts of the beginning and end of the processes of depolarization and repolarization of the sections of the conduction system of the heart are determined. These timestamps serve as GMEAH parameters. With an increase in physical activity (analogous to the stimulus in Fig. 4), the frequency of activation of the sinus node increases. Since the speed of propagation of excitation impulses remains unchanged, the prerequisites for AV block of the II degree arise. It is obvious that with increasing load, the *P-R* interval is a decreasing function of the previous *P-R* interval, and this circumstance, taking into account the constancy of the absolute and relative refractory periods in the atrioventricular junction, is used to determine the condition for the occurrence of II-degree AV block. Based on the results of the simulation, a graph of the Cantor function is constructed, which characterizes the degree of fitness of the cardiovascular system.

First of all, in order to study according to the proposed algorithm of the Wenckebach periodicals, it is necessary to determine the model for the propagation of excitation from the sinus node to the His bundle in the atrioventricular junction. In this case, for the purposes of functional diagnostics, it is possible to use the axiomatic τ-model of Wiener-Rosenblatt, which makes it possible to qualitatively describe the process of propagation of excitation in the CCS. The Wiener-Rosenblatt model is based on the principles of myocardial cell operation, describing its three states – rest, excitation and refractoriness; and Noble's ionic model is based on the mechanisms of myocardial cell functioning. Since in the study of Wenckebach periodicals only qualitative states of the myocardial cell are used – rest, excitation and refractoriness, the use of the Noble model is inappropriate due to the lack of demand for modeling results (up to the level of distribution of membrane currents) and high computational costs.

The Wiener-Rosenblatt model postulates that each cell, which is an element of the active environment, can be in one of three states:

1. Excitation – τ, while the potential of the membrane $\varphi m > \varphi mppor$, the cell is not excitable, but can excite a neighboring cell at rest.
2. "Refractory" tail – $(R-\tau)$, while the potential of the membrane $\varphi mp < \varphi m < \varphi mpor$, the cell is not excitable, and cannot excite a cell at rest.
3. Rest – at the same time, the membrane potential $\varphi m = \varphi mp$, in this state the cell can be excited by the neighboring one, provided that the TMAP of the neighboring cell is higher than the threshold value of the cell in question.

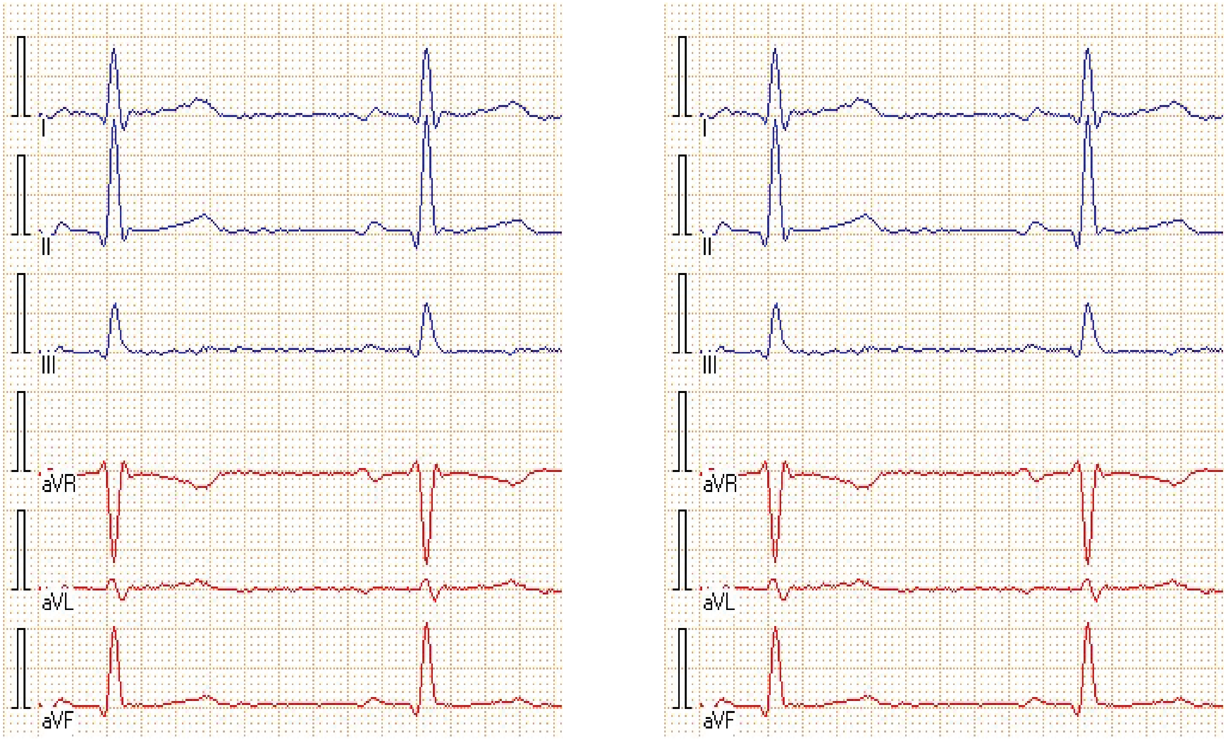
Fig. 7 shows the electrocardiogram before and after exercise.

