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Cardiovascular system adaptability to exercise according to morphological, temporal, spectral and correlation analysis of oscillograms

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Summary **Background.** Diseases of the cardiovascular system (CVS) are among the most common diseases of humankind (WHO). Monitoring of blood pressure (BP) is an accessible method for evaluating global hemodynamic processes. The functional reserves of the circulatory system are traditionally determined by the use of functional loading trials and tests.
Objectives. The aim of the study is to enhance the information collected during the blood pressure measurement process by studying the levels of adaptation of the CVS to physical activity with morphological, temporal, spectral and correlation analyses of arterial oscillography (AO).
Material and methods. In 178 healthy individuals aged 18–20 years, arterial oscillograms were recorded during blood pressure measurement and correlations of the functional reserve of the cardiovascular system at various stages of adaptation to a Ruffier test were investigated.
Results. The proposed methods of AO analysis significantly increase the informativeness of the procedure for blood pressure measurement, provide an opportunity to conduct a visual analysis of AOs and to assess the state of the cardiovascular system, its reserve capabilities and its ways of adapting to shoulder compression at rest, after physical load and in the process of recovery.
Conclusions. Using the information technologies proposed by the authors of the morphological, temporal, spectral and correlation analysis of arterial oscillograms, their evaluation and clinical interpretation significantly increase the informativeness of the blood pressure measuring process. They can be used for early detection of pre-morbid conditions and functional blood circulation reserves, which will help the physician to more effectively plan a preventative, diagnostic and therapeutic process.
Key words: cardiovascular system, exercise, regeneration.

Background

Diseases of the cardiovascular system are among the most common diseases of humankind (WHO). The "rejuvenescence" of vascular catastrophes leading to severe disability shows that the current priority is to search for modern information technologies to aid in the early detection of pre-morbid conditions and reserve capacities of the body. They will help physicians to more effectively plan a preventative, diagnostic and therapeutic process [1–5].

Traditional risk factors for cardiovascular and other diseases are only indicators of risk [5]. The basis of the paradigm of medical prophylaxis and the reduction of mortality from cardiovascular and other diseases should be the strategy of individual mass prophylaxis, based on the principles of measuring human health reserves [3–6]. The stock of functional reserves is information,

energy and metabolic resources, the costs of which are accompanied by constant recovery [4–7]. When they are depleted, there is a functional deficiency of the body, which is manifested by pathological syndromes or diseases.

Functional reserves of the circulatory system are traditionally determined by the use of functional loading trials and tests [2–4, 6–8]. Reserves of homeostasis are also evaluated by the amount of time the internal environment indices can be maintained within the limits of physiological norms, the ability to respond to the load without pathological manifestations and the rate of return to the original level of regulation [2–4, 8].

An accessible method for evaluating global hemodynamic processes is blood pressure (BP) monitoring [9–11]. The response of the blood vessels to compression at the same time indicates the state of coordination between local self-regulatory mechanisms and central neurohumoral regulation of the CVS [7, 9, 11], the level of functioning of the ANS (autonomic nervous system), the functional capacity of the heart, the reflex reaction of CVS [11, 12], the status of the peripheral blood vessels (tone, elasticity, flexibility and patency) [10, 11], the activity of mechanisms of urgent reaction to compression (baroreceptor, chemoreceptor or reflex to ischemia) and others [4, 5, 7, 9–11]. The methods for studying and evaluating the state of peripheral vessels, as an active hemodynamic factor contributing to peripheral hemocycling, require improvement [5, 9]. Arterial forms of the signal (besides the values of systolic, diastolic and mean blood pressure) contain information that can provide deeper insight into the general state of hemodynamics [9–12]. The waveform of the arterial signal can show the characteristic morphological features and recognizing those will help in the early detection of diseases, in the diagnosis of complicated hemodynamic situations and in the study of the results of treatment [9–15]. Various invasive and non-invasive devices are used to determine the arterial signal [1, 16–20]. They differ in the method of removing biosignals, their primary reproduction, the algorithm of information processing and the level of automation of research. The use of simple, accessible, non-invasive devices for registering arterial signals and the introduction of information technology for their analysis will facilitate the work of family doctors and will enable the diagnosis and treatment of CVS diseases in a timely manner [1, 5, 19–23].

Objectives

The purpose of this research is to improve the capabilities of blood pressure measurement. To this end, morphological, temporal, spectral and correlation analyses of arterial oscillograms (AO) recorded during measurement of blood pressure (BP) was performed in order to examine and evaluate the state and functional reserves of the cardiovascular system (CVS) and its mechanisms for adapting to physical activity (PA) in individuals aged 18–20 years [3, 10].

Material and methods

Study design

In order to improve the informative capabilities of the process and results of blood pressure measuring, the AOs recorded during the measurement of blood pressure were subjected to morphological, temporal, spectral and correlation analyses. The state and functional reserves of the CVS were studied and evaluated in this way in order to determine the mechanisms for its adaptation to shoulder compression at rest and after physical activity in persons aged 18–20 years.

Setting

The data used for the analysis are based on the results of functional tests (Ruffier test) performed and a control group of students who were patients of I. Horbachevsky Ternopil State Medical University, V. Hnatiuk Ternopil National Pedagogical University and their therapeutic prophylactic bases (2013–2017).

Participants

178 generally healthy people (68 in the experimental group and 110 in the control group), males and females aged 18–20 years with no complaints about their health, were examined. Arterial oscillograms were recorded during the measurement of blood pressure, during the period of compression growth, with the help of a VAT 41-2electronic tonometer (the cuff was placed on the shoulder) and an electrocardiograph. In 68 representatives of the experimental group (45 males and 23 females), the AOs were recorded at a state of rest (before physical activity) and immediately after the Ruffier test (30 squats in 45 seconds) and after 2 or 5 minutes of rest. In 54 subjects from the main group, an electrocardiogram (ECG), which was subjected to temporal and spectral analysis (Europe), was also recorded before the load simultaneously with the oscillogram. In 110 individuals from the control group, the AOs were recorded at rest; the resulting data was used for comparison with the initial status of AOs of the representatives of the experimental group.

Due to the absence of such studies, information on circulatory mechanics [11], plethysmography, reorientation [23–26], arterial oscillography [9, 10, 26, 27] and magnetic resonance angiography [10] was used for morphological analysis of the oscillograms, analysis of the waveforms of the arterial signal, recorded by invasive and non-invasive methods [9–11, 17, 26–29]. The information gathered is subject to logical–visual, scientific, theoretical conclusions, tested with an analysis of 1200 oscillograms of 380 healthy people [1] and used to study the effect of metered physical activity on the state of hemodynamic processes in people of the main group.

The temporal and spectral analysis of the oscillograms were conducted on the basis of the study, statistical analysis and evaluation of the variability of the duration of pulsations. For this purpose, the methods, indicators and terminology used in the study and the evaluation of heart rate variability (HRV) [6, 7, 13, 30–36] were chosen. HRV provides the opportunity to acquire information from the four levels of regulation of CVS activity: peripheral (autonomous), vegetative, hypothalamic–pituitary and the central nervous system (CNS). An indicator of autonomous circuit activity is respiratory (sinus) arrhythmia. The inclusion of higher levels of regulation (estimated by the degree of stabilization of the heart rate) is due to the inability of the last one to cope with their functions. At the same time, higher levels inhibit the activity of lower ones [6, 7, 30, 33]. Studying their activity provides an opportunity to assess the level of the body's adaptive ability. This information is used in the analysis of the variability of the duration of AO oscillations [1]. The obtained results are subject to statistical analysis.

