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STRUCTURAL AND FUNCTIONAL INTERDEPENDENCES OF BIOLOGICAL ORGANISMS IN EXTREME CONDITIONS

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Investigations of the adaptation of living organisms to various extreme factors are important indeed.

Aim. To characterize and analyze the results of research of structural and functional interdependencies of organisms in extreme conditions.

Methods. Comparative analysis of the registered biochemical, physiological characteristics of the body, mathematical modelling of underlying mechanisms on their basis, information and computer technologies.

Results. Deviations of organisms' functions during adaptation processes caused changes in some structures of organism. Significant role of quantitative and qualitative changes of the erythrocyte formation system in the reliability of organisms functioning in extreme conditions in highlands was confirmed. The changes in red and white blood cells reflected largely the relationships between the organisms' reactivity and resistance. The dependences on degree of rarefaction of the air, mode of climbing, effects of athlete's training, etc. were revealed. Adaptive hemolysis of erythrocytes, when the biologically active substances were released from blood cells and acted as messengers, were shown to be the triggers capable to change cell metabolism; they played significant roles in reliability of organisms functioning. The set of program models was developed. Results were applied successfully for training of athletes for high-altitude climbing.

Conclusions. Results of the studies on the structural and functional interdependencies of organisms in extreme conditions were reviewed and analyzed. Results of mathematical modeling coincided with the results obtained in experiments and observations. In the process of adaptation to hypoxia human organism behaved likes an ultrastable system. Obtained results can be applied in practice.

Key words: structural and functional interdependencies of organisms; theoretical analysis; comparative analysis; mathematical model; adaptation; hypoxic state.

The pool of the problems linked with interrelations between structures and functions includes ones with which all scientists are faced in their everyday research work. Moreover, theoreticians had united such kind of the problems as a special direction; it attracts the interest from both philosophers and researchers-experimenters. In process of their work scientist, representatives of academician or research groups obtain and accumulate a lot of the data, facts, regularities discovered on the basis of these data. With time one can see that such data arrays enable to recognize some dependencies and rules that demonstrate the links between different structures and their functions (in case of biology or medicine — namely biological or physiological functions).

Regularities in the relations between biological structures and functions attract researchers' attentions because of possibility to find new methodologies for investigations or to perfect the latter, to solve new tasks successfully. Surely this is a possibility to understand better our wonderful World around, admire harmony of the Nature. Numerous experimental data from the spheres of contemporary biotechnology, molecular biology, genetics, and molecular effects in neurophysiology and brain research demonstrated bright examples of structural and functional interdependences. Such results had been already shown in numerous publications, which formed following contemporary directions of investigations. Structural and functional interdependencies (SFI) are studied today at different levels of objects organization in the Nature; from nanoparticles — to macro objects like cells, organs and organisms. SFI at the level of nanoparticles (NP-SFI), including development of techniques one can find in [1–10], and in [11–16] the use of NP-SFI techniques in chemistry was represented (for the purposes of analytical chemistry in [15, 16]). Results of NP-SFI studying using different physical methods and implementation of this paradigm in physics were published in [17–25]; continuation of NP-SFI application in physics for interfaces construction was in [26–31], as well as studies for biosensors construction [32–39]. Results of SFI at the level of molecules, including biological macromolecules one can find in [40–49]. The next volume of investigations was done at the level of molecular complexes [50–67], like liposomes [63], biofilms [64], lipid bilayers [66], and model cell membranes [67]. Some of such works were about drug delivery studies for medicine [56, 57]. Numerous works were devoted to NP-SFI for biotechnologies [68–86]. For example, the results of [73] were used in medicine, [74] — for targeting bacteria, [76] — simultaneous qualitative and quantitative detection of biomarkers. In medicine also were used the results of NP-SFI [87–95]. Among them the works [90, 95] were devoted to the development of new strategies in biomedicine. Another direction of the NP-SFI united the works with different biological objects [96–107]. For example, in the work [98] antimicrobial activities of biomaterials were studied, in [100] it was studied nanoparticles to Daphnia Magna, in [102] — interaction of nanoparticles with biological systems, and in [106, 107] — nanoparticles interaction with cell cultures. Finally, some works [108–120] were the closest ones to our studies presented in this article. They all devoted of SFI on macro objects. In [108] nanoparticles dispersed in peritoneal dialysis fluid, [109] — heme-nitrosyls as electronic structure implications for function in biology, [110, 111] were about the progress towards NP-SFI therapeutic applications, [112] was about the regulation of a cell signaling system using low nanomolar solutions of inorganic nanocrystals. [114] was about hemoglobin bioconjugates with surface-protected gold nanoparticles in aqueous media, [115] about the bio-nano interactions between blood proteins and monolayer-stabilized graphene sheets. [116–120] were devoted to structural and functional interactions between different types of receptors, nanochannels and biologically active molecules. The results, described in the last pool of the articles were the most close to our, described in present article.