Based on the analysis of these ECGs and modeling the process of propagation of excitation at different frequencies of the sinus node, the change in the S–H interval from its previous value is determined. The results of the analysis and determination of the values of the time interval from the stimulus to the beginning of the response impulse in the His bundle, as well as the interval from the beginning of activity in the His bundle until the next stimulus arrives from the sinus node are summarized in Table 1.

These values are approximated by a curve of the following form:

$$SH = 89 + 114e^{-HS/41}, \qquad (9)$$

the graph of which is shown in Fig. 8.



a *b*

Fig. 7. Heartbeat from electrocardiogram device: *a* — electrocardiogram before exercise; *b* — after exercise

Table 1

Results of the analysis and determination of the values of the time interval from the stimulus

Time interval from the beginning of activity in the His bundle until the next stimulus arrives from the sinus node, *vx* (*HS*), ms	Time interval from the stimulus to the beginning of the response impulse in the His bundle, *vy* (*SH*), ms
486.52	88.75
475.29	89.625
444.59	87.857
410.15	89.643
388.44	89.107
377.2	91.143
351	88.304
345.76	89.732
311.31	90.161
295.59	88.661
260.4	89.821
246.17	89.804
225.21	88.571
209.48	90.875
194.51	91.768
175.04	90.982
160.82	92.571
151.08	94.089
144.34	91.25
132.36	93.821
124.13	93.75
119.63	97.125
117.39	100.25
112.15	95.268
100.17	103.91
99.418	99.54
96.423	97.857
85.94	101.79
82.945	107.3
76.955	106.16
73.96	110.7
71.714	103.93
64.226	117.13

Establishment of the adequacy of the regression curve of cardiac recovery (RCH) of a random sample of simulation results was carried out according to the Fisher criterion:

$$F = \frac{R^2}{1-R^2} \cdot \frac{N-m-1}{m},$$

where m is the number of degrees of freedom of smaller dispersion; R^2 is the index of determination of the assessment of the adequacy of the regression model, calculated using the expression:

$$R^2 = 1 - \frac{\sum_{i=1}^{N} SH_i^M - SH_i^{reg}}{\sum_{i=1}^{N} SH_i^M - M_{SH}},$$

where are SH_i^M the values of the SH coordinate of the simulation results; SH_i^{reg} are the values of the *SH* coordinate calculated using the regression *RCH* when the *I* coordinates coincide; M_{SH} is the mathematical expectation of the *SH* coordinate for sampling the simulation results.

Table 2 shows the typical results of estimating the parameters of the regression *RCH* and the corresponding value of the Fisher criterion for the extreme values of the range of variation of the SH_0 component (variant 1 and 3) and for the best version of the *CVR* regression (variant 2).

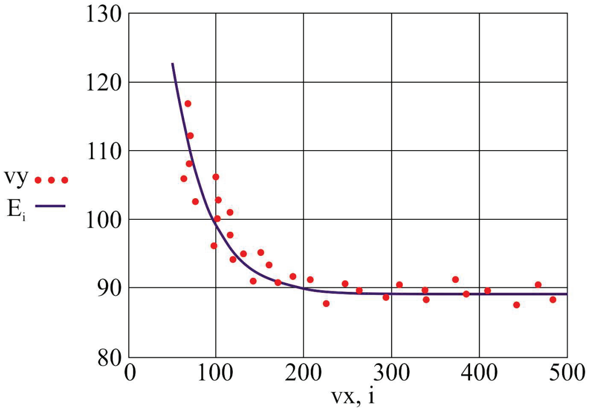


Fig. 8. Construction of cardiovascular system recovery curve

Table 2

Results of estimation of the parameters of the regression RCH

Type of distribution for approximation	Weibull-Gnedenko distribution		
Variation	1	2	3
SH_0, ms	87	87.32	88.2
Parameter B, ms^2	2125	1987	1607
Form parameter	0.807	0.794	0.741
Scale parameter, ms	86	77	54.9
Fisher criterion F	353	375	351

From the analysis of Table 2, it follows that all values of the Fisher criterion obtained for the regression *RCH* in the variable range of the SH_0 component are within the range of acceptable values for the level of statistical significance α=0.05. Therefore, all obtained variable range curves can be used to predict AV block.

Fig. 9 shows the graphs of the derivatives of the RCH.

From Fig. 9, it can be seen that:

– AV block of the III degree – heart rate 304 bpm;

– AV block of the II degree with the loss of half of the impulses – heart rate 260 bpm;

– AV block II degree with loss of individual impulses – heart rate 234 bpm;

– AV block of the 1st degree – heart rate 200 bpm.