The relevance of this work is related to the expediency of implementation of the proposed methods of accounting and analysis of AOs in practical medicine. A general practice doctor can use it for the early detection of pre-morbid conditions and functional blood circulation reserves, which will help to more effectively plan a preventive, diagnostic and therapeutic process.

Variables

All patients from the experimental and control groups were included in the analysis. Comparison of the like indicators of ECGs and arterial oscillograms was carried out. We studied the dynamics of the indicators obtained from the arterial oscillograms at a state of rest, immediately after exercise, after 2 minutes or rest and after 5 minutes of rest following a Ruffier test.

Basis

The patients were included in the general study group by random sampling. Random sampling was also conducted in the control group of individuals who were volunteers in the experiment and did not have any pathology. The measurements were carried out using the adopted methods for measuring blood pressure and recording ECGs.

Data sources

In this study, we used the results of measurements of volunteers in the experimental group from a blood pressure device (VAT – 41-2) during the Ruffier test (before, after, after 2 and 5 minutes of rest); in the control group, measurements from a blood pressure device (VAT – 41-2) and electrocardiographs were used. The data were subsequently uploaded to a personal computer and subjected to an analysis developed by the authors of the study: the OscEcgReoPuls software program.

Study size

The study size was calculated by a representative sampling of the general group. From this group, the study groups were formed. Each subsequent stage of the study was carried out, taking into account the results of the previous one. By generalizing the results of the statistical methods and correlation analysis used, clustering k-means are developed for a picture of the correlations in each state.

Quantitative variables

The following quantitative variables were considered in the analysis: the data were recorded by a VAT – 41-2 blood pressure device (with methods of arterial oscillography) and a Cardio electrocardiograph, then uploaded to a personal computer and analyzed with the program OscEcgReoPuls, developed by the authors of the study. For the analysis of the obtained data, the methods of morphological, temporal, spectral and cluster analysis of arterial oscillograms, 459 indicators were used; 129 indicators – temporal, spectral and cluster analysis – were used for the electrocardiographs. Correlational portraits of each stage of the study with the subsequent formation of the markers of each state were built.

Statistical methods

Statistical analysis of the data was conducted using the software package "OscEcgReoPuls", which was developed in "Matlab". The statistical significance of differences between the arithmetic average and relative values was estimated by Student's *t*-test (*t*) for the normally distributed data set. For samples that differed from the normal distribution, the Wilcoxon method was used. During the comparison of all variants of indicators within the limits of one experiment, we conducted a liaison analysis of the correlation coefficient (*r*) by the Pearson method [37,38]. Statistical calculation was additionally processed in Statistica 10 software.

For a deeper analysis and clustering of indicators within every experiment in a group in order to better predict the quality of adaptive mechanisms at the primary level, we construct correlation portraits of each stage of the study with the subsequent formation of markers of each state by means of k-mean clustering [39] and sorting according to the following criteria:

1. The analysis was subjected to correlates that were in intervals [0.9; 1] and [-0.9; -1] (significant) sorted by the following criteria – the components of the correlation portrait were analyzed.
2. In the experiment, the value of the cluster was unique (specific) to a particular factor from the entire list of the experiments conducted.
3. When studying certain types of influence, we investigated common and unique correlates at different stages of the experiment.
4. The amount of significant correlates before and after the experiment
5. The amount of correlates with direct and inverse relationships.
6. In the conducted experiments, the values of correlates in the cluster did not go beyond one cluster and were not sensitive to operating factors.

The resulting array of signals provided the opportunity to build markers of qualitative adaptation to physical activity and to conduct a biological interpretation of those involved in these mechanisms.

Descriptive data

All of the individuals participating in the study, including the control group, were students of I. Horbachevsky Ternopil State Medical University and V. Hnatiuk Ternopil National Pedagogical University, and permanent residents of Ternopil. No occupational hazards were found.

Outcome data

Further morphological, temporal and spectral analysis of the AOs was carried out with the help of special computer programs proposed by the authors [1]. Due to the lack of such studies, the authors used the information used in plethysmography and rheography for morphological analysis of oscillograms [23–26] by the authors, as well as logical-visual, scientific and theoretical conclusions of the authors according to the analysis of 1200 oscillograms of 380 healthy individuals [1]. The temporal and spectral analyses of the oscillograms were carried out according to the methods used in the study of the cardiac heart rate variability (HRV) of the electrocardiological signal [1, 7, 11]. In 110 individuals of the experimental group, we recorded electrocardiograms simultaneously with the oscillograms, which were subjected to temporal and spectral analysis. For convenience of the analysis, we used terminology from the study of the variability of cardiac rhythm in ECGs [6, 7].

Ethical consideration

The conclusion of the Commission on Bioethics of I. Horbachevsky Ternopil State Medical University, Ministry of Health of Ukraine, dated June 1, 2018 (protocol No. 47) was as follows: "Materials of the article of Associate Prof. D.V. Vakulenko, Prof. V.P. Martseniuk, Associate Prof. L.O. Vakulenko, Prof. P.R. Selskyy, O.V. Kutakova and V.V. Lesiv on the subject *Cardiovascular system adaptability to exercise according to morphological, temporal, spectral and correlation analysis of oscillograms* regarding the examination of patients, and conducting scientific research conform to the requirements of the rules and principles of bioethics. In carrying out the work, the rules of patient safety, the rights and canons of human dignity, as well as moral and ethical standards in accordance with the main provisions of the GSP (1996), the Council of Europe of the Convention on Human Rights and Biomedicine (04.04.1997), the Helsinki Declaration of the World Medical Association on the ethical principles of carrying out scientific medical research with the participation of a person (1964–2000), the Order of the Ministry of Health of Ukraine No. 281 of the 1st of November, 2000 and the Ethics Code of the Ukrainian scientist (2009) were observed".

Main results

For the morphological analysis of the oscillograms, the information technologies developed by the authors of their weight estimation (on the basis of analysis of 1640 AOs), both separate
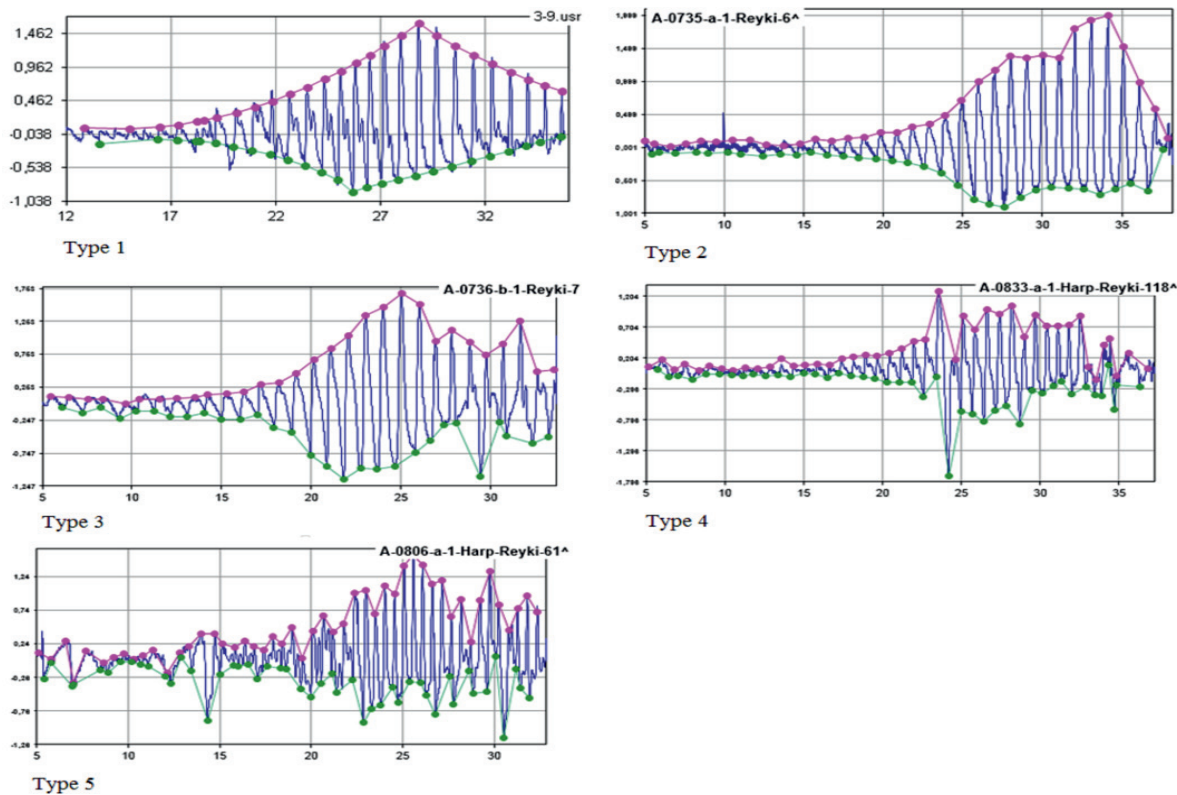
Figure 1. Types of oscillograms, differentiated by the rhythm of pulsations, their form and dynamics of growth and decrease of amplitudes