Moreover we would like to illustrate on the basis of the results (experimental and derived from the observations and examinations as well), which were obtained during long years of investigations at Elbrus Medical and Biological Station (EMBS) of the National Academy of Sciences of Ukraine. From the beginning of XXI c. it was called ICAMER — International Centre of Astronomical and Ecological Researches. The studies were carried out by Ukrainian scientists at this unique scientific and research center in Caucasus Mountains, at the slopes of Mountain Elbrus, which is situated at the territory of Kabardino - Balkar Republic at the altitude 2100 m above sea level (m a.s.l.) [121, 122]. The groups of scientists from Ukraine, some other republics of former USSR, as well as some countries far abroad had carried out their researches there, at that's unique research center in high mountains conditions, and many projects of our research group were linked with EMBS and continue its traditions [121–133]. Surely, it is true that high mountains conditions attract attention of numerous scientists of the world, being so like "natural laboratory" for studying of many interesting and unique phenomena [121–126]. Previously we had already characterized some of the main directions of scientific research at EMBS. We also had already written about the EMBS history, emphasizing the role of Ukrainian investigators in those works [121, 122]. For example, we had published the information about such directions of investigation at EMBS, as large-scale studying of hypoxia problems and experience of development of different methods for hypoxic effects treatment as well as about other pathological states of organism and their corrections in high-mountain condition [121–126]. There were also other phenomena had been studied as well, such as adaptation of various organisms to high altitudes, trainings of athletes and representatives of special contingents in those conditions, works for aviation and cosmonautics [121], development of methods for medical treatment of different organisms' disorders and organisms' rehabilitation, phenomena of human health and longevity in high mountain conditions [121–126], and others. Ukrainian scientists based on EMBS research data had developed and proposed some mathematical models [121–126]. A set of specific mathematical methods were selected, developed and used for such purposes [127]. Adaptations of different biological organisms were studied by some research groups during decades: vertebrates (including human) and invertebrates (insects) as well [131–133]. It is necessary to mention that those works were done in continuation of large-scale investigations of the first organizer of EMBS, namely Academician, Prof. M.M. Sirotinin. Ukrainian representatives of his scientific school continued his traditions. They studied organisms under extreme conditions at various levels: submolecular, molecular, cellular, organ, and systemic. They always tried to understand the patterns of such structural-functional interdependence at all these levels, because they saw organism as complex, unified, integrated, multi-level, balanced, coordinated, multifunctional, organized system with interdependent relationships. Therefore we had supposed that methodological approach for investigation of adaptation processes should be based on the principles of structuralism and synergism, because we were interested greatly in the reactions of organism as a whole system [121, 122].

Present article systematizes some results of research of structural and functional patterns of the organisms such as adaptation in high mountain conditions. During numerous examinations of different people by our research groups during different periods, they registered a phenomenon that under the conditions of short-term adaptation to hypoxia the changes in some body functions occur; and those changes of some functions were the first in time. Further, with continued stay at altitude, those changes caused sequences of morphological and structural changes in organism, which were registered by researchers. So, the results of studying of some structural and functional interrelations in organisms and their changes in high mountain conditions we have described in present article. Our conclusions were confirmed in practice, and were used in the preparation of alpinists to climb the highest point in the world — Mount Everest, and those data were described in the article as well. The mathematical models of the main functional systems of organism, combined with traditional experimental methods of contemporary physiology were developed. They have become rather effective means of studying of systemic mechanisms of the formation and development of organism adaptive reactions to hypoxia, which cause structural and functional changes in it [121, 122]. Purposes of the work were to observe, characterize and analyze the results of research of the structural and functional interdependencies of organisms in high mountain conditions analyzing some registered biochemical, physiological characteristics and mathematical modelling on their base. The practical method proposed as the result of those investigations was based on the use of information and computer technologies. This method can be useful also in biotechnological processes in order to find the most optimal solution to problems that require coordination, control, and cross-functional interaction of all links of biotechnological processes and any other processes of management.

