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SYSTEM AND ALGORITHM OF INTELLIGENT BIOMEDICAL SIGNAL PROCESSING AND ANALYSIS FOR HUMAN HEALTH STATUS REMOTE MONITORING SYSTEM[1]

Abstract: *Continuous and steady running of health status remote monitoring systems is essential not to omit episodes of acute exacerbation of chronic disease. Running time of such systems is largely determined by performance capabilities of the patient's wearable system elements. To ensure its long-term operation and efficient performance, the monitoring system must have multilayered structure with the elements realizing recording and picking off biomedical signals, signal processing and analysis, estimation of patient current condition, dynamics of the disease and its prognosis. For this purpose, it is necessary to use smart monitoring algorithms. A specific feature of such algorithms is change of the number of channels used for biomedical signal recording and processing according to the change of patient's condition. To detect the exacerbation first symptoms by means of the patient's wearable computer, additional channels are activated for recording biomedical signals used to evaluate the expanded complex of diagnostically significant parameters of the disease and their integration when specifying the patient's condition. The system and intelligent monitoring algorithm is tested with the use of heart rate remote control and atrial fibrillation episode detection system. The testing results of the developed system and algorithm are discussed.*

Key words: system, remote monitoring, health status, processing and analysis, biomedical signals, algorithm, intelligent monitoring

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СИСТЕМА И АЛГОРИТМ ИНТЕЛЛЕКТУАЛЬНОЙ ОБРАБОТКИ И АНАЛИЗА БИОМЕДИЦИНСКИХ СИГНАЛОВ В СИСТЕМАХ УДАЛЕННОГО МОНИТОРИНГА СОСТОЯНИЯ ЗДОРОВЬЯ ЧЕЛОВЕКА

Аннотация. *Непрерывная продолжительная работа систем мониторинга имеет большое значение для исключения пропуска эпизодов обострения заболевания. В системах удаленного мониторинга продолжительность непрерывной работы определяется возможностями носимых пациентом устройств. Они предназначены для съема и регистрации комплекса биомедицинских сигналов, предварительной обработки и анализа сигналов и данных.*

Цель настоящей статьи – разработка алгоритма интеллектуального мониторинга состояния здоровья. Он обеспечивает эффективное использование вычислительных и энергетических ресурсов носимых устройств пациента, снижение тока потребления, увеличение автономности его работы. Для решения проблемы используется методология теории интеллектуальных измерений. Она заключается в изменении

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интеллектуальным элементом системы количества используемых измерительных каналов, методов и алгоритмов измерений и обработки сигналов в зависимости от изменения состояния объекта измерений.

Для реализации алгоритма интеллектуального мониторинга состояния здоровья система должна иметь многоуровневую структуру. Носимая система должна состоять из устройства пациента, предназначенного для регистрации комплекса биомедицинских сигналов, и носимого компьютера пациента, предназначенного для обработки и анализа сигналов, контроля текущего состояния пациента. Алгоритм интеллектуального мониторинга заключается в следующем. Фоновый режим устанавливается, когда состояние пациента соответствует состоянию нормы. В этом режиме оцениваются не более двух показателей, наиболее значимых для диагностики, и контролируется состояние нормы. Режим активного мониторинга устанавливается, когда контролируемые в фоновом режиме параметры выходят за границы нормы. В этом режиме активируются дополнительные каналы регистрации биомедицинских сигналов, оценивается расширенный комплекс значимых для диагностики показателей. Экспериментальная апробация системы и алгоритма интеллектуального мониторинга была проведена с использованием системы удаленного мониторинга сердечного ритма и эпизодов фибрилляции предсердий. Результаты апробации показали целесообразность и эффективность использования предложенной структуры и алгоритма мониторинга.