Note: The X-axis shows the time that the oscillogram was recorded (c); the Y-axis shows the value of the pressure fluctuations in the cuff under the influence of pulsations of the arterial wall (mm Hg).

pulsations and the oscillogram as a whole, differentiated by 5 degrees of deviation from the signals taken as the norm were used [1] (Figure 1).

As can be seen from Figure 1, for AO type 1, the standard form of individual pulsations is characteristic: an anacrotic limb, a decaying limb and a dicrotic wave (its location and size depend on the phase of compression) [9–12, 18, 23]. There is a rhythm of pulsations, a harmony of growth and a decrease in their amplitude, maintaining maximum amplitudes in 2 of them (despite the increase in compression). By the height of the amplitudes of oscillations, one can judge the tone and vascularity of the vessels, the state of the CVS and the ANS, the blood pressure and the neuro-reflex effects on their activity [4, 11, 23, 25]. The above data indicate a satisfactory condition of CVS, neuroreflective mechanisms of blood circulation regulation and visco-elastic properties of the vascular wall of the examined patient. AO types 2, 3 and 4 record different degrees of deviation from the above signals during individual or all compression phases. AO type 5 AO features distorted forms as separate pulsations, and the whole pulsogram. Deviation from the norm for AO types 2, 3, 4 and 5 indicates a different degree of violation of the functional state of the CVS and ANS, the adaptive capacity of the neuro-reflex mechanisms of blood circulation to compression and the visco-elastic properties of the vascular wall [1, 11].

The results of the analysis and evaluation of the AOs were compared with five variants of the health level created by the physiological interpretation of the HRV of the electrocardiograms [7] (Table 1).

As can be seen from the table, the most commonly encountered type from the AO grading options before exercise was type 3 – conditionally healthy.

The results obtained are compared with 5 variants of the health level created by the physiological interpretation of the HRV of the electrocardiological signal [7].

Table 1. Morphological characteristics of the arterial oscillogram type in the experimental group before and after exercise and their physiological interpretation (according to Baievskyi [8])				
Types of os-cillograms	**%**		**Physiological interpretation (according to Baievskyi)**	
	Before exercise	**After exercise**	**Health level**	**Adapta-tion level**
Type 1	8.8	2.9	healthy	optimal adaptation
Type 2	23.5	32.3	almost healthy	tense ad-aptation
Type 3	44.1	41.2	condi-tionally healthy	excessive adaptation
Type 4	20.6	17.6	pre--disease condition	adaptation failure
Type 5	2.9	5.9	sick	adaptation to disorders

The analysis of oscillograms of the experimental group provided the following findings: type 1 – healthy (optimal adaptation) – was recorded in 8.8% of the examined patients before exercise and in 2.9% after exercise; type 2 – almost healthy (hard adaptation) – in 23.5% and 32.3%, respectively; type 3 – conditionally healthy (adaptation overstrain) – in 44.1% and 41.2%; type 4 – the state of pre-existing diseases (adaptation failure) – 20.6% and 17.6%; type 5 – sick (adaptation to disorders) – 2.9% and 5.9%. Thus, type 3 of gradation levels (conditionally healthy) was the most frequent before exercise.

After exercise, a change of gradation in the direction of improvement was recorded in 41.2% of the subjects (Figure 1,
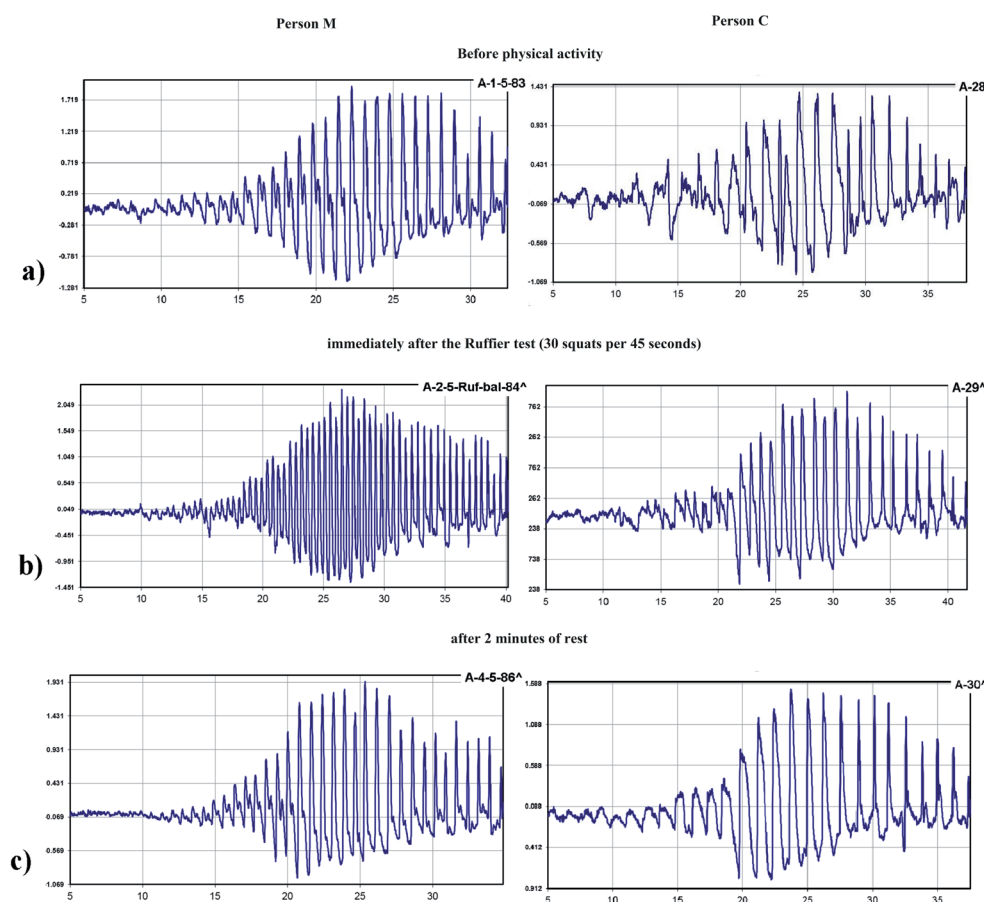
Person M   **Person C**

Before physical activity

a)

immediately after the Ruffier test (30 squats per 45 seconds)

b)

after 2 minutes of rest

c)

Figure 2. Oscillograms of healthy individuals M. (left column) and S. (right column): a) before exercise, b) after 30 sit-ups and c) after two minutes of rest

Note: The X-axis shows the time that the oscillogram was recorded (s); the Y-axis shows indices of pressure oscillations in the cuff under influence of the artery vessel wall (mm Hg).

right column), while some deterioration was found in 23.5% of the cases. The first finding testifies to the functional nature of violations caused by the lability of the autonomic nervous system [7, 11, 13, 31] and the positive effect of metered exercise; the second one demonstrates the reduction in functional capacity of the cardiovascular system under excessive physical activity. The improvement indicates the functional nature of the violations caused by the lability of the ANS (the most accurate marker of reactivity and resistance of the body) and the positive effect of metered physical activity. The deterioration indicates a decrease in the functional capacity of the CVS under excessive physical activity).