Problem of adaptation to extreme conditions

The problem of adaptation of biological organisms to various extreme factors, to gradual or sudden changes in the environment is extremely important, because knowledge of adaptation mechanisms, criteria for evaluating the capabilities of the organism will allow to optimize the work capacity and to ensure good health in whole. To that end, it is important to determine the degree of so-called "tension" of one or another system of the organism (respiration, blood circulation, hematopoiesis, etc.), establish interdependencies between different systems, and conduct a correlation analysis among numerous adaptive reactions. That is, in the concept of "structural-physiological interdependencies" we include not only the dependence between the function (for example, blood circulation) and the structure (morphological changes in the heart muscle), but also the change in their quantitative and percentage ratios during the response of organs or systems to a stimulus, because each system responds to the action of the same factor in a unique way. Thus, our proposed method enables comparing the structural and physiological interdependencies of various functional systems, which allows reflecting the general reaction of biological organism. So, we would like to observe and characterize the results of research of the structural and functional interdependencies of organisms in mountain conditions basing on the results of their studies (elevation) in barochamber as well on the results of training of the group of alpinists who were prepared to climb Everest.

Multifunctional nature of adaptation phenomena in organisms

Each organism has its specific structure, organization, and individual characteristics. Accordingly, this determines the high reliability of organism's functioning (ROF) in extreme environmental conditions, the ability for adaptation (adaptability) [122, 124–126]. Determining the principles, regularities of intersystem relationships, a peculiar pattern of reactions of various organism systems to a stimulus could be a good support in the studied problems of ROF formation. Therefore, the problem is not only in the study of the type of organism reaction. It is also in the determination of the most informative adaptation criteria, the development of new methodological approaches for the study of qualitative and quantitative relationship, primarily between oxybiotic systems that provide the organism energy demands in conditions of hypoxibaric and hypermetabolic development hypoxia. This problem is also a natural continuation of our previous works in mathematical modeling of physiological processes with the possibility of predicting of the state of organism in specific environmental conditions.

In the process of evolution in the world of animals, the signs and properties that characterize the ROF in specific environment were determined by the nature. Researchers are particularly interested in extreme critical situations, when the survival requires high energy losses in conditions of hypoxibaric hypoxia. At the same time, all energy resources are mobilized and used for the compensatory and adaptive needs of organism, regardless of the economy. Such strategy is biologically necessary, its choice is defined by the need to survive and win; it is determined by the regulatory and functional systems of the organism. First of all, the functions of respiratory and cardiovascular systems are responsible for the delivery of mobilized oxygen. During the research, we tried to answer the following questions: how to determine and predict the ability of biological organism to maintain vital energy costs, which will be qualitative and quantitative relationships, relationships of regulatory and functional systems, what morpho-functional changes ensure this, how efficiently and economically they work, what are the quantitative relationships between the levels of oxygen consumption, and approximately the same problems, especially those related to their use in practice. However, while studying these problems, scientists often do not reach a consensus due to different methodological approaches, classifications, test parameters, contingents of examined people (age, gender), elevation above sea level (in cases of research in mountains), and etc.

Some results of investigation of functional-structural interdependencies in organisms during their adaptation in extreme conditions

Scientists at EMBS had examined different groups of people: - healthy, sick, and people of different ages. Special contingents such as climbers, rescuers, athletes of the highest qualifications were among them. Practical and theoretical tasks they had to solve were also different. They had to study the patterns of functional and structural organization, the mechanisms of ROF in stressful situations, to establish deep interdependencies in the response of various organism systems, to determine the most informative indicators of adaptation process, to develop the most effective methods of hypoxic training with the aim of prevention, treatment, increase of endurance and working capacity. They had to select and rank operators, promising athletes for one or another sport, monitor the intensity of physical exertion or the effectiveness of hypoxytherapy, establish a diagnosis, predict the course of pathological process or the organism's ability to perform special tasks in extreme conditions, etc. Such problems appeared constantly in the field of view of scientists, doctors, and trainers. Currently, we had the opportunity to receive a huge array of information on those problems with the help of modern devices, but the task was to be able to do this quickly and efficiently.