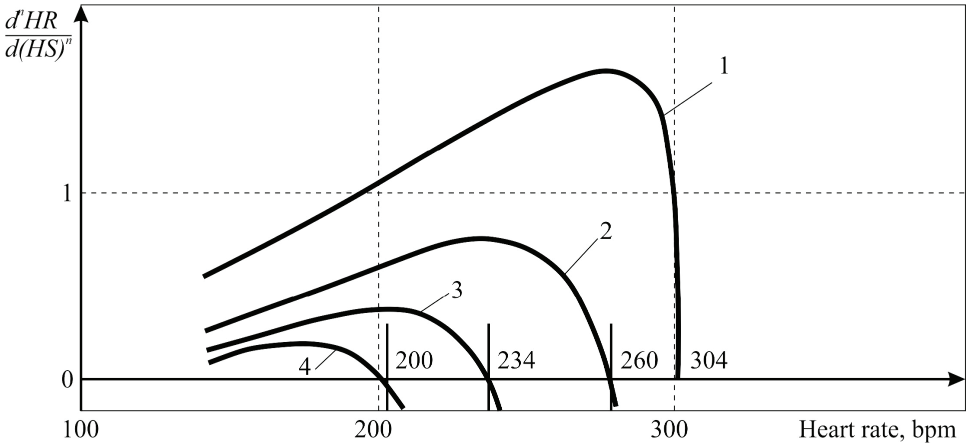


Fig. 9. Graphs of RCH derivatives: 1 — the first derivative of the heart recovery curve; 2 — the second derivative of the heart recovery curve; 3 — the third derivative of the heart recovery curve; 4 — the fourth derivative of the heart recovery curve

5. 3. Implementation of the developed method in a portable electrocardiography monitoring system

The developed method was implemented on the basis of a portable ECG monitoring system that was previously developed by the authors [19], which allows to monitor the state of the heart during the patient's free active activity. Fig. 10 shows the experiments using a portable ECG device (*a*) and a photo apparatus (*b*). The consent of the participants to the publication of pictures has been obtained.

To determine the ECG of the device, let's create a unique ID for each device and associated it with a specific user, so when transferring data, let's also transfer the device ID.

Next, let's write a listener function and a signal handler or as it is also possible to call it the data packets (Fig. 12). The listener first of all looks at the address of the transmitted data, if they are addressed to our IP, let's receive the data. Now transfer our data further for processing and, if necessary, to store in our database under a specific user.

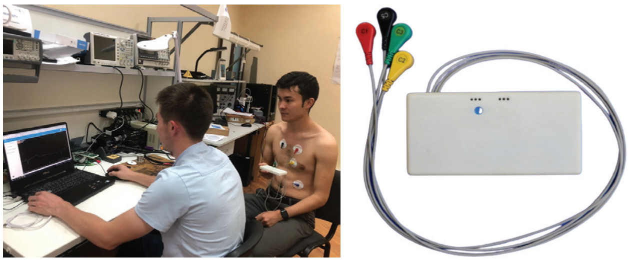


Fig. 10. Taking an electrocardiosignal using a portable cardiac analyzer: *a* — participant of the experiment with connected single-channel electrocardiography electrodes; *b* — photo of a portable electrocardiography device used in the experiment

In our project, to receive and transmit data, let's use a programming interface – a socket, which allows to always accurately determine the state of a person and ensures immediate data exchange. In vue.js, sockets are quite mature and are constantly being improved. To use sockets, it is enough to refer to the web socket initialization function WebSocket(). The first attribute is the address directed to our server. It is worth paying attention to the explicit indication of the id of the patient whose data we want to see.