After two minutes of rest in 85% of cases, a partial or complete return of the studied parameters to the baseline level was recorded, which indicates the high adaptive capacity of the CVS of the examined patients. In 12% of them, they were better than at a state of rest.

Examples of the AOs of individuals in the main group before and after exercise are presented in Figure 2.

In the analysis of the AO of subject M. (Figure 2), an AO of type 1 was recorded before exercise. After exercise, the frequency of pulsations had increased. The rhythm, harmonic growth and decrease of amplitudes, acute peaks and the lower placement of the dicrotic wave remain intact. The same maximum amplitudes remained at 6 pulsations.

After 2 minutes of rest, the abovementioned characteristics of the AO had returned; the HRV had become smaller than before the physical activity. The noted dynamics of AO factors indicates morphological changes that occur after exercise and after 2 minutes of rest, with adequate activity of blood circulation regulation mechanisms [1, 11, 18, 24, 29, 30]. In subject C., an

AO of type 3 was recorded before the exercise, after which type 2 was improved. A doctor can give an assessment of AO already with his visual analysis.

The temporal analysis of oscillograms in individuals of the principal and control groups was carried out by determining the duration of intervals between the peaks of oscillations. The values of the following indices were studied [1, 6, 7, 13, 29–34]: SDSD (0.45 ± 0.02) s, RMSSD (0.36 ± 0.2) with pNN50 (10.6 ± 0.02), Mo (0.87 ± 0.02) s, AM (37.1 ± 1.1) %, BP (0.6 ± 0.01), IVR (75.2 ± 7.6), VPR (0.75 ± 0.03), IN (32.3 ± 2.9) and HVR-index (29.2 ± 0.12). The indicators of the AOs of representatives of the experimental and control groups did not differ significantly. Some of them were put into the range of oscillations (the difference is not true-to-fact) of the data obtained from the analysis of the HRV of ECG signal from literature sources: Mo (0.9 ± 0.03) s, AMo (37.5 ± 3) %. RMSSD (0.43 ± 0.19) c, pNN50 (18.1 ± 13) [30]. This makes it possible to confirm the reliability of the data obtained in the analysis of the AO and its affiliation with the characteristics of the activity of both the heart and blood vessels.

In order to confirm the reliability of the data obtained and to determine the mechanisms of adaptation to shoulder compression and physical activity, a comparative analysis of the time indices of AO and ECG was done. The last one was recorded synchronously with the oscillogram in 54 people of the main group. There were cases of strong correlation between the Mo index, HRV (Figure 3) and RMSSD (0.97 ± 0.02, p < 0.05) between the ECG and oscillograms. Studies have shown the following data (Figure 3).

Mo (moda) reflects the value of the interval most commonly found in this dynamic series and indicates the most likely level of functioning of the circulatory system; RMSSD is a measure of the power of high-frequency neurohumoral influences that are
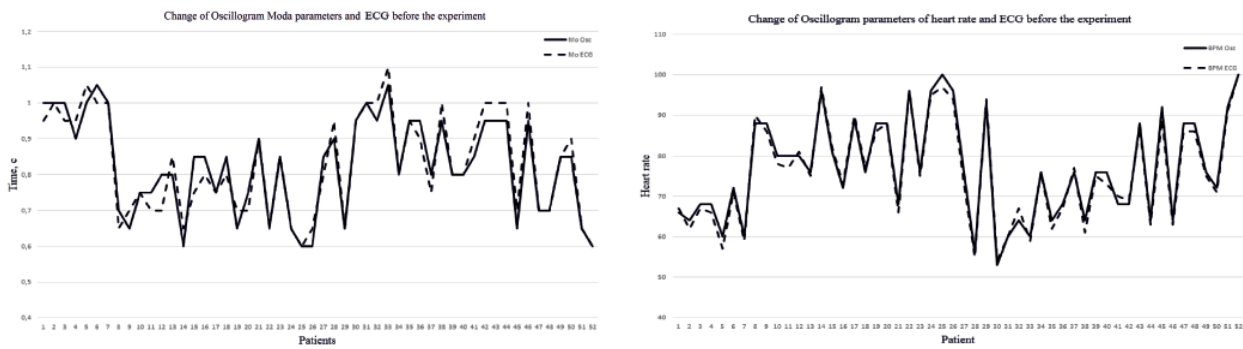
Figure 3. The moda index (on the left) and heart rate index (on the right) of oscillograms and ECGs before the experiment

Note: The X-axis is a representative sample of 54 individuals; the Y-axis on the left shows the duration of R–R intervals (s), and that of the right graph shows heart rate.
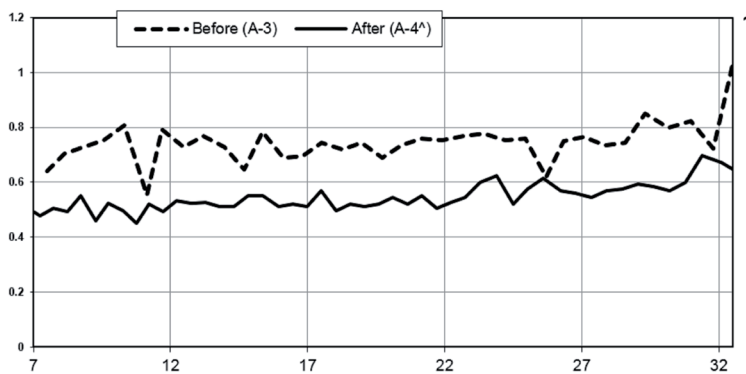

Figure 4. Figure 4. The duration of the intervals between the extremes in the process of increasing the compression of the shoulder of subject M. Solid line – before exercise, the dotted line – after exercise

Note: The X-axis represents time (s); the Y-axis shows the interval duration (ms).

identified with the activity of the parasympathetic link of the ANS [6, 7, 13, 30]. The coincidence of Mo and RMSSD indices determined by ECG and oscillogram suggests that these indicators characterize not only the level of cardiac control but also the blood vessels ("peripheral heart") [1, 7, 11, 23]. A lack of certainty between other indicators of temporal analysis makes it possible to predict their dependence on the sensitivity of the receptor apparatus and the flexible-elastic properties of the vascular wall, which the ECG does not register [1].

Attention is drawn to the fact that in each of the individual oscillograms (Figure 4) during the measurement of BP, the difference in the duration of the intervals between the extremums decreased (stabilized), indicating an increase in the activity of the sympathoadrenal system.

