New application of blood pressure monitor with software environment Oranta-AO based on Arterial Oscillography methods

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Abstract

The authors for the first time offered new application of blood pressure monitor. For this the original methods of arterial oscillography are substantiated and developed. The methods were implemented in developed Oranta-AO information system. The methods application to the arterial oscillogram registered at measurement of arterial pressure gives the possibility to carry out the supplementary systematic assessment of health, functional state of cardiovascular system, its reserve possibilities; to study the condition of blood vessels; to identify the state of a pre-disease, the effectiveness of therapeutic, preventive and rehabilitative measures. The authors also developed an expert system (based on machine learning methods) for the differential diagnosis of risks of heart, lung, mental illnesses and prognosis of some blood parameters.

Based on the methods and algorithms developed as a result of research, Oranta-AO information system was developed allowing the user to take measurements with an electronic blood pressure monitor, load them into the system, get calculated indicators, view them in a convenient way and see analytical information on the basis of which one can assess the state of the cardiovascular system and decide on further action. Information system is deployed on AWS servers and is being tested now.

The software developed will significantly expand the scope of electronic pressure monitors. The developed environment aims to be integrated into new models of electronic meters. The next step will be to establish cooperation with manufacturers of electronic pressure monitors and certification in Europe, America and other countries. The activities of Oranta-AO information system provides the ability to integrate into patient monitoring systems and other information systems as well.

Keywords 1

Arterial oscillography methods, blood pressure monitor, ANS, heart rate, health level, vessels, pulsation, information system, machine learning

1. Introduction

The cardiovascular system is an indicator of the body’s adaptive capacity. Cardiovascular system (CVS) disease is one of the most common human diseases (by WHO). Their "rejuvenation" dictates the need to find new, improve existing methods of prevention, early diagnosis and treatment of these dangerous diseases [1-4].

Blood pressure (BP) measurement is a mandatory procedure in the work of a doctor at all stages of medical care [5, 6]. To evaluate the waveforms in arteries of the upper extremities, the authors first

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proposed a new method – Arterial Oscillography (AOG), which allows significantly expanding the informativeness for blood pressure measuring [4, 7].

The rapid development of digital technologies penetrates all spheres of life, it's time to apply them to the pulsations that occur when measuring BP. The oscilloscope was designed for the first time by L. I. Uskov (1934). The essence of this method is to register with an oscilloscope the magnitude of the pulse oscillations of the arterial wall at different pressures in the cuff, and the resulting curve reflects the amplitude of stretching of the artery wall [4]. Now the analysis of arterial oscillograms is performed in each electronic blood pressure monitor, but the whole analysis comes down to the determination of systolic and diastolic pressure and heart rate, sometimes there is a violation of pulsations rhythm [4, 8, 9, 10].

The authors developed Oranta-AO method (Arterial oscillography) to analyze pulsations occurring in the cuff in response to compression of the shoulder (other part of the body) under the influence of pulse vascular activity on compression or (and) decompression to assess the body's adaptive resources, the state of the autonomic nervous and cardiovascular systems, the state of blood vessels and the risks of various diseases [11 - 13].

For registration of arterial pulsations the electronic tonometer VAT41-(1,2) and meters of other manufacturers capable to register values of pressure in a cuff during the period of increase (and/or decrease) of compression (to carry out calculations by methods of arterial oscillography (AOG)) and to export the obtained values for further analysis in the user's personal account in the web environment.

The validity of studies is confirmed by registered and analyzed 4000 AOGs in people of different ages and sexes, almost healthy and with abnormalities in health (14 nosological conditions)), at rest and under the influence of various external factors. In addition, the correspondence of values of some studied indicators of AOG to the indicators of heart rate variability (HRV) of the electrocardiographic signal obtained from the literature was confirmed. Also the coincidence of some studied parameters values obtained from simultaneously made by the authors electrocardiograms (ECG) and AOG (correlation 0.75–0.98) in 354 almost healthy people and people with abnormalities in health was registered. The same direction of dynamics of the studied parameters obtained by the authors before and after the procedure of segmental reflex massage in patients with dorsopathy of the cervical spine, registered by AOG (VAT41-1,2) and HRV (Omega-M) was observed, which was confirmed by the dynamics of biochemical parameters (adrenaline, noradrenaline in the urine, acetylcholinesterase in the blood) [14 -18].