Ключевые слова: система, удаленный мониторинг, состояние здоровья, обработки и анализ, биомедицинские сигналы, алгоритм, интеллектуальный мониторинг

Для цитирования: Система и алгоритм интеллектуальной обработки и анализа биомедицинских сигналов в системах удаленного мониторинга состояния здоровья человека / Нгуен Чонг Туен, Чан Чонг Хыу, Нгуен Мау Тхач, З. М. Юлдашев // Изв. вузов России. Радиоэлектроника. 2018. № 5. С. 81–90. doi:10.32603/1993-8985-2018-21-5-81-90

Introduction. In the development of remote health monitoring systems, much attention is paid to the issue of ensuring continuous long-term health monitoring for timely and prompt detection of the body functional disorders and provision of emergency medical care [1]–[5]. Such systems are used for remote detection of atrial fibrillation episodes [6]–[8], sleep apnea [9], [10], hypertension [11], [12], epileptic attack, bronchial asthma [13], [14], which should identify life-threatening disorders within a few seconds and form an effect for the body normalization. To provide high accuracy, sensitivity and specificity, a set of important diagnostic indicators of the disease is used, measured by several biomedical signal channels,

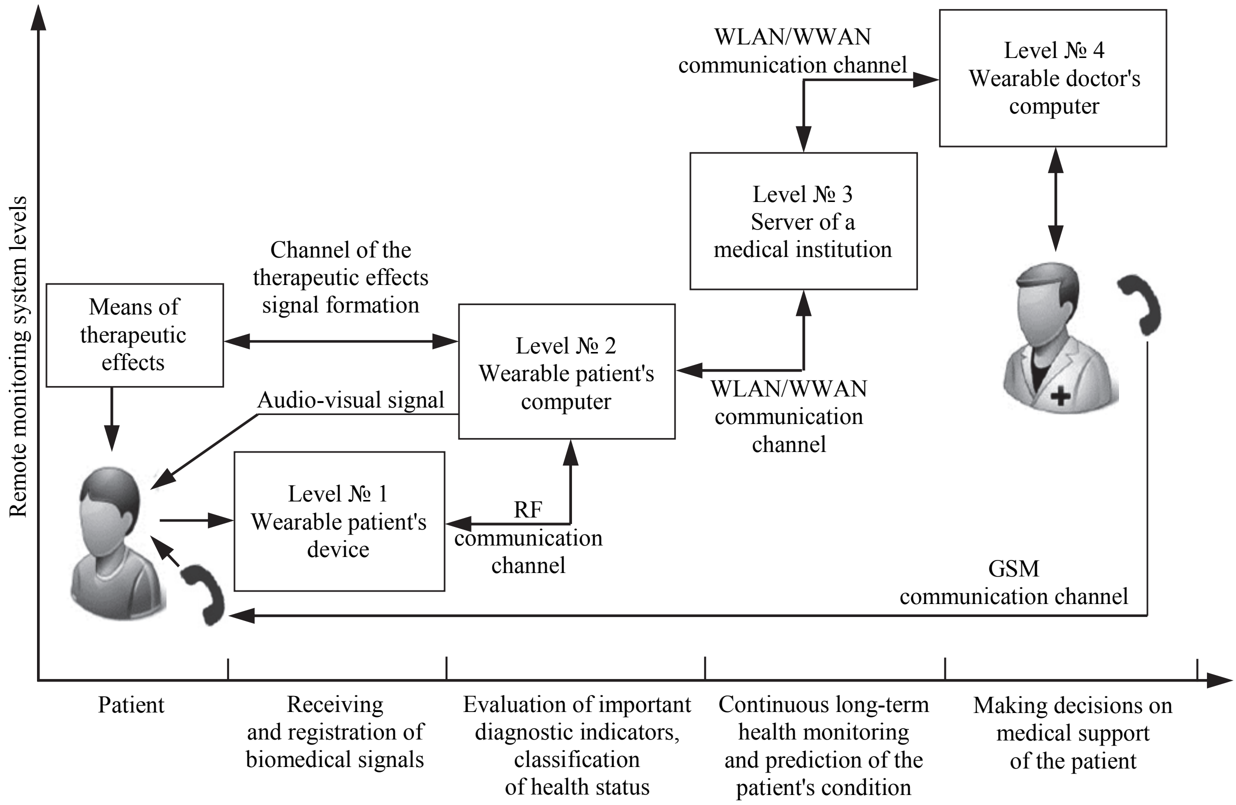

Fig. 1

i.e. ECG, breathing, plethysmogram, oximetry, EMG, etc. It is obvious that simultaneous synchronous processing of all biomedical signals in real time requires high performance microprocessor devices, such as high processor clock speed and parallel signal processing. However, this causes a significant increase in current consumption and a decrease in the autonomy of the means of registration and processing of medical and biological signals, assessment of diagnostically significant parameters of the disease [15]–[18]. To guarantee remote continuous monitoring of the patient's medical condition, the system (Fig. 1) should include the following elements: equipment for receiving and registration of biomedical signals, made in the form of a small-sized wearable patient's device (WPD); wearable patient's computer (WPC) with wireless communication channels, made as a smartphone-based device, for processing and analysis of medical and biological data, evaluation of important diagnostic indicators, comparing them with thresholds (individual norm), classification of medical status; server of a medical institution (MIS) to form a database of identified episodes of the disease, to assess the disease dynamics and support doctor's decision making; wearable doctor's computer (WDC), used for analysis of comprehensive medical status data, diagnosis, and forming instructions to provide necessary medical assistance.

The duration of the system autonomous operation is to be determined solely by the WPD and WPC autonomy, their power supply resource and current consumption. Therefore, WPD and WPC should use algorithms to register biomedical signals, process and analyze the data, which use minimal computing, hardware and power resources when the patient's condition agrees with the physiological standard. When condition disagrees with the physically normal state, additional channels for registration of biomedical signals, processing and analysis of an expanded set of diagnostic indicators are applied. Thus, the problem of intellectualization of algorithms for processing and analysis of complex medical and biological data in the systems of continuous long-term health monitoring of people with chronic diseases is one of the priorities in increasing the system autonomous operation.