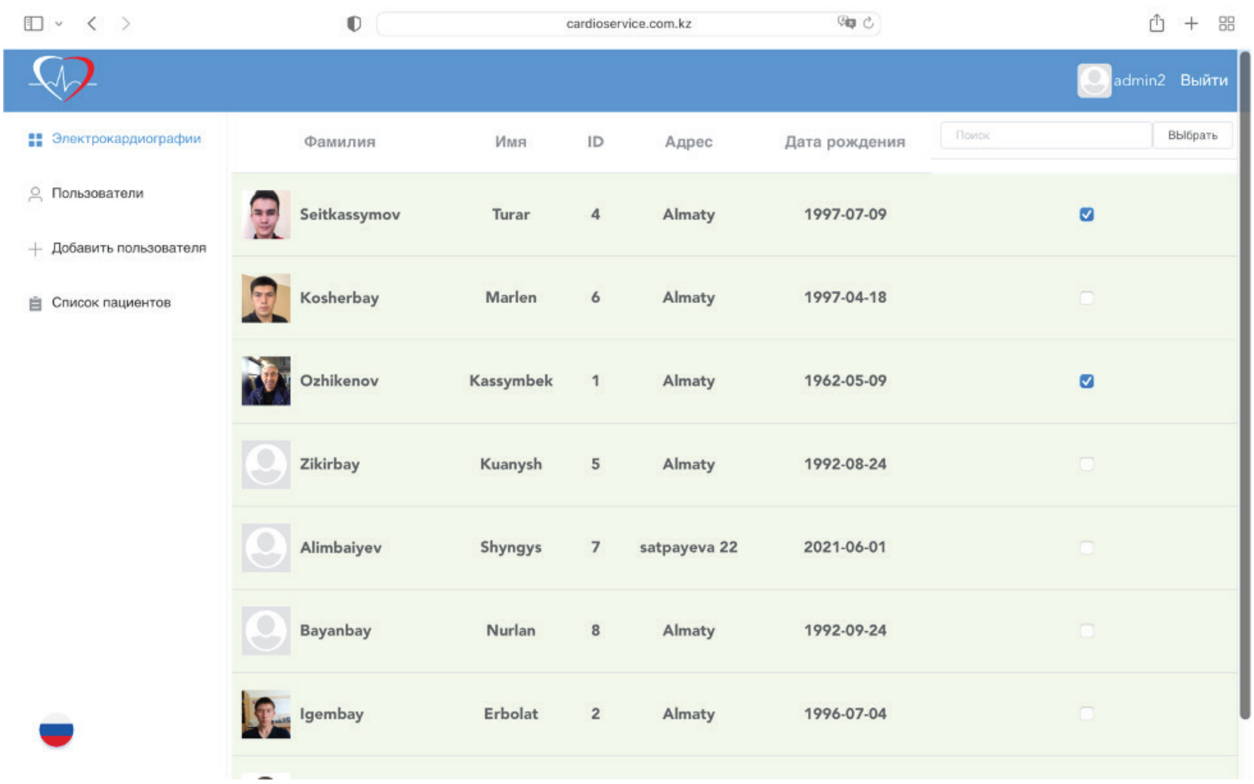
When running this script, it is possible to observe the calculations aimed at the "arction/lcjs" library, which is designed to visualize graphs. When drawing graphs, this library uses graph theory, which allows to effectively arrange the received data in the form of integers. Thanks to this, the user can visually observe the pacemaker in real time (Fig. 13).

An important point in our system is the definition of dangerous cardiac arrhythmias. The key value in determining dangerous cardiac arrhythmias is – heart rate. To calculate the heart rate value, it is necessary that our device receives an ECS within 60 seconds, this will be enough. Knowing the formula for determining heart rate in advance, let's rewrote the formula into a similar function, the syntax of which is written below:

$$heartrate = \frac{60}{R-R'},$$

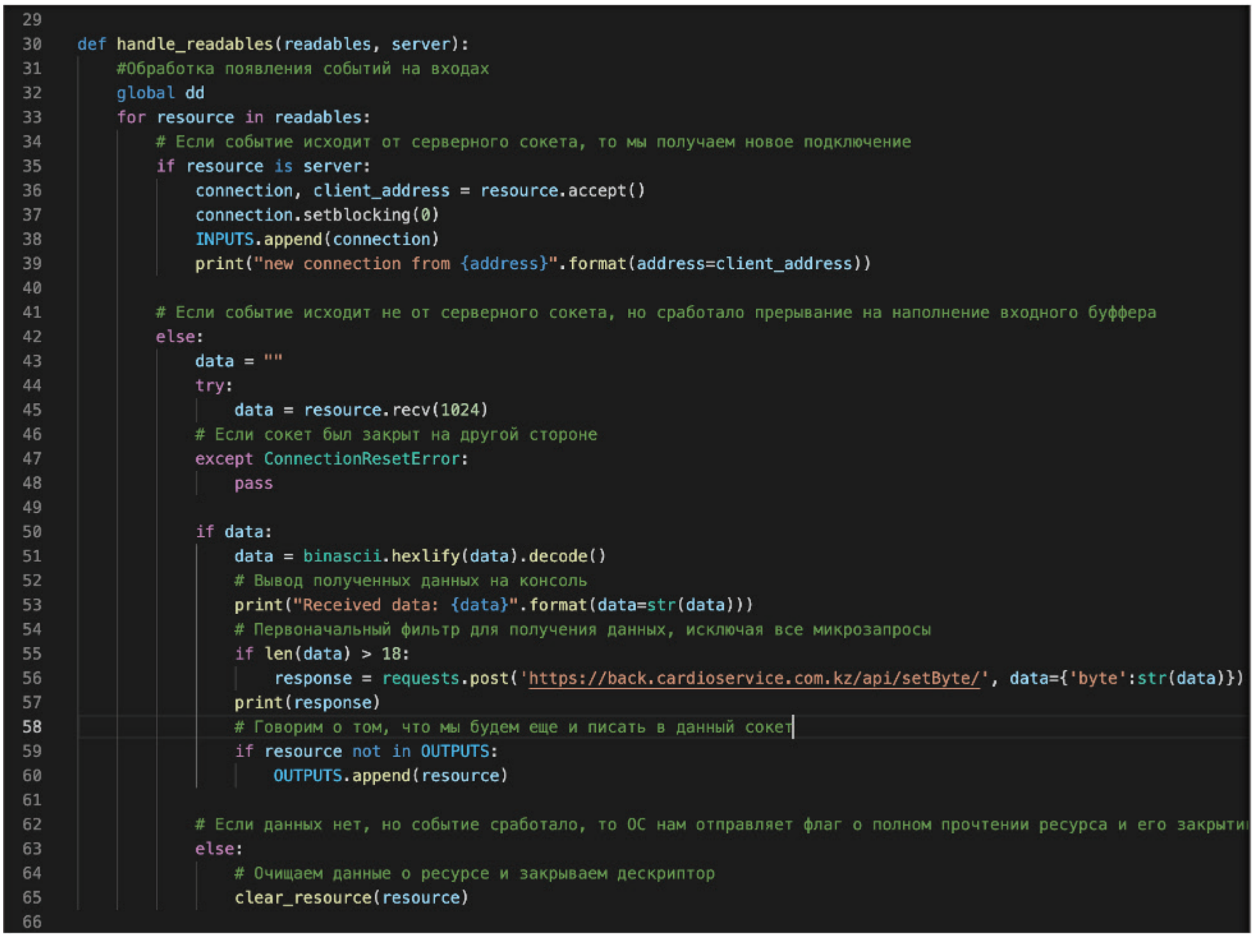
where 60 is the number of seconds in a minute, *R-R* is the duration of the interval, expressed in seconds.