Immediately after exercise, the signs of respiratory arrhythmia decreased and the intervals of intervals stabilized. After exercise, there was a significant decrease in the indices of SDSD, HVR index (Triangular index) ($p < 0.001$) (Figure 5.1a), Mo ($p < 0.001$) (Figure 5.2a) and AMO ($p < 0.01$) and in IVR, IN, pNN50 and the mean quadratic deviation of oscillation amplitudes ($p < 0.001$ non-normal distribution of Wilcoxon methods), which (by analogy with ECG [1, 6, 7, 13, 30, 31]) indicates an increase in sympathoadrenal effects and centralization of circulatory system management. We observed a significant decrease in the indices of SDSD, pNN50 (Figure 5.1a) and Mo ($p < 0.001$) (Figure 5.2a) and an increase in AMo ($p < 0.01$), IVR, IN, HVR index and mean square deviation amplitudes of oscillations ($p < 0.001$ non-normal distribution of Wilcoxon methods), which (by analogy with ECG [1, 6, 7, 13, 30, 31]) indicates an increase in sympathoadrenal effects and centralization of circulatory system management (Figure 5).

After 2 minutes of rest, in most of the surveyed individuals, the above-mentioned indices returned (or approached) to the baseline values (Figure 5b).

At the same time, it is noteworthy that in the participants who had the highest indices of the triangular index (80 ± 12) 2 minutes after the Ruffier test had even lower levels than before the load (40 ± 8) respectively. This indicates the functional character of the marked deviations and the positive effect of physical activity on the state of the CVS.

Physical activity, accompanied by an increase in the tone of the sympathetic link of the autonomic nervous system, contributed to an increase in the proportion of the anacrotic phase in the duration of the entire oscillation (from 14.5% ± 6.7% before exercise up to 26% ± 4.1% after it, $p < 0.05$), which makes it possible to show an increase in left ventricular tension during systole [1, 7, 9, 11, 17] and to show an increase in the tonic tension of the vascular wall [1, 7, 11, 18], which tended to return to the initial level 2 minutes after the completion of the test (up to 18% ± 8.4%, $p > 0.05$).

According to the analysis of R–R interval duration of the oscillograms of individuals in the experimental group, the histograms (graphic image of time slot's repetition frequency) scattergrams (correlation rhythmograms) and chaosgrams (nonlinear 'chaotic' fluctuations of oscillation duration) were developed [8]. After physical activity in the overwhelming (85%) number of histograms (Figure 5), chaosgrams and scattergrams, the shift of indicators of interval duration to the left were recorded, indicating an increase in the influence of the sympathetic link of the VNS and the level of concentration of the effect on the blood circulation system [7]. They are presented with eutonia, sympathic tone and vagotonia in Figure 6.
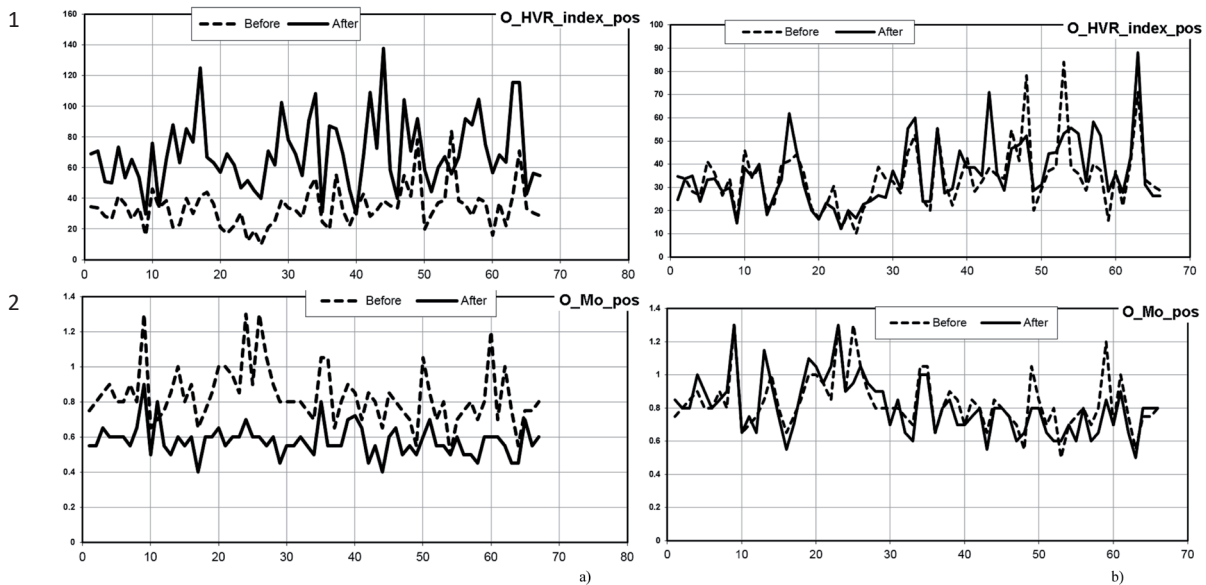
Figure 5. Dynamics of the indicators HVR index (Triangular index) (1) and Mo index (2): a) before and after the Ruffier test; b) before the Ruffier test and after two minutes of rest. Dotted line – before exercise, solid line – after exercise

Note: The X-axis shows a representative sample of 68 subjects; the Y-axis of the top row of images shows indicators of Triangular index (measures of power of neuro-humoral influences, etc.) (HVR index); the Y-axis of the bottom row of images shows the value of oscillation intervals happening most often (Mo, s) in each of the examined patients.
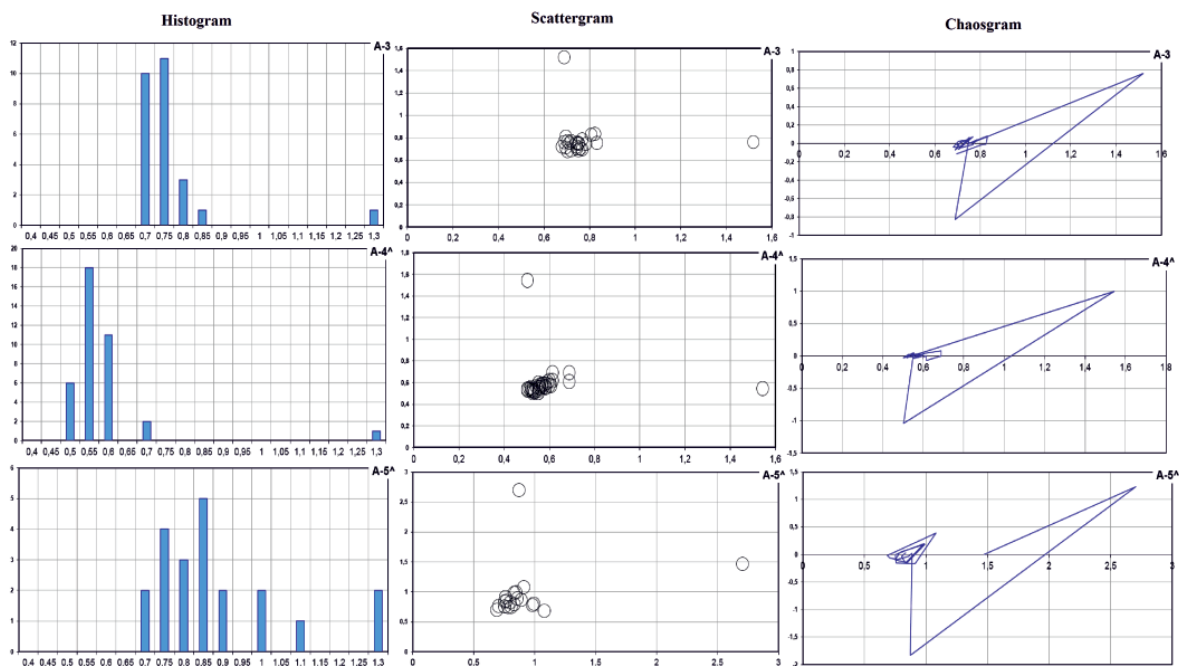

Figure 6. Types of histograms (left column), scattergrams (middle column) and chaosgrams (right column) created by analyzing the duration of R–R intervals of the oscillograms a) eutonia b) sympathicotonia and c) vagotonia

As can be seen from the figures, the duration of the oscillations is characteristic of eutonia 0.7–1.0 s. In case of vagotonia, they shift to the right, sympathicotonia – to the left.