In addition, in spring 2020, a comprehensive clinical study was conducted, where 172 people were examined: 112 without health complaints, 60 with diseases of CVS (aged 18–65). The general, biochemical analysis of blood, coagulogram, ELISA G, M (COVID-19), Endothelin were studied in each patient. Spirogram, ECG (12 leads) was recorded. In addition, a rheogram (8-channel rheo-complex REOCOM) was recorded in the following leads: central hemodynamics (by Kubicek), on both forearms, on the shoulder, cuff pressure channel and ECG channel. And also – a test with a 5-minute contraction of the shoulder with a cuff (to assess the endothelium condition). Vascular stiffness (VAT-41-2) was determined. Some results were published.

Regarding the contingent of respondents the method is new. The examination of healthy people made it possible to develop standards of AOG indicators, which highlight the participation of cardiovascular and hemodynamic factors and levels of regulation of their activity in the compression of the shoulder at rest and under the influence of various factors. The calculated indicators from the registered measurement make it possible to use them for comparison with different groups of indicators obtained earlier, which are characteristic for different diseases. Currently, the most studied are AOG and ECG. Among them there are diseases of various stages and clinical manifestations: coronary heart disease (303 people), hypertension (160), psychoneurological diseases (294), patients diagnosed with tuberculosis (204), COVID-19 (74 people, 287 measurements) and others [19 -21].

The analysis of the results obtained gave the authors an opportunity to develop and substantiate the new methods of arterial oscillography. The obtained results are presented in the thesis work of the doctor of biological sciences, monograph, methodical recommendations (approved by the Ministry of Health), 5 patents for utility model; in 6 articles indexed in Scopus, 35 articles in professional journals [11 - 13, 19, 20, 24, 25, 26, 27].

The use of morphological, temporal, spectral analysis of the arterial oscillogram registered at measurement of arterial pressure gives the possibility to carry out in addition a complex assessment of health, a functional condition of cardiovascular system, its reserve possibilities; get information from 4 levels of regulation of CVS activity; to study the condition of blood vessels; identify the state of the disease, the effectiveness of therapeutic, preventive and rehabilitative measures. The authors also developed an expert system (based on machine learning methods) for the differential diagnosis of risks of heart, lung, mental diseases and prognosis of some blood parameters [11 -14].

Based on the methods and algorithms developed as a result of research, Oranta-AO information system was designed and developed, which allows the user to take measurements with an electronic blood pressure monitor, load them into the system, get calculated indicators, view them in a convenient way and see analytical information on the basis of which one can assess the state of the cardiovascular system and decide on further action [11-15, 21 - 24].

Application of AO (arterial oscillography) methods (D. Vakulenko, L. Vakulenko) is possible in the electronic blood pressure monitors supporting work with Oranta-AO information system. The scope of the AO method is possible in all accepted areas of application of blood pressure monitors. The AO innovation provides extended and additional diagnostics, especially relevant for sports, space and military medicine, daily monitoring, fitness, preventive and functional examinations, as well as for household use. A patient, nurse, family doctor, cardiologist and others can be a user of the AO [25- 27].

No approaches similar to the arterial oscillography was found. This conclusion is based on the analysis of publications in the world, visits to medical exhibitions in Ukraine, Austria and Germany (Dusseldorf, Medica 2016, 2018, 2020). Oranta-AO software is designed to supplement the informativeness of the dynamic adaptive properties of blood vessels in Doppler, rheographic, pulse examination and heart electrocardiographic examination.