It is also important to calculate the RR value (the distance between two signal amplitudes, that is, heartbeats). Having obtained these values, we can easily determine three extremely dangerous diagnoses: "Sinus rhythm" (AV block), "Sinus bradycardia" and "Sinus tachycardia".



	Фамилия	Имя	ID	Адрес	Дата рождения	
	Seitkassymov	Turar	4	Almaty	1997-07-09	☑
	Kosherbay	Marlen	6	Almaty	1997-04-18	☐
	Ozhikenov	Kassymbek	1	Almaty	1962-05-09	☑
	Zikirbay	Kuanysh	5	Almaty	1992-08-24	☐
	Alimbaiyev	Shyngys	7	satpayeva 22	2021-06-01	☐
	Bayanbay	Nurlan	8	Almaty	1992-09-24	☐
	Igembay	Erbolat	2	Almaty	1996-07-04	☐

Fig. 11. User registration in the system

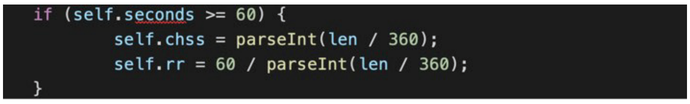


```

def handle_readables(readables, server):
    #Обработка появления событий на входах
    global dd
    for resource in readables:
        # Если событие исходит от серверного сокета, то мы получаем новое подключение
        if resource is server:
            connection, client_address = resource.accept()
            connection.setblocking(0)
            INPUTS.append(connection)
            print("new connection from {address}".format(address=client_address))

        # Если событие исходит не от серверного сокета, но сработало прерывание на наполнение входного буффера
        else:
            data = ""
            try:
                data = resource.recv(1024)
            # Если сокет был закрыт на другой стороне
            except ConnectionResetError:
                pass

            if data:
                data = binascii.hexlify(data).decode()
                # Вывод полученных данных на консоль
                print("Received data: {data}".format(data=str(data)))
                # Первоначальный фильтр для получения данных, исключая все микрозапросы
                if len(data) > 18:
                    response = requests.post('https://back.cardioservice.com.kz/api/setByte/', data={'byte':str(data)})
                print(response)
                # Говорим о том, что мы будем еще и писать в данный сокет
                if resource not in OUTPUTS:
                    OUTPUTS.append(resource)

            # Если данных нет, но событие сработало, то ОС нам отправляет флаг о полном прочтении ресурса и его закрыти
            else:
                # Очищаем данные о ресурсе и закрываем дескриптор
                clear_resource(resource)

```

Fig. 12. Handling the occurrence of events on inputs

Igembay Erbolat
1996-07-04
Almaty 2

Fig. 13. ECS visualization in real time



```
if (self.seconds >= 60) {
        self.chss = parseInt(len / 360);
        self.rr = 60 / parseInt(len / 360);
}
```