The research objective is to develop a system and algorithms for intelligent processing and analysis of biomedical signals for continuous monitoring of human health.

Methods and approaches to the problem solution. To solve the formulated problem we used methods and approaches of smart information-measuring systems, in which the characteristics of the measuring channels and algorithms for the measured result processing depend on the state of the measuring object, the construction principles of adaptive biotechnical systems, ensuring optimal coordination of the characteristics of the elements of the system measuring channels with the ones of biological objects, methods of the theory of pattern recognition, taking into consideration the set of significant indicators and their weight to achieve a given classification accuracy in the classification of object conditions; methods of system analysis of biological systems, allowing to take into account the interaction of body systems to ensure homeostasis.

It is known that for such a complex system as a biological object, and, in particular, a person, to classify their state it is necessary to use a set of indicators important for diagnosis. These indicators characterize the functioning of various body systems-cardiovascular, respiratory, nervous, musculoskeletal etc. The body under the action of an arbitrary system maintains homeostasis-dynamic constancy of the internal environment and the major physiological functions makes changes in the functioning of other body systems. For example, an increase in physical activity on the body (performing physical work) leads to an increase in the heart rate (HR), pulse rate (PR) and breathing rate (BR). Such systemic changes also appear in the development of the disease and dysfunction of the body system. For example, the heart rate, emergency care, blood pressure increases with the exacerbation of obstructive sleep apnea, blood oxygen saturation changes. This means that a sufficiently large set of indicators characterizes the state of the norm and the disease, and a set of diagnostic indicators for different types of diseases may vary. It is impossible to detect accurately the disease, based on a limited number of patients. In the conditions of continuous long-term monitoring of the patient's health, to improve the accuracy and reliability of the disease detection, it is necessary to use additional channels for receiving and registration of biomedical signals and integration of diagnostically significant indicators into the decisive rules of the disease diagnosis [15]. To control the compliance of the patient's condition with the physiological norm, it is sufficient to use a limited number of indicators and channels for registration of medical and biological signals.