2. Goal and tasks

The goal of the work is to develop concepts, substantiation, methods, and algorithms of the new application of blood pressure monitor. For this task information technology for assessment and prediction of human health based on arterial oscillography data obtained from a blood pressure monitor is developed. To achieve this goal, two tasks were set:

1. Development of methods for the analysis of pulsations that occur in a pressure monitor cuff in response to shoulder (or other part of the body) compression under the influence of pulse activity of blood vessels on compression or (and) decompression. Selection and justification of the use of mathematical apparatus to solve problems for the methods implementation. These methods should provide the analysis of:
   - morphological component of the arterial oscillogram, individual pulsations and their components in different phases of compression;
   - intervalogram at positive and negative intervals – for the use of methods of heart rate variability;
   - the spectral component of the signal itself, both total and instantaneous power;
   - similarity of AOG components (fractal analysis);
   - additional evaluation of adaptive components involved in the reaction to cuff compression (correlation analysis);
   - probabilities of similarity of the calculated AOG indicators to the studied diseases conditions (machine learning methods – classification problem);
   - forecasting the values of blood parameters, the activity of central hemodynamics, blood vessels, nervous system and other indicators (by regression analysis).
2. Development of software allowing the user to go through all the stages from direct measurement to full analysis of the results. In more details, to receive data from the pressure monitor, transfer data for calculations, make calculations on the basis of the developed methods, save the results and present them to the user in the form convenient for the analysis.

3. Arterial oscillogram analysis methods

3.1. Arterial oscillogram analysis methods types

Significant advances in the analysis of electrocardiograms, rheograms and encephalograms and the scientific substantiation of the results made it possible to adapt this knowledge to the analysis of arterial oscillograms. Since the necessary terminology that would characterize the calculations characteristics and results to describe the pressure oscillogram was not found, the terms and methods used in related areas of cardiovascular research (rheography, electrocardiography) and nervous (encephalography) systems were used. In Electrocardiography, methods of temporal and spectral analysis (Fourier Transform), in Rheography - methods of morphological analysis, and in Encephalography - methods of spectral analysis of the signal (Fourier Transform) are used. Since during the pressure measurement the body builds an adaptive response to shoulder compression and there are different types of reactions, the Hilbert-Huang transformation was additionally introduced to assess the body instantaneous adaptive reactions [1 - 4, 11-14, 24-28].

In world practice, there are 3 types of pulsations that can be analyzed: compression, decompression and both. More than 500 sequentially recorded oscillograms of each type were analyzed to understand better the characteristics of each type of pulsations.

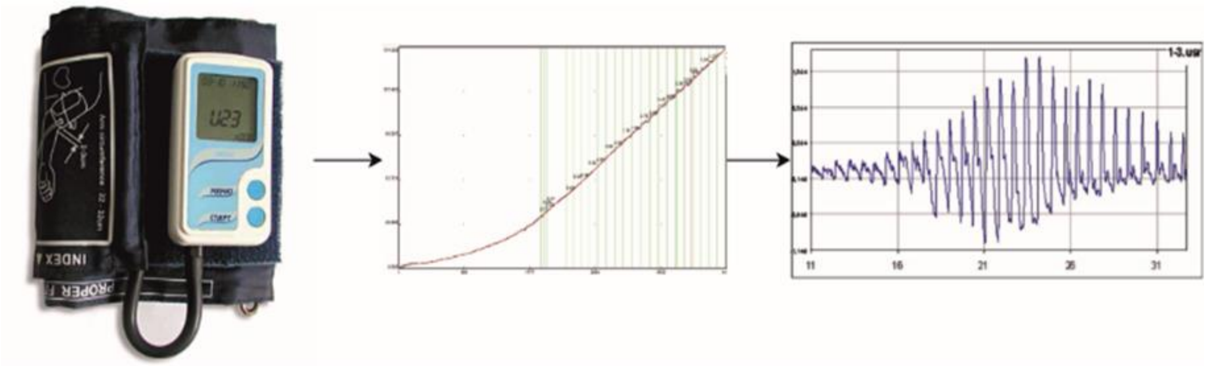

Figure 1: Registered pressure changes in the cuff under the impact of compressor and pulse activity of the vessels with subsequent separation of the vessels' pulse activity

Morphological analysis provides the following information: vascular tone and patency, functional capacity, cause of abnormalities (functional or organic), cardiac activity, blood pressure and neuro-reflex effects on their condition.