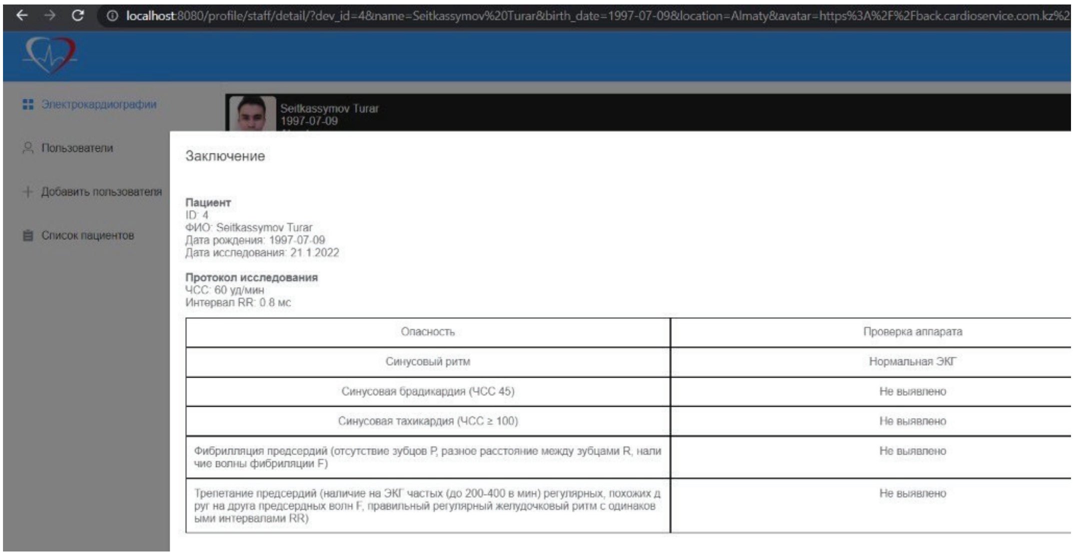
Fig. 14. Formula for calculating heart rate written in the JavaScript programming language

```
<div>
  <b>{{ $t("protocol") }}</b>
</div>
<div>{{ $t("hs") }}: {{ chss }} {{ $t("bl_min") }}</div>
<div class="mb10">{{ $t("interval") }} RR: {{ rr }} мс</div>
<div></div>
<div class="table-conclusion">
  <div>{{ $t("danger") }}</div>
  <div>{{ $t("device_check") }}</div>
</div>
<div class="table-conclusion">
  <div>{{ $t("sinus_rhythm") }}</div>
  <div>{{ $t("normal_ecg") }}</div>
</div>
<div class="table-conclusion">
  <div>{{ $t("sinus_bradycardia") }} ({{ $t("hs") }} 45)</div>
  <div v-if="chss > 45">{{ $t("not_found") }}</div>
  <div v-else>{{ $t("found") }}</div>
</div>
<div class="table-conclusion">
  <div>{{ $t("sinus_tachycardia") }} ({{ $t("hs") }} ≥ 100)</div>
  <div v-if="chss < 100">{{ $t("not_found") }}</div>
  <div v-else>{{ $t("found") }}</div>
</div>
```

Fig. 15. Code to visualize the conclusion

When let's finally calculate the values needed for the conclusion, the user can see the final diagnosis of his/her condition (Fig. 16).

In the automatic report, AV block is listed as "Sinus Rhythm". The results obtained are consistent with the heart rate values known to modern health care.



Заключение

Пациент
ID: 4
ФИО: Seitkassymov Turar
Дата рождения: 1997-07-09
Дата исследования: 21.1.2022

Протокол исследования
ЧСС: 60 уд/мин
Интервал RR: 0.8 мс

Опасность	Проверка аппарата
Синусовый ритм	Нормальная ЭКГ
Синусовая брадикардия (ЧСС 45)	Не выявлено
Синусовая тахикардия (ЧСС ≥ 100)	Не выявлено
Фибрилляция предсердий (отсутствие зубцов P, разное расстояние между зубцами R, наличие волны фибриляции F)	Не выявлено
Трепетание предсердий (наличие на ЭКГ частых (до 200-400 в мин) регулярных, похожих друг на друга предсердных волн F, правильный регулярный желудочковый ритм с одинаковыми интервалами RR)	Не выявлено

Fig. 16. Visualization of diagnostic result

6. Discussion of experimental results of development of an atrioventricular block prediction algorithm

Within the framework of the proposed approach to diagnosing the state of the cardiovascular system (CVS), a generalized model of the electrical activity of the heart (GMEAH) is proposed, which allows taking into account the spatiotemporal organization of the process of excitation propagation, modeling the shape of the transmembrane action potential (TMAP) of various anatomical regions of the heart, and synthesizing a model electrocardiosignal (ECG) taking into account the "geometry" of the patient's heart and torso. Fig. 2 and Fig. 5 show the shape of the TMAP of the His bundle calculated according to the Noble model and the shape of the TMAP in the Wiener-Rosenblatt model. The expediency for functional diagnostics of CVS of the hierarchical organization of the description of the process of propagation of excitation in the heart is shown:

– the spread of excitation in the conduction system of the heart is described by the Noble model;

– the spread of excitation in the heart muscle is described by the Aliev-Panfilov model;

– the equivalent electrical generator of the heart is described by the Titomir model.