Before exercise, the mean value of R–R intervals of the AOs of the subjects in the experimental group was in the range 0.80––1.15 s (Figure 7a), which indicates a slight increase in the functional state of the parasympathetic link of the ANS [1, 7, 13, 31].

After exercise, on the overwhelming (85%) number of histograms (Figure 7b), chaosgrams and scattergrams, a displacement of the interval duration indicators towards the left was noted, indicating an increase in the influence of the sympathetic link of the ANS and the level of concentration effect on the circulatory system [1, 7, 13, 29, 31].

After 2 minutes of rest, the abovementioned indicators returned or approached the baseline level (Figure 7), indicating a decrease in the level of centralization of circulatory system management, an increase in the tone of the parasympathetic link of the ANS and the quality of the recovery processes [1, 7, 29]. A similar dynamic was observed in 85% of the oscillograms.

Thus, a temporal analysis of oscillograms evaluates the autonomic nervous system state and the level of centralization in the management of the cardiovascular system. The use of the Ruffier test makes it possible to evaluate the level and mechanisms of body adaptation process to controlled physical activity and recovery afterward.
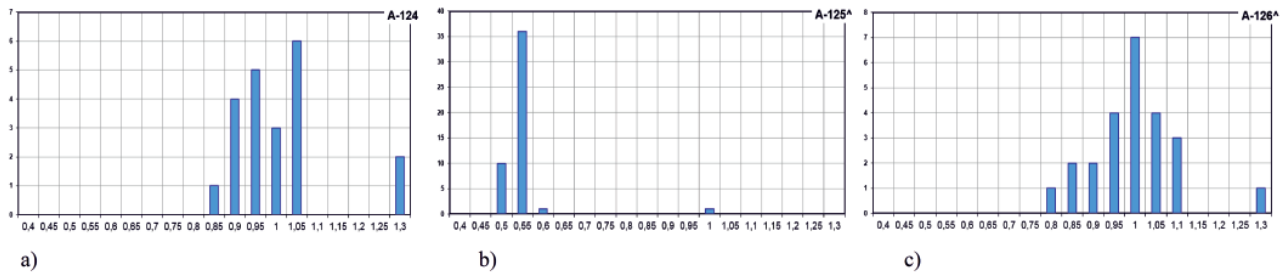
Figure 7. Histogram created by intervals between maximum oscillation extremes, recorded a) before the Ruffier test, b) immediately after it and c) two minutes after exercise (subject M., 18 years old)

Note: The X-axis represents the duration of intervals between extremes; the Y-axis represents the number of intervals.
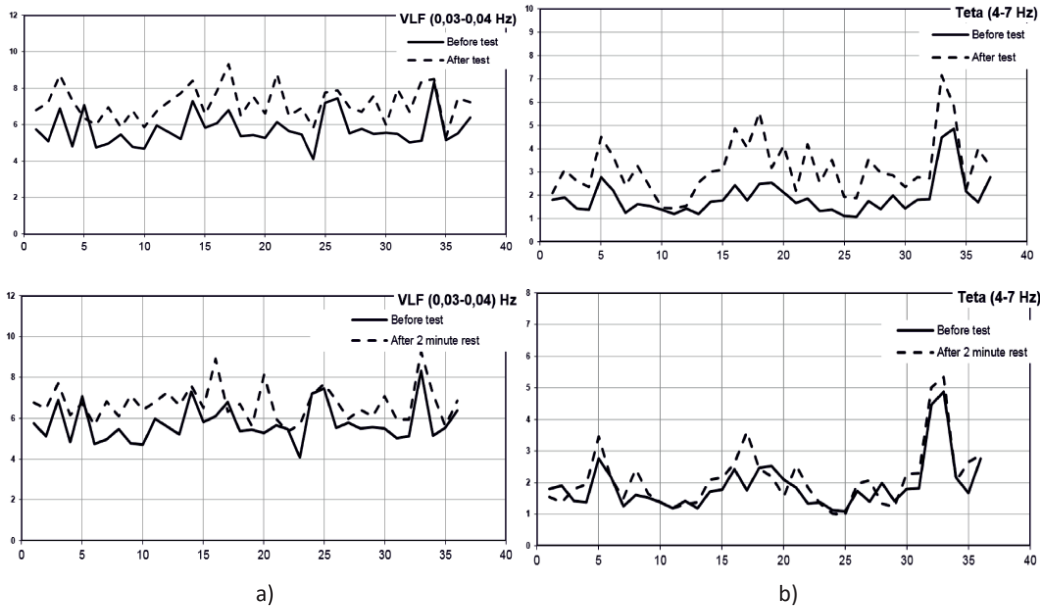

Figure 8. Dynamics of VLF (top row of images) and Theta (bottom row of images) spectrum power indices before and after the Ruffier test. Left column – before exercise and after it; right column – before exercise and after 2 minutes of rest. Dotted line – before exercise; solid line – after exercise

Note: The X-axis shows a representative sample of 68 subjects; the Y-axis shows spectrum power (ms²).

Spectral analysis of the AOs confirmed that exercise contributes to increasing the spectrum power rate of low (%LF, $p < 0.01$) and very low (%VLF, $p < 0.01$) frequency and the power of Theta rhythm spectrum ($p < 0.01$) and a decrease in high frequency rate (%HF, $p < 0.01$) in the overall frequency spectrum [1, 7, 30, 31, 36, 40] (Figure 8). In this case, the synchronism of changes in indices of %VLF and Theta spectrum is noteworthy.

After resting (Figure 8), the studied parameters returned (or are approaching) to the baseline values, which indicates a high adaptive capacity of the body. Its slowdown is associated with reducing adaptive capacity and low-stress resistance of the body, which is a vegetative correlator of anxiety [1, 7, 13, 31].

The correlation analysis of the arterial oscillograms of the representatives in the experimental group showed that before exercise direct correlations were found in 28 pairs of correlates, mainly between temporal indices of oscillogram – Mo, AMo, NN50 and IVR – but additionally between the relative and percentage waves of high (HF) and the lowest (VLF) frequency spectral analysis in the total capacity of all frequency bands (HF, LF and VLF) and between them. Studies testify the coordinated activity of lower levels of regulation by the activity of the CVS against the background of a limited number of correlations between the indicators of biorhythmic activity of the brain. Immediately after the Ruffier test, the noted correlations had mostly disappeared. There were new ones – between the absolute

and percentage values of the Delta, Theta and Alpha (not Beta) rhythms of the brain in the total power of oscillations (from 0 to 100 Hz). The results indicate the appearance of coordinated activity after physical activity, brain activity rhythms which impede the activities of lower levels [7, 30, 31]. The signs of brain activity disappeared two minutes after the squats, when we observed the recovery of the vast majority of correlations that were inherent in the indicators before the examinees performed the exercises.