The objects of research in morphological analysis are the general shape of the oscillogram and the nature of individual pulsations in different phases of compression. In the general analysis of the oscillogram the following features are used: rhythmicity of oscillations, nature of amplitude growth, achievement of maximum and their decrease in the process of shoulder compression, number of maximum amplitude oscillations, shape and symmetry of envelope placement created at maximum and minimum extremes [4, 11-13].

The nature of individual oscillations in different phases of compression is evaluated by: duration of ascending and descending part in one pulsation, forms of peaks of maximum and minimum extremes, dynamics of change of ascending and descending oscillations areas, presence, localization, magnitude of dichroic and additional waves on separate oscillations. In AO, depending on the degree of compression, there are three (from the registered oscillations at the minimum pressure in the cuff to reaching diastolic pressure (APd), between APd and systolic pressure (APs), from APs to maximum compression) and five parts (from registered oscillations at the minimum pressure in the cuff to achieving APd, from the appearance of APd to 70% of the pulsation amplitude, from 70% to 100% of the amplitudes, from 100% to the appearance of APs, from the appearance of APs to maximum compression).

Variability of the oscillations duration (using methods and indicators of temporal analysis and variation pulsometry, adopted to assess electrocardiographic signals), correlation rhythm or scatterogram, chaosgram are analyzed and evaluated.

To obtain additional information about the nature and the mechanisms involved in the adaptation to various influences in the studies, the indicators are further subjected to correlation analysis for further inclusion in the Expert System. The block diagram of the applied methods in Oranta-AO software is given in Figure 2.