The use of GMEAH makes it possible to determine the "electrical portrait" of the patient's heart during the cardiocycle, which makes it possible to extract diagnostic features when analyzing indirect parameters determined on the basis of modeling electrical processes in the myocardium.

The proposed method for predicting AV block allows to determine the heart rate at which the development of AV block is possible. Prediction of AV block allows assessing the degree of "training" of the patient's heart. Fig. 6 shows an algorithm for determining the degree of fitness of the CVS. According to the algorithm, based on the results of the ECG analysis, the time counts of the beginning and end of the processes of depolarization and repolarization of the sections of the conduction system of the heart are determined. These timestamps serve as OMEAS parameters. With an increase in physical activity (analogous to the stimulus in Fig. 4), the frequency of activation of the sinus node increases. Since the speed of propagation of excitation impulses remains unchanged, the prerequisites for AV block of the II degree arise. It is obvious that with an increase in load, the P-R interval is a decreasing function of the previous P-R interval, and this circumstance, taking into account the constancy of the absolute and relative refractory periods in the atrioventricular junction, is used to determine the condition for the occurrence of II-degree AV block.

To increase the practical value of the method proposed by the authors implemented in a real platform of a portable ECG monitoring system. The main advantage of the developed system is its mobility and the ability to detect AV block in the free activity of patients. The technical result of the implementation of real-time monitoring of the state of the heart is to minimize the time of monitoring, decision-making and provision of medical care in conditions of free motor activity of the patient.

The technical result is achieved by:

– receiving a signal from the ECS recording device (Fig. 11);

– performing its preliminary processing (Fig. 12, 13);

– diagnosis of life-threatening arrhythmias of the heart (Fig. 14);

– visualization and notification of the patient about the results of diagnostics and data transfer to the application server (Fig. 15, 16).

The direction of further research may be to determine the components of the ionic currents of the epicardium based on the solution of the inverse problem of electrocardiography, and their knowledge expands the functionality of the standard electrocardiographic approach and increases the efficiency of diagnosing the state of the heart. In such pathological conditions as coronary heart disease, hypertension, congenital and acquired heart defects, myocardial hypertrophy, electrolyte and hormonal disorders, there is a significant decrease in the repolarizing currents of delayed and abnormal rectification, which, in turn, is accompanied by an increased risk of complex rhythm and conduction disturbances. Thus, the control of anomalous rectification potassium currents as a result of using the proposed method and a portable monitoring system will allow a cardiologist to predict the occurrence of pathologies and quickly use high-tech cardiac surgical methods of treatment.

7. Conclusions

1. A model of the electrical activity of the heart is proposed, which makes it possible to determine the "electrical portrait"

of the patient's heart during the cardiocycle, which makes it possible to extract diagnostic features in the analysis of indirect parameters determined on the basis of modeling electrical processes in the myocardium. The results of the study show the adequacy of the applied model of the electrical activity of the heart.

2. An algorithm is developed to determine the degree of fitness of the cardiovascular system. The developed algorithm makes it possible to analyze abnormal coordination between atrial and ventricular contractions and to detect atrioventricular heart block. Experiments were carried out to determine the effect of physical activity on the occurrence of Wenckebach's periodicals. The proposed method made it possible to determine the heart rate (HR), at which the development of AV block is possible. AV block of the III degree – heart rate 304 bpm; AV block of the II degree with the loss of half of the impulses – heart rate 260 bpm; AV block II degree with loss of individual impulses – heart rate 234 bpm; AV block of the 1st degree – heart rate 200 bpm. Prediction of AV block allows assessing the degree of "training" of the patient's heart. The obtained quantitative results are consistent with the heart rate values known to modern health care.

3. The developed method was implemented on the basis of a portable ECG monitoring system previously developed by the authors. Tests of the portable ECG monitoring system indicate an increase in the sensitivity and specificity of diagnosing cardiac arrhythmia and confirm the achievement of the goal of this study: improving the efficiency of diagnostics and expanding the functionality of the portable ECG monitoring system.