All of the above discussion leads one to a conclusion about the involvement of higher levels of management of adaptation processes in the adaptive process of the reaction to physical activity. After all, the highest aspect that binds the waves of brain activity to human health is the ability to change these states in accordance with the requirements of the situation [1, 7, 29, 34, 40–42].

Discussion

Key results

The authors have proposed information technologies for morphological, temporal, spectral and correlation analyses of arterial oscillograms obtained during measurement of blood

pressure on the shoulder [1]. The indicated methods were used in the analysis of 1,640 AOs (healthy and sick), recorded at a state of rest and after the influence of various (mechanical, thermal, physical and psychological, etc.) factors. The criteria for their clinical interpretation, assessment and decision-making by the physician have been developed. In this paper, the results obtained are used for the study and clinical interpretation of the effect of shoulder compression on the state of the cardiovascular system (CVS) at rest and after metered physical activity. The application of the proposed methods of AO analysis makes it possible to assess the functional state of the autonomic nervous system (ANS) and the adaptive capacity of the body to compress the shoulder at a state of rest and after physical activity and to study the mechanisms of the development of these processes. The urgency of the work is connected with the expediency of implementation of the proposed methods of recording and analyzing AOs in practical medicine. They can be used by a general practice doctor for the early detection of pre-morbid conditions and functional blood flow reserves, which will help to more effectively plan a preventive, diagnostic and therapeutic process.

The proposed methods of morphological, temporal, spectral and correlation analyses of arterial oscillograms significantly increase the information gained from the procedure of measuring blood pressure, and they make it possible to assess the state, quality and adaptation mechanisms of the cardiovascular system and its reserve capabilities, at rest, after exercise and in the process of recovery after exercise.

A morphological analysis of oscillograms, based on individual pulsations and the whole pulsogram, provides an opportunity to visually assess the quality of the circulatory system's adaptation to increase shoulder compression during the measurement of blood pressure at a state of rest, after physical activity and during recovery from exercise.

In our morphological analysis of oscillograms, we found a decrease in the level of health in 67% of cases; this finding coincides with the studies of other authors [5]. However, the use of physical exercise makes it possible not only to assess the quality of the circulatory system's adaptation to physical activity, but also to differentiate the causes of deviations from the norm which are adopted. An improvement of the morphological status immediately after exercise (which was characteristic in 41.2% of the subjects) indicates the functional nature of the violations caused by the lability of the autonomic nervous system – the most accurate marker of reactivity and resistance of the body [8] – and by the positive effect of physical activity in this. The deterioration noted in 23.5% of the cases was due to a decrease in the functional reserves of the cardiovascular system and inadequate exercise. A high level of functional reserve of the cardiovascular system in 85% of the subjects in the experimental group was confirmed by the results of temporal, spectral and correlation of AO analyses.

Thus, the generally accepted views on the need for functional tests to determine the level of health and functional reserves of the human body are objectively confirmed [5] as well as the high informativeness of the methods of morphological, temporal, spectral and correlation analyses of arterial oscillograms [1]. The above directs the preventative activities of a doctor. Low levels of health and reserve capacity are the cause of chronic diseases [7]. Therefore, individuals with the 3rd type of grading options require some lifestyle correction, while those with the 4th type need a detailed study of the status of their peripheral vessels and the cardiovascular system as a whole, as well as preventative rehabilitation; those with the 5th type require urgent examination and treatment [7]. Studies firmly confirm that physical activity is an important element in the process of rehabilitation.

The results of the temporal, spectral and correlation analysis of the AO made it possible to determine the mechanisms of adaptation of the CVS to shoulder compression and physical activity. The use of a standard Ruffier test along with information technologies for the morphological, temporal, spectral and correlation analyses of oscillograms makes it possible to assess the level and development mechanisms of the body adaptation process to physiological stress (controlled physical activity and compression of the shoulder with a cuff) and the quality of restorative processes after it. To preserve homeostasis when exercising, the following mechanisms are included: increased level of the sympathetic link of the autonomic nervous system, increased centralization of the control of the circulatory system's functioning, increased tone of the blood vessels in the shoulder and tension in the activity of the left ventricle during systole. After the end of exercise, the return to the initial state is accompanied by an increase in the tonus of the parasympathetic link of the VNS, a decrease in the level of centralization in controlling the functioning of the blood circulation system, and a decrease in the tone of the shoulder vessels and load on the left ventricle. These results correspond to the dynamics adopted for the analysis of the heart rate variability [7, 8, 13, 30, 31, 33].

This research confirms other authors [7, 9, 11, 23–25, 27, 28], that the heterogeneous response of smooth muscle in the blood vessels to compression and physical activity is due to a different initial state of the body (functional state of the cardiovascular and autonomic nervous systems, the quality of centralization of the CVS activity management control and the elastic and flexible properties of the vascular wall) and the level of adaptive capacity of the circulatory system (sensitivity of receptor devices of baro- and chemoreceptors controlling different parameters of blood circulation, flexibility of adaptive capacity of the heart and blood vessels to changing environment conditions). The time and quality of restorative processes testify to the ability of the body to recover from external influences, which is also an objective indicator of one's level of health [2–4, 8, 29].

The reliability of studies is confirmed by comparing the numerical indices produced with literature source data, synchronous records of ECG and correlation and statistical analyses.

Limitations of the study

The proposed information technology of arterial oscillography has not yet been widely introduced in electronic blood pressure devices. Although studies have been conducted and legalized methods of arterial oscillography (according to D.V. Vakulenko and L.O. Vakulenko) exist in Ukraine [21] (in the future in other countries of the world), the software and hardware solutions developed will provide comfortable and effective use in the practice of a family doctor and other professionals, both for diagnosing and evaluating the effectiveness of medical interventions.

Conclusions

The reliability of studies is confirmed by comparing the numerical indices produced with literature source data, synchronous records of ECG and correlation and statistical analyses.

The use of information technology offered by the authors for morphological, temporal, spectral and correlation analyses of oscillograms (recorded at rest and after physical activity) for clinical interpretation, evaluation and decision-making by a physician significantly increases the information gained from the blood pressure measuring procedure. These tools provide an opportunity to assess the adaptive capacity of the body to shoulder compression at a state of rest and after physical activity, as well as the mechanisms by which these processes develop. They can be used for the early detection of donozological and pre-morbid conditions and functional circulatory system reserves, which will help to more effectively plan a preventive, diagnostic and therapeutic process.