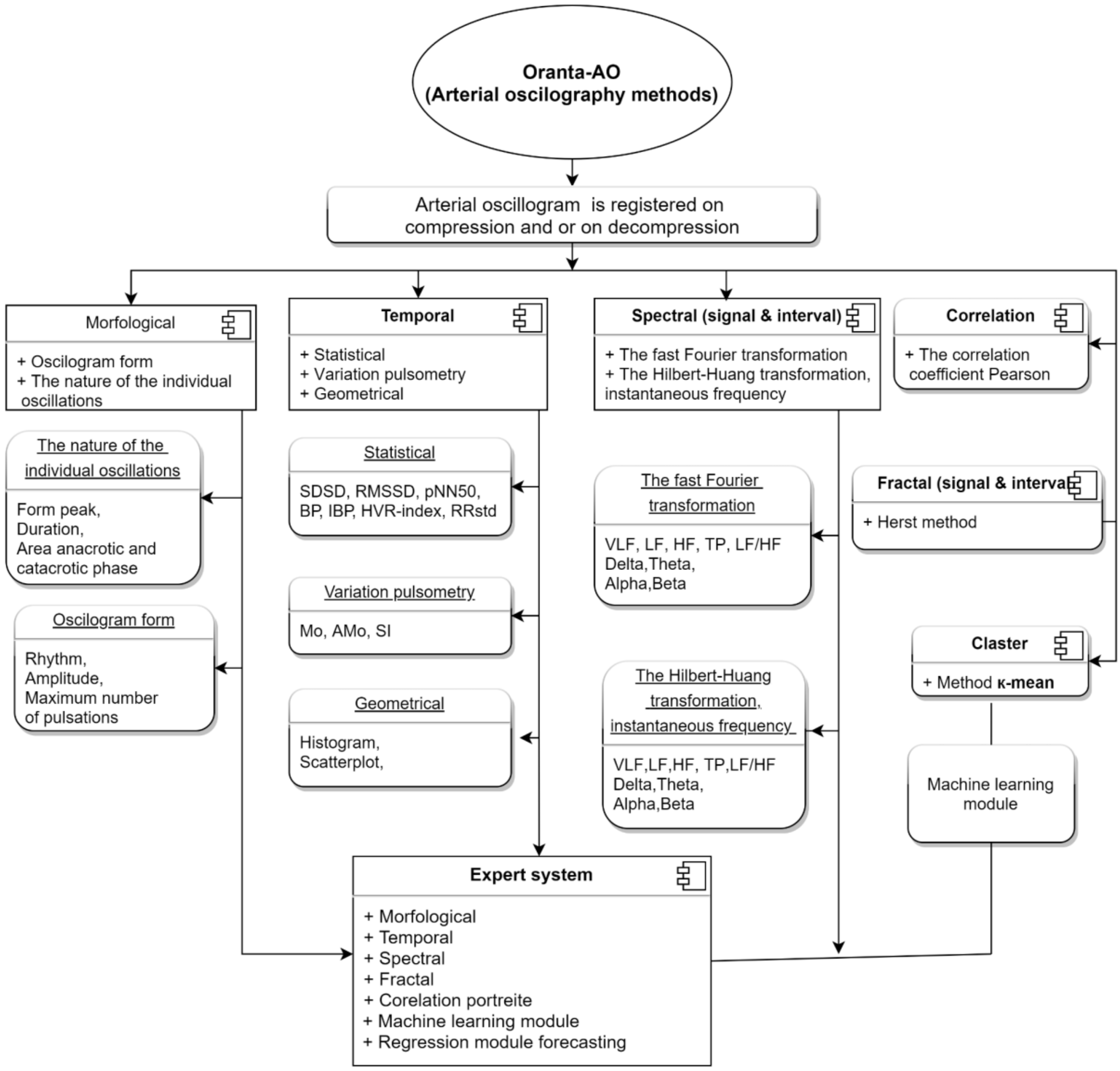

Figure 2: Block diagram of the methods used for the arterial oscillogram analysis

To solve the problems shown in Figure 2, the following tasks were solved: separation of the compressor pulsations component from vessels pulsations; identification of positive and negative extremes, artifacts, morphological features of each pulsation (amplitude, vertex radius, dichroic tooth, phase of slow and rapid expulsion); Fourier and Hilbert-Huang transformation algorithms selection.

Morphological analysis (10 indicators), temporal (37 indicators) and spectral analysis (485 indicators) of oscillograms are used for the analysis of arterial oscillograms. The spectral analysis calculates the spectral power of the intervalogram (45 indicators), the arterial oscillogram according to the Fourier transform (340 indicators) and the instantaneous frequency and phase according to the Hilbert-Huang transformation (90 indicators). The arterial oscillogram is divided into 5 parts: until diastolic pressure is reached, from diastolic pressure to 70% of the amplitude of the oscillogram, from 70% to 100% of the amplitude of the oscillogram, from 100% to 70% of the amplitude and from 70% to the end of the measurement. For each of these AO intervals, Fourier transform (68 indicators) and the instantaneous frequency and phase of the Hilbert-Huang transformation (18 indicators) was used [29 - 39].

3.2. Solving classification problem with decision tree induction method as part of expert system

The goal is to apply the decision tree induction method for software implementation in the decision-making system regarding classification and forecasting risks of diseases appearance based on arterial oscillogram analysis.

A study of almost healthy patients and patients with abnormalities in health (14 nosological conditions), at rest and under the influence of various external factors was conducted. Among them are diseases of various stages and clinical manifestations: coronary heart disease (303 patients), hypertension (160), psychoneurological diseases (294), patients diagnosed with tuberculosis (204), COVID-19 (74 patients, 287 measurements) and others.

Let D is the set of N learning data tuples. Here any with value $(A^i_{1,} A^i_2,...,A^i_{p,}, C^i)$ includes attributes $A_1,\ldots,A_p$. Can be accept both numerical and categorized values for attributes $A_1,\ldots,A_p$.. The attribute class's C receives one of the K discrete values: $C \in \{1,\ldots,K\}$. The goal is to predict the value of class attribute C using decision tree on the basis of the values of the attributes $A_1,\ldots,A_p$. .

Decision tree generation. The Attribute Selection Algorithm at the recursion step j is based on the following information indicator:

$$\mathrm{Gain}(A_i) = \mathrm{Info}(D_j) - \mathrm{Info}_{A_i}(D_j) \qquad (1)$$

$$\mathrm{Info}(D_j) = \sum_{k=1}^{K} p^l_j \log_2 (p^l_j) \qquad (2)$$

Information needed to classify a tuple ($A_1, A_2,\ldots,A_p$.) in D_j

$$\mathrm{Info}_{A_i}(D_j) = \sum_{k=1}^{K} \frac{\#(D^l_j)}{\#(D_j)} \mathrm{Info}(D_i) \qquad (3)$$

Information needed to classify ($A_1, A_2,\ldots,A_p$.) in D_j after splitting D_j into subsets D^l_j with respect to the values of attribute A_i.