Let us consider an example of constructing a system of continuous long-term monitoring of the heart rate of a patient with atrial fibrillation (AF) outside the hospital and implementing an algorithm of smart monitoring to detect episodes of the disease.

Atrial fibrillation is a dangerous violation of the heart rhythm, manifested in the strengthening of irregular heartbeat and flickering of the atrial muscles. It can occur spontaneously, lasting from several seconds to

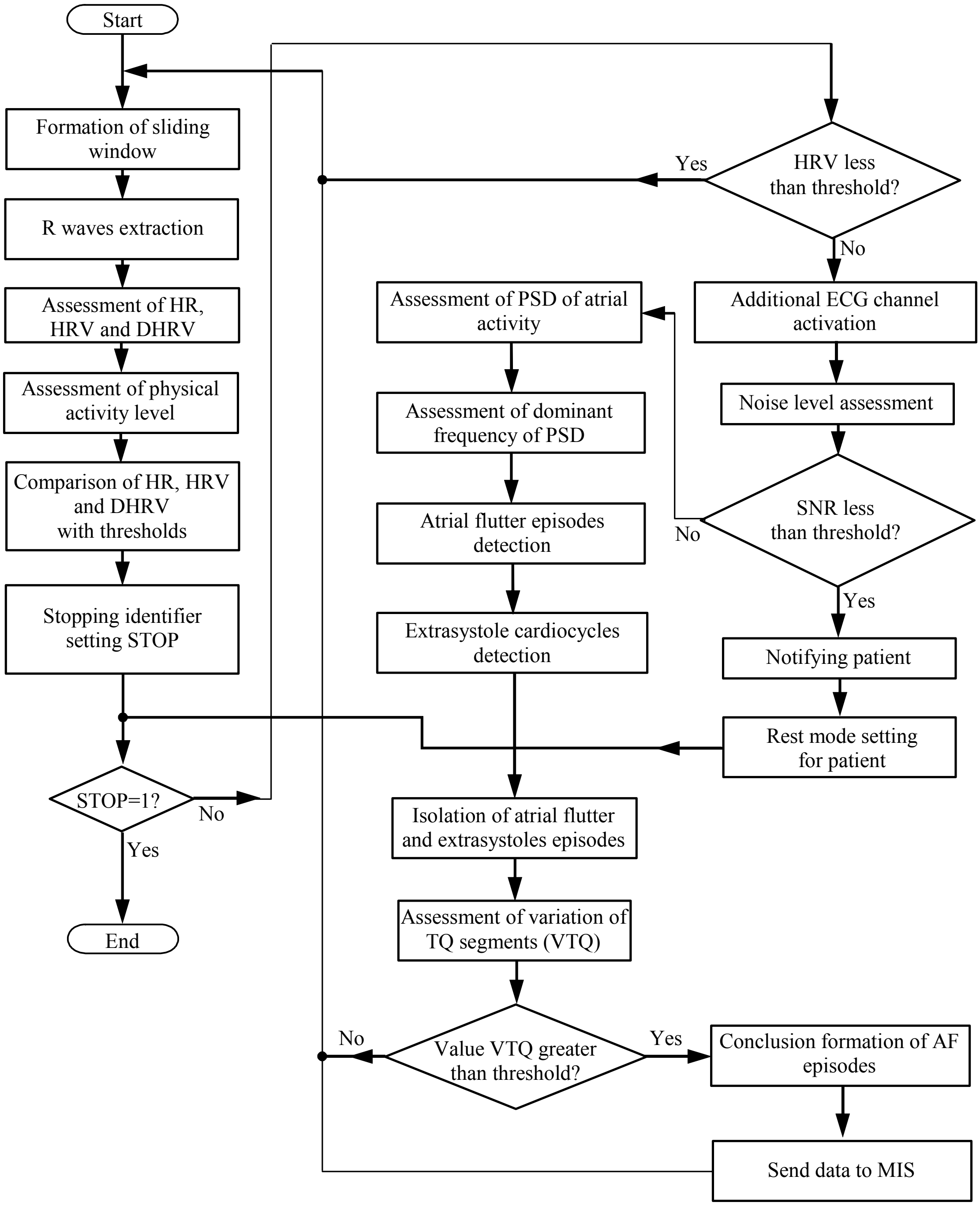

Fig. 2

several hours and cause irreversible disturbances in the structure of the atrial myocardium. Detection of AF in real time allows using medical treatments to restore the normal sinus rhythm of the heart, reduce the risk of death of the patient with the help of a defibrillator.

When the heart rate of the patient is being controlled outside the hospital to identify episodes of AF, it is necessary to carry out the receiving and recording of ECG signals of the chest wire, to assess a set of indicators of cardiac activity: heart rate (HR), heart rate variability (HRV), with TQ segment variability, the amplitude of the P-prong, F-wave strength and characteristics of the prevailing frequency, to identify episodes of AF and extrasystole.

The main sign of arrhythmia, including AF, is increased heart rate. However, it can be caused by increased physical body activity and correspond to the state of norm. Therefore, to detect episodes of increased HR caused by various arrhythmias, it is necessary to conduct continuous monitoring of physical activity using accelerometers. There should be at least four of them, fixed on the limbs, as the increasing physical activity can be directed to the feet or hands, while sitting (rowing, cycling etc.).

Another significant sign of AF, as well as other cardiac arrhythmias, is an increase in heart rate variability (HRV). With a normal sinus rhythm of the heart, the heart rate is relatively stable, while with arrhythmias, there is a violation of cyclicity.

Both HR and HRV are diagnostically significant indicators not only for AF, but also for various other ventricular fibrillations. To increase the accuracy of diagnosis of AF, as well as their distinction from atrial flutter (TP), it is necessary to evaluate with indices characteristic only of AF. A significant indicator of AF is the TQ segment increased variability. The weight of this