References

1. Вакуленко ДВ. *Інформаційна система морфологічного, часового, частотного та кореляційного аналізу артеріальних осцилограм у фізичній реабілітації: монографія*. Тернопіль: ТДМУ; 2015. (in Ukrainian).
2. Mercedes R. Carnethon. Physical activity and cardiovascular disease: how much is enough? *Am J Lifestyle Med* 2009; 3(1 Suppl.): 44S––49S, doi: 10.1177/1559827609332737.
3. Fletcher GF, Ades PA, Kligfield P, et al. Exercise standards for testing and training: a scientific statement from the American Heart Association. *Circulation* 2013; 128(8): 873–934, doi: 10.1161/CIR.0b013e31829b5b44.
4. Амосов НМ, Бендет ЯА. *Физическая активность и сердце.* 3rd ed. Киев: Здоровья; 1989 (in Russian).
5. Лущик УБ, Новіцький ВВ. Обґрунтування потреби інноваційних медичних технологій у сучасних інформаційних програмних носіях на прикладі технологій діагностики та корекції серцево-судинної патології. *Запорожский медицинский журнал* 2013; 76(1): 97–100 (in Ukrainian).
6. Heart rate variability. Standards of measurement, physioligical interpretation and clinical use. *Circulation* 1996; 93: 1043–1065.
7. Баевский РМ, Берсенева АП. *Оценка адаптационных возможностей организма и риск развития заболеваний.* Москва: Медицина; 1997 (in Russian).
8. Fletcher GF, Ades PA, Kligfield P, et al. Exercise standards for testing and training: a scientific statement from the American Heart Association. *Circulation* 2013; 128(8): 873–934, doi: 10.1161/CIR.0b013e31829b5b44.
9. Nirmalan M, Dark PM. Broader applications of arterial pressure wave form analysis. *Continuing Education in Anaesthesia Critical Care & Pain* 2014; 14(6): 285–290.
10. Moxham IM. Understanding arterial pressure waveform. *Southern African Journal of Anaesthesia and Analgesia* 2003; 9(1): 40–42, doi: 10.1080/22201173.2003.10872991.
11. Caro CG, Pedley TJ, Schroter RC, et al. *The mechanics of the circulation.* 2nd ed. London: Cambridge University Press; 2012.
12. Tartiere JM, Tabet JY, Logeart D, et al. Noninvasively determined radial dP/dt is a predictor of mortality in patients with heart failure. *Am Heart J* 2008; 155(4): 758–763.
13. Goldberger AL, Stein PK. Evaluation of heart rate variability. UpToDate [cited 02.09.2018]. Available from URL: https://www.uptodate.com/contents/evaluation-of-heart-rate-variability.
14. Romano SM, Pistolesi M. Assessment of cardiac output from systemic arterial pressure in humans. *Crit Care Med Aug* 2002; 30(8): 1834–1841.
15. Hamilton MA, Cecconi M, Rhodes A. A systematic review and meta-analysis on the use of preemptive hemodynamic intervention to improve postoperative outcomes in moderate and high-risk surgical patients. *Anesth Analgesia Jun* 2011; 112(6): 1392–1402.
16. Ekelhof S. The genesis of the Wheatstone bridge. *Eng Sci Educ J February* 2001; 10(1): 37–40.
17. Warner HR, Swan SH, Connolly DC, et al. Quantitation of beat-to-beat changes in stroke volume from the aortic pulse contour in man. *J Appl Physiology* 1953; 5: 495–507.
18. Langewouters GJ, Wesseling KH, Goedhard WJ. The static elastic properties of 45 human thoracic and 20 abdominal aortas in vitro and the parameters of a new model. *J Biomech* 1984; 17(6): 425–435.
19. Chamos C, Vele L, Hamilton M, et al. Less invasive methods of advanced hemodynamic monitoring: principles, devices, and their role in the perioperative hemodynamic optimization. *Perioper Med* (Lond) 2013; 2(1): 19, doi: 10.1186/2047-0525-2-19.
20. Martsenyuk V, Vakulenko D, Vakulenko L, et al. *Information system of arterial oscillograph for primary diagnostics of cardiovascular diseases.* 17th International Conference, CISIM 2018; 2018 September 27–29; Olomouc, Czech Republic. New York: Springer; 2018: 46–56, doi: 10.1007/978-3-319-99954-8_5.
21. de Fátima Marin H, Massad E, Guiterre MA, et al. eds. *Global health informatics. How Information technology can change our lives in a globalized world.* Academic Press; 2016.
22. Shachak A, Borycki E, Shmuel P. *ReisHealth Professionals' Education in the Age of clinical information systems, mobile computing and social networks.* Academic Press; 2017.
23. Покровский АВ. *Клиническая ангиология.* Москва: Медицина; 1979 (in Russian).
24. Смирнов ИВ, Старшов АМ. *Функциональная диагностика. ЭКГ, реография, спирография.* Москва: Эксмо; 2008 (in Russian).
25. Яруллин ХХ. *Клиническая реоэнцефалография.* Москва: Медицина; 1983 (in Russian).
26. Thiele RH, Durieux ME. Arterial waveform analysis for the anesthesiologist: past, present, and future concepts. *Anesth Analg* 2011; 113(4): 766–776.
27. Esper SA, Pinsky MR. Arterial waveform analysis. *Best Pract Res Clin Anaesthesiol* 2014; 28(4): 363–380.
28. Shah SA, Kambur T, Chan C, et al. Relation of short-term heart rate variability to incident heart failure (from the Multi-Ethnic Study of Atherosclerosis). *Am J Cardiol* 2013; 112(4): 533–540.
29. Chantler PD, Lakatta EG, Najjar SS. Arterial-ventricular coupling: mechanistic insights into cardiovascular performance at rest and during exercise. *J Appl Physiol* 2008; 105: 1342–1351.
30. Бабунц ИВ, Мириджанян ЗМ, Машаех ЮА. *Азбука анализа вариабельности сердечного ритма* [E-book]. Ставрополь; 2002 (in Russian).
31. Lombardi F, Stein PK. Origin of heart rate variability and turbulence: an appraisal of autonomic modulation of cardiovascular function. *Front Physiol* 2011; 2: 95, doi: 10.3389/fphys.2011.00095.
32. Sassi R, Cerutti S, Lombardi F, et al. Advances in heart rate variability signal analysis: joint position statement by the e-Cardiology ESC Working Group and the European Heart Rhythm Association co-endorsed by the Asia Pacific Heart Rhythm Society. *Europace* 2015; 17(9): 1341–1353, doi: 10.1093/europace/euv015.
33. Яблучанский НИ, Мартыненко АВ. *Вариабельность сердечного ритма в помощь практическому врачу. Для настоящих врачей.* Харьков: [б. в.]; 2010 (in Russian).
34. Klaus Forstner, inventor. Microlife Intellectual Property Gmbh, assignee. System and method for processing and presentation of arrhythmia information in the detection and treatment of arrhythmias. US 7907996 B2 (Patent) 2011 March. Available from URL: https://patents.justia.com/inventor/klaus-forstner.
35. Goss CF, Miller EB. Dynamic Metrics of Heart Rate Variability 2013; 1–4. arXiv:1308.6018. Bibcode:2013arXiv1308.6018G. Available from URL: https://arxiv.org/abs/1308.6018.
36. Takahashi N, Kuriyama A, Kanazawa H, et al. Validity of spectral analysis based on heart rate variability from 1-minute or less ECG recordings. *Pacing Clin Electrophysiol* 2017; 40(9): 1004–1009, doi: 10.1111/pace.13138.

37. Winters R, Winters A, Amedee RG. Statistics: a brief overview. *Ochsner J* 2010; 10: 213–216.
38. Lee Rodgers J, Nicewander WA, Thirteen ways to look at the correlation coefficient. *Am Stat* 1988; 42(1): 59–66.
39. Coates A, Ng AY. Learning Feature Representations with K-means. Stanford University, 2012. Available from URL: https://www-cs.stanford.edu/~acoates/papers/coatesng_nntot2012.pdf.
40. Сивер Дэвид. Майнд машины. Открываем заново технологию ABC, 2000. Available from URL: http://www.mindmachine.ru/book/ (in Russian).
41. Selskyy P, Vakulenko D, Televiak, A, et al. On an algorithm for decision-making for the optimization of disease prediction at the primary health care level using neural network clustering. *Fam Med Prim Care Rev* 2018; 20(2): 171–175.
42. Mintser O, Martsenyuk V, Vakulenko D. *On data mining technique for differential diagnostics based on data of arterial oscillography.* In: Zawiślak S, Rysiński J, eds. *Engineer of the XXI Century.* Mechanisms and Machine Science 2020; vol 70. Cham: Springer. Available from URL: https://doi.org/10.1007/978-3-030-13321-4_23.

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