In (2) the probability that any tuple from D_j is from set C_{k,D_j} is estimated as $p^j_k = \frac{\#(C_k D_j)}{\#(D_j)}$ where $C_k D_j$ is the set of tuples from D_j for which class attribute C = k. Here #(•) is the number of elements in the set.

From (3) $\frac{\#(D^l_j)}{\#(D_j)}$ is the estimate of probability that any tuple from D_j belong to the set D^l_j , where D^l_j is the set of tuples from D_j for which the attribute $A_i = a^l_i$. Attribute is $A_i \in \{a^i_{1,} a^i_2,...,a^{K_i}_{i,}\}$.

$\mathrm{Gain}(A_i)$ estimates decrease of information which is needed to classify any set of tuples in D_j when taking into account the known value of the attribute A_i. Therefore, from available attributes for each node of the decision tree for splitting condition it is necessary to select the attribute $A_i \bullet$ with the greatest value $\mathrm{Gain}(A_i \bullet)$. As a result of such selection for completing classification process in D_j we need the least amount of information [14].

Using machine learning methods (problems classification and regression analysis methods), training and analysis of the results is made. The results are integrated into the calculation kernel of Oranta-AO information system to calculate the probabilistic risk assessment of diseases (Cardiovascular (±4,165%), Pulmonary (±6,35%), Mental Illness (±3,67%), Covid-19 (±12,32%) and others).

4. Oranta-AO information system

Oranta-AO information system performs the following tasks:

- obtaining measurements from a pressure gauge;
- transmission of measurement data to compute indicators that characterize the level of health, risks for heart and vessel, lung and mental diseases and predicted some indicators of blood, central hemodynamics and mental states;
- saving measurement data and computed indicators;
- displaying the measurement data and computed indicators in a user-friendly form, which allows to qualitatively analyze the patient's state and make recommendations for further action to maintain/improve the patient's health.

Oranta-AO information system consists of the following parts: mobile application, calculation kernel and web system (Figure 3).

To obtain arterial oscillograms on compression, a blood pressure monitor VAT 41-2, Iks-Techno, Ukraine was used. Pressure monitors Omron, Japan and Dr. Frei, Switzerland were selected to obtain arterial oscillograms on compression and decompression. Since the pressure monitors of these manufacturers do not provide the ability to obtain arterial oscillograms, the authors developed a module for obtaining pulsations from the pressure sensor, storing them and sending them to the Python core on a server via PC or mobile application with subsequent display in the web application.