indicator, depending on the stage of the disease, can reach 45 %. In order to assess this indicator with high accuracy it is necessary to activate additional channels for recording the ECG of the thoracic leads (as a rule, three channels of thoracic leads are used). When diagnosing other diseases, registration channels, such as breathing signals, plethysmograms, muscular activity, etc., can be connected and used to evaluate an additional complex of diagnostically significant indicators and their integration in classifying the state of human health. To activate additional channels for recording biomedical signals, the control signals from the patient's computer must go to the input of the control channels so the signals of the patient's wearable device can be recorded. This is the essence of the algorithm for intellectual monitoring of the patient's health. Therefore, when patient’s health condition conforms to physiological norm, a limited number of channels for recording biomedical signals as well as a limited number of diagnostically significant WPC indicators is used. At the first signs of functional disorders in the body, additional channels for recording signals are activated and an expanded complex of diagnostically significant indicators is evaluated.

To separate AF from other types of ventricular fibrillation, it is necessary to establish the absence of R-waves, to ensure the appearance of F-waves with a clearly defined dominant frequency, to exclude the episodes of atrial flutter and extrasystole from the analyzed signal.

To identify the disease exacerbation, it is necessary to assess the duration of AF episodes, as well as to consider the dynamics of the AF episode frequency during a certain period of time and their duration.

To identify short AF episodes, the ECG signal processing and analysis, evaluation of diagnostic indicators is to be carried out in a 'sliding' time window of 10 seconds long. The sliding window should be shifted discretely by the value of the cardiocycle. Increasing duration of the sliding window can improve the accuracy of the diagnosis of AF but lead to omissions of short AF episodes.

When analyzing the ECG for AF in a sliding time window, it is necessary to exclude episodes of atrial flutter and alternating extrasystoles. In case of significant myographic interference, the WPC should recommend the patient to reduce their physical body activity.