Acknowledgment

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References

1. Timmis, A., Vardas, P., Townsend, N., Torbica, A., Katus, H., De Smedt, D. et. al. (2022). European Society of Cardiology: cardiovascular disease statistics 2021. European Heart Journal, 43 (8), 716–799. doi: https://doi.org/10.1093/eurheartj/ehab892
2. Opoku-Acheampong, A. A., Rosenkranz, R. R., Adhikari, K., Muturi, N., Logan, C., Kidd, T. (2021). Tools for Assessing Cardiovascular Disease Risk Factors in Underserved Young Adult Populations: A Systematic Review. International Journal of Environmental Research and Public Health, 18 (24), 13305. doi: https://doi.org/10.3390/ijerph182413305
3. Holter, N. J. (1961). New Method for Heart Studies: Continuous electrocardiography of active subjects over long periods is now practical. Science, 134 (3486), 1214–1220. doi: https://doi.org/10.1126/science.134.3486.1214
4. Chou, I.-C., Hsueh, H.-C., Lee, R.-G. (2009). Example for mobile ECG holter design using FMEA model. Biomedical Engineering: Applications, Basis and Communications, 21 (01), 61–70. doi: https://doi.org/10.4015/s101623720900109x
5. Liu, S.-H., Huang, Y.-F., Chen, C.-R. (2014). The wireless holter ECG system based on Zigbee. 2014 IEEE International Conference on Systems, Man, and Cybernetics.
6. Gabbouj, M., Kiranyaz, S., Malik, J., Zahid, M. U., Ince, T., Chowdhury, M. E. H. et. al. (2022). Robust Peak Detection for Holter ECGs by Self-Organized Operational Neural Networks. IEEE Transactions on Neural Networks and Learning Systems, 1–12. doi: https://doi.org/10.1109/tnnls.2022.3158867
7. Zbitnieva, V. O., Voloshyna, O. B., Balashova, I. V., Dukova, O. R., Lysyi, I. S. (2021). Incidence of cardiac arrhythmias in patients with COVID-19 infection according to 24-hour electrocardiogram monitoring, Zbitnieva V. O., and etc., Zaporozhye medical journal, 23 (6), 759–765. doi: https://doi.org/10.14739/2310-1210.2021.6.239243
8. Basnet, B. K., Manandhar, K., Shrestha, R., Shrestha, S., Thapa, M. (2009). Electrocardiograph and Chest X-ray in Prediction of Left Ventricular Systolic Dysfunction. Journal of Nepal Medical Association, 48, 176. doi: https://doi.org/10.31729/jnma.343
9. Katscher, U., Weiss, S. (2022). Mapping electric bulk conductivity in the human heart. Magnetic Resonance in Medicine, 87 (3), 1500–1506. doi: https://doi.org/10.1002/mrm.29067
10. Aliev, R. R. (2010). Computer simulation of the electrical activity of the heart. Uspekhi fizicheskikh nauk, 41 (3), 44–63.
11. Noble, D. (1962). A modification of the Hodgkin-Huxley equations applicable to Purkinje fibre action and pacemaker potentials. The Journal of Physiology, 160 (2), 317–352. doi: https://doi.org/10.1113/jphysiol.1962.sp006849
12. Herve, D., Drouard Haelewyn, C., Rousselot, J. F. (2002). The A.B.C. of ECG. Pratique Medicale and Chirurgicale de l'Animal de Compagnie, 37 (6), 487–489.
13. Simova, I., Predovski, M., Christov, I., Simov, D. (2017). Remote ECG Interpretation: Guidelines and their Implementation. 2017 Computing in Cardiology Conference (CinC). doi: https://doi.org/10.22489/cinc.2017.366-095
14. Orlov, V. N. (2017). Rukovodstvo po elektrokardiografii. Moscow: 560. Available at: https://ivgma.ru/attachments/16530
15. Pravdin, S. F., Epanchintsev, T. I., Nezlobinskii, T. V., Panfilov, A. V. (2020). Induced drift of scroll waves in the Aliev–Panfilov model and in an axisymmetric heart left ventricle. Russian Journal of Numerical Analysis and Mathematical Modelling, 35 (5), 273–283. doi: https://doi.org/10.1515/rnam-2020-0023
16. Li, A., Stroik, D., Schaaf, T., Yuen, S., Kleinboehl, E., Cornea, R. L., Thomas, D. D. (2020). Biophysics of the SERCA2A/DWORF Complex, Implications for Treatment of Heart Failure. Biophysical Journal, 118 (3), 593a. doi: https://doi.org/10.1016/j.bpj.2019.11.3210
17. Von Rosenberg, W., Hoting, M.-O., Mandic, D. P. (2019). A physiology based model of heart rate variability. Biomedical Engineering Letters, 9 (4), 425–434. doi: https://doi.org/10.1007/s13534-019-00124-w
18. Stenzinger, R. V., Tragtenberg, M. H. R. (2022). Cardiac reentry modeled by spatiotemporal chaos in a coupled map lattice. The European Physical Journal Special Topics, 231 (5), 847–858. doi: https://doi.org/10.1140/epjs/s11734-022-00473-1
19. Alimbayev, C., Alimbayeva, Z., Ozhikenov, K., Bodin, O., Mukazhanov, Y. (2020). Development of measuring system for determining life-threatening cardiac arrhythmias in a patient's free activity. Eastern-European Journal of Enterprise Technologies, 1 (9 (103)), 12–22. doi: https://doi.org/10.15587/1729-4061.2020.197079