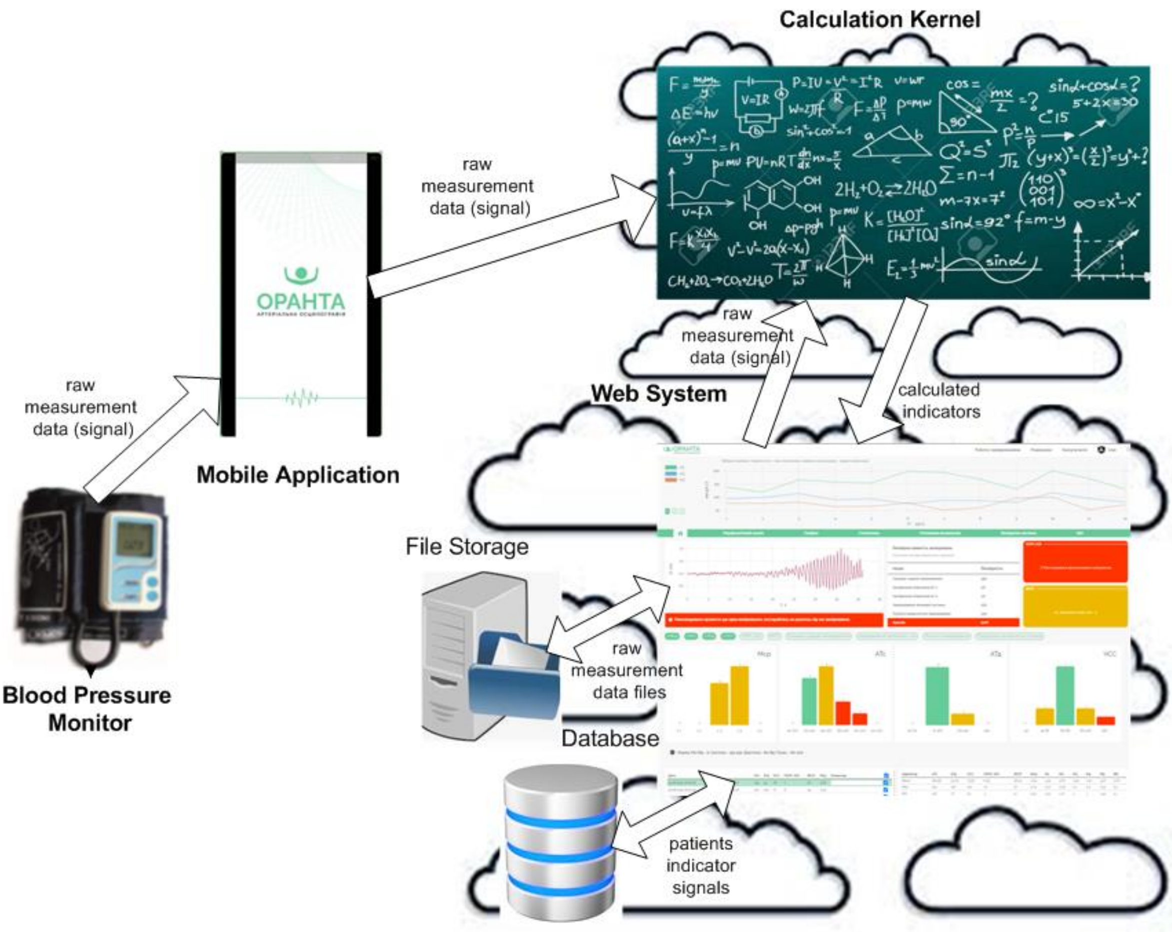

Figure 3: Oranta-AO information system structure

The mobile application is designed to transfer measurement information from the blood pressure gauge to the computational kernel. A program with this functionality is necessary because the blood pressure gauge itself cannot do this. Before using the application, the user must log in with the name and password that he receives when registering on the web system. The measurement data transmitted from the mobile application to the calculation core is in a file with the txt extension, which records a sequence of numbers that represent the oscillogram values.

The mobile application was developed on Flutter 2.2.3 [37], so it is multiplatform. Its testing was performed on Android and iOS devices.

Computational kernel is the central part of the information system, based on the methods developed in this research. It calculates indicators that can be used to analyze and predict the activity of the cardiovascular system and other systems of the human body. It is developed in Python 3.7 [38]. A set of libraries Numpy 1.19.5, Pandas 1.2.4, Scipy 1.6.3, Hurst 0.0.5, Emd 0.3.2 was used to implement algorithms for temporal, fractal, spectral, morphological and other types of signal analysis, as well as a set of libraries Scikit-learn 0.24.2, Lightgbm 3.1.1 for the implementation of algorithms for predicting the indicators of the human body cardiovascular system and the classification of human health states.

Computational kernel can work in two directions of data transmission:

1. Receive measurements from the mobile application, perform computations and send a request with the result to the web system for storing and displaying;
2. Receive measurements from the web system, perform calculations and transfer the result back to the web system for storing and displaying.

The computational core is able to receive input data in four formats:

- raw measurements data (txt);
- previously calculated data with specification (json);
- multiple measurements with some additional data specified (ini);
- MATLAB files (mat).

The results are returned in json format, which can contain results for one or more measurements.

The web system is designed to store the results of calculations performed by the computational kernel, and display these results in a form convenient for analysis by the patient or doctor. The web system consists of backend and frontend parts.

The backend part provides the REST API for the frontend part. It is developed using nodejs 12.16 [39] and express framework 4.16 [40]. Also mongodb 4.2 [41] database server was used. The frontend part is developed on the basis of TypeScript language and Angular 11 [42] framework. The structure of the web system functions is shown in Figure 4.