If the HR and HRV exceed the thresholds individually specified for the patient, the patient's wearable computer must provide additional ECG channels for chest leads. In this case, the channels of ECG registration, the WPD is activated, and the discrete signal samples will be transmitted to the CPU of the WPC.

In accordance with the above, the structure of the algorithm for continuous long-term monitoring of HR and detection of AF episodes is as follows (Fig. 2).

The system development and atrial fibrillation episode detection algorithm approbation. In accordance with the structure shown in Fig. 1, a system was developed for heart rate remote monitoring and signalizing when detecting atrial fibrillation episodes [16], [17].

Fig. 3

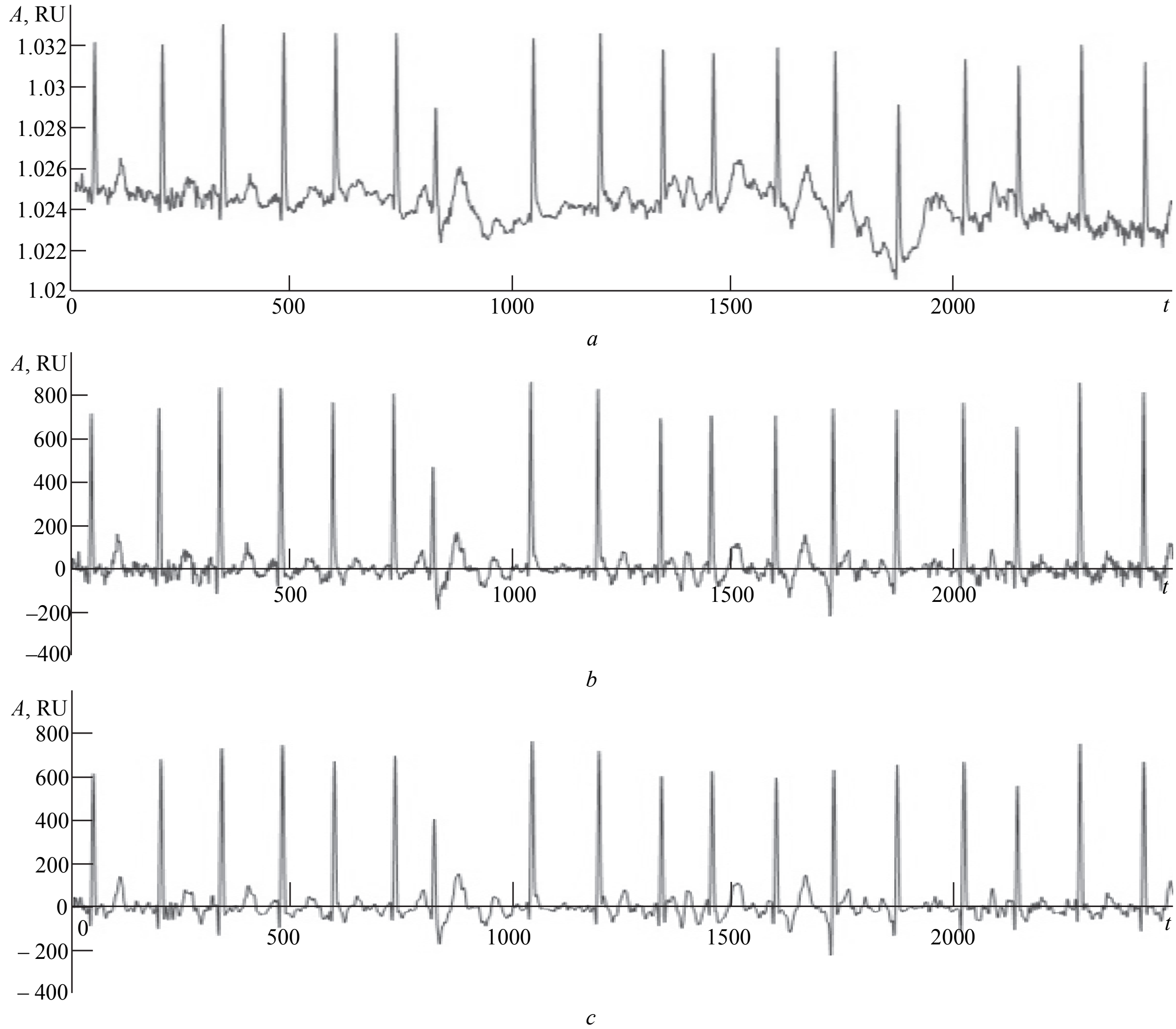

Fig. 4

The wearable patient's device was developed based on integrated circuit Analog Front End AD8232, amplifying and filtering the electrocardiographic signal, suppression of common-mode interference, a 32-bit microcontroller STM32F407VG6, Bluetooth controller of class 2 of Cambridge Silicon Radio BC417. The wearable patient's computer operated on the basis of Android 5.1 powered smartphone. To calculate diagnostically significant parameters, Android NDK was used for intensive calculation of data flows, modeling of physical processes, signal processing and analysis requiring a lot of memory. The user interface of the wearable patient's computer appears as below (Fig. 3).

To assess the effectiveness of the AF episode detection algorithm, an experimental study was con-

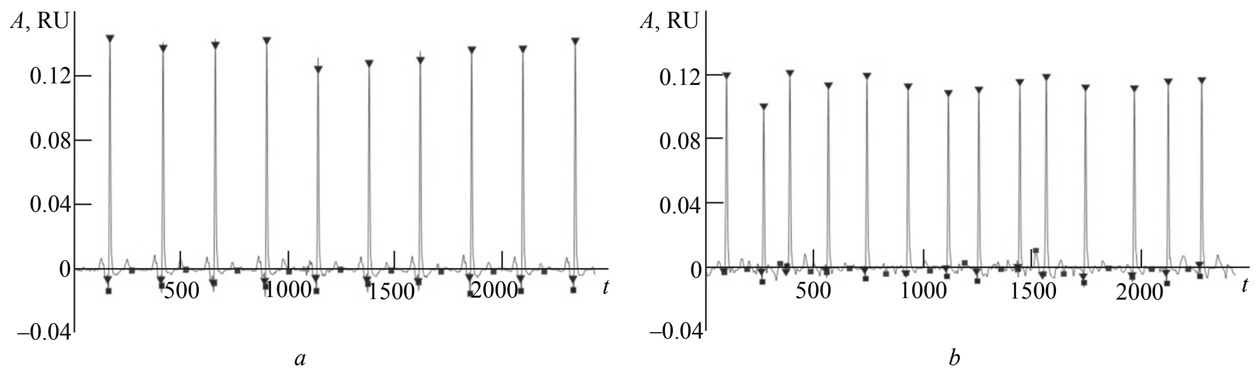

Fig. 5

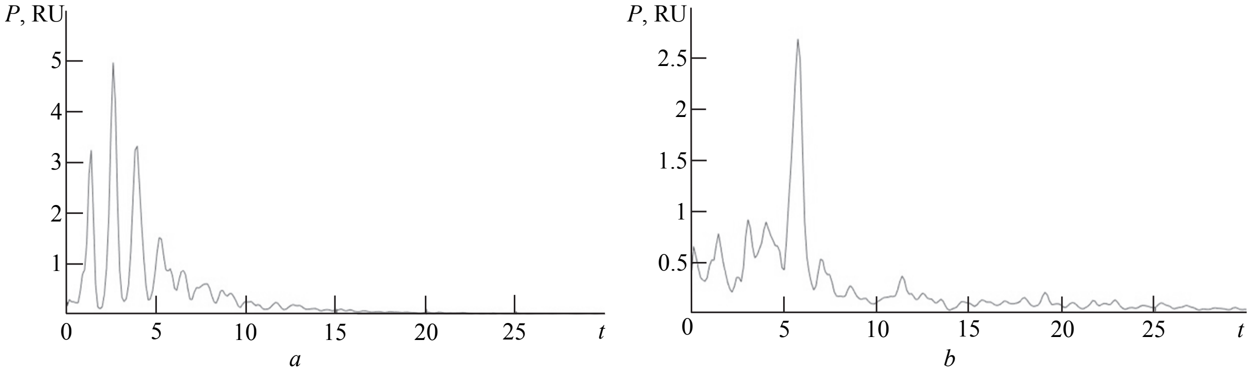

Fig. 6

Record	Indices of the efficiency detection of atrial fibrillation episodes									
	TP_S	FN	TP_P	FP	ES_E	E+P	ERef	ETst	DSe	D+P
30007502.dat	1	0	8	0	100	100	1	8	99.32	100
80003725.dat	4	8	4	59	33.33	6.35	12	63	37.33	0.82
FF5060526111605.dat	6	0	5	8	100	38.46	6	13	99.37	99.44
Kot21984512.dat	29	2	27	81	93.55	25	31	108	89.08	37.72
ME18120405155453.dat	13	7	12	25	65	32.43	20	37	98.78	96.55
Gross	53	17	56	173	75.71	24.45	70	229	99.11	95.43

ducted using verified MIT-BIH AF Database records and database of the Almazov National Medical Research Center.

Fig. 4 there are the signal diagrams demonstrating the processing steps of the original ECG-signal (Fig. 4, *a*), the isoline drift with the use of median filter (Fig. 4, *b*), the ECG-signal smoothing with the use of the Savitsky-Golay of 7-th order filter (Fig. 4, *c*). Fig. 5 shows extracting the fiducial points of ECG-signal in sinus rhythm (Fig. 5, *a*) and atrial fibrillation (Fig. 5, *b*). Fig. 6 shows evaluation of the spectral power density in sinus rhythm (Fig. 6, *a*) and atrial fibrillation (Fig. 6, *b*).

The table shows the results of the study based on the developed algorithm for each record and the total results for the AF episode detection in all these records, where Se = TP/(TP + FN), +P = TP / (TP + FP), DSe = ref_overlap / ref_duration, D + P = test_overlap / test_duration.

The table provides the results of the research based on the data of the Almazov National Medical Research Center.

To evaluate the efficiency of the algorithm, the following indices of the sensitivity of DSe and the specificity of D + P were calculated. At the same time, the sensitivity and specificity indices for all the records made 99.11 % and 95.43 % respectively. As a result, for both databases, the obtained sensitivity, specificity and accuracy indices were 95.00, 94.00 and 94.5 %. The use of the intelligent monitoring mode allows to increase the duration of heart rate continuous monitoring up to 16 hours with the possibility of recharging the power source of the wearable patient's device during the patient's sleep.

Conclusion.

1. To ensure long-term continuous monitoring of the human health, it is necessary to use the hierarchical structure of the system. In such system, the wearable device of the patient must have channels for recording biomedical signals, which are activated to evaluate the expanded complex of diagnostically significant parameters when revealing the first signs of functional disorders of the body.

2. To increase the duration of continuous work of the wearable device and the patient's computer, to effectively use their computing power and energy resources, it is necessary to use the human health status intelligent monitoring algorithm. This algorithm consists of the process of changing the number of actively operating channels for recording biomedical signals and the process of evaluating the diagnostic indicators of the disease, depending on dynamics of the patient's health status.

3. High accuracy of diagnostics of functional disorders of the body during long-term continuous monitoring of the health status outside the medical institution is

achieved by using a complex of diagnostically significant parameters of the disease and their integration in the classification of the state of the body.

4. The experimental development of the remote monitoring heart rate system for the patient with atrial fibrillation based on the complex of diagnostically significant parameters and their integration for classification of the condition and approbation of the developed system in clinical conditions confirmed the advisability of using the intelligent monitoring mode to ensure long-term continuous monitoring and high efficiency detection of atrial fibrillation episodes.

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