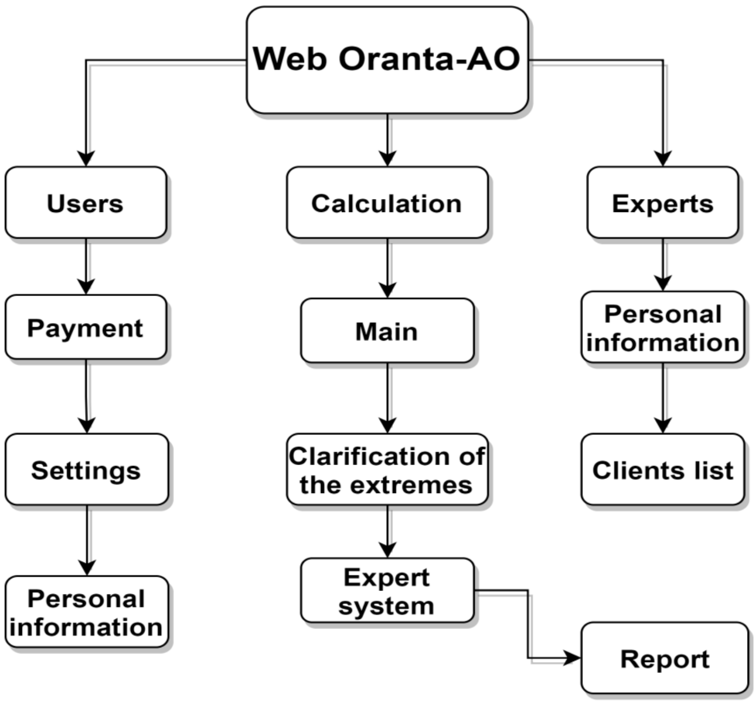

Figure 4: Oranta-AO web system structure

Web system can be used with patients and experts or consultants (doctors). A patient can upload his or her personal measurements data and view the calculated indicators. They also can select consultants to help at interpreting the data. A consultant can upload the measurements data of his patients and view the calculated indicators for them.

Both computational kernel and web system are deployed on AWS servers and are available in test mode now.

5. Conclusion

The authors for the first time offered new application of blood pressure monitor. For this original concepts, substantiation, methods, and algorithms of the new application of blood pressure monitor were substantiated and developed. The methods were implemented in developed Oranta-AO information system.

The application of the methods to the arterial oscillogram registered at arterial pressure measurement gives the possibility to make the supplementary systematic assessment of human health in general, the functional state of cardiovascular system, its reserve possibilities; get information from 4 levels of regulation of CVS activity (peripheral-autonomous, autonomic, hypothalamic-pituitary, central nervous system); to study the condition of blood vessels: their tone, elasticity, quality of adaptation to different levels of compression when measuring blood pressure; identify the state of a disease, the effectiveness of therapeutic, preventive and rehabilitative measures. The authors also developed an Expert System (based on machine learning methods) for the differential diagnosis of risks of heart (±4,165%), lung (±6,35%), mental illness (±3,67%) and prognosis of some blood parameters.

Based on the methods and algorithms developed as a result of research, Oranta-AO information system was designed and developed allowing the user to take measurements with an electronic blood pressure monitor, load them into the system, get calculated indicators, view them in a convenient way and see analytical information which is the basis for one to assess the state of the cardiovascular system and decide on further action.

Oranta-AO information system consists of three interrelated parts: mobile application, computational kernel and web system. Computational kernel and web system are deployed on AWS servers and are being tested now. Version in Ukrainian is available; English version is being developed.

The software developed will significantly expand the scope of electronic pressure monitors. The developed environment aims to be integrated into every new model of electronic meters in the world. Certification (ISO 14155: 2015) in Ukraine is currently being completed, PCT priority has been obtained. The next step will be to establish cooperation with manufacturers of electronic pressure monitors and certification in Europe, America and other countries. The activities of Oranta-AO information system provides the ability to integrate into patient monitoring systems and other information systems as well.

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