During research at EMBS, the attention was focused on the proposed methodological approach called structuralism. This is a direction related to the application of structural approach (structural analysis, structural representation, mathematical analysis and modeling of the process, etc.) during the study, decoding, definition, evaluation of a given phenomenon, information, response, manifestations, relations, joint action of various systems (synergism), the degree of orderliness. Such methodological approach enabled to determine correlational interdependencies, deep relationships, degree of the system orderliness, heterogeneity of stochastic time series; stability, adaptability, organism ability for adaptation. This approach gave us a possibility to carry out mathematical modeling of ROF mechanisms, adaptation processes and thereby helped to predict the state of the organism, placed in certain possible situations. It is also feasible to use obtained information for efficient treatment, training, improvement of sports results, increase of organism resistance; determine the most informative indicators, reveal the principles of interaction, etc. [121]. At the same time, our scientists used specially developed computer programs that helped to solve a number of mentioned problems.

For example, such programs made it possible to determine the most informative criteria for assessing the process of adaptation to hypoxia, changes in the indicators of cardiovascular system in the process of adaptation to the conditions of mountain heights in comparison with original, initial data obtained at sea level, quickly indicate pulmonary pathology, visually show the peculiarities of functioning of oxybiotic systems of highlands aborigines in comparison with inhabitants of the plains, to evaluate the adaptation process (Figs. 1, 2), to determine the differences in adaptation processes for women and men (Fig. 3), to present visually the distribution of the oxygen consumption rate and blood circulation in tissues (brain, heart, skeletal muscles, etc.), working organs, individual indicators of the oxygen consumption rates and blood flow, oxygen tension in arteries, veins, as well as in the tissues of the brain, heart, and skeletal muscles.

Studying the processes of adaptation to the natural conditions of mountain heights, researches were carried out starting from sea level, and at heights of 2000±100 m, 3000±100 m, 4000±100 m, 4800±100 m, 5500±100 m a.s.l. Studies in pressure chambers (barochambers) were carried out at the same “altitudes”, as well as (for highly qualified athletes) — at the “altitude” of 7,500 m a.s.l. The researches were carried out in hospitals at a temperature of 20±1 °C in the first half of the 2nd, 7th, 12–13th, 22–23rd days after arrival to each altitude (blood samplings were carried out; the primary metabolism was studied on an empty stomach). Some of the obtained results can be presented below (Figs. 1–3).

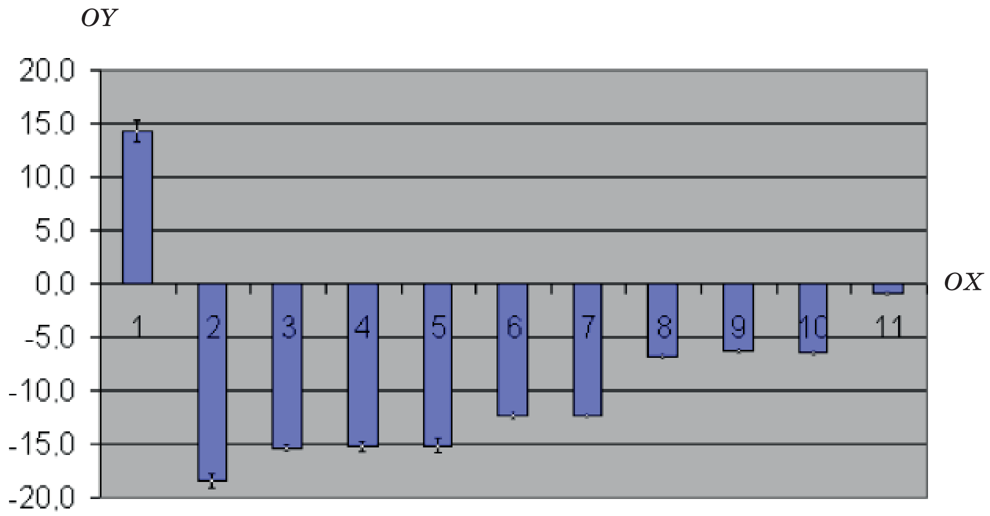

Fig. 1. **Functional diagram of central hemodynamics**

Note: see also the results in Table 1 on the 2nd and 21st day of stay at village Terskol at Elbrus mount slope (women, n = 14, 25–38 years old).

Axes: *OX* — number of indicators; *OY* — Delta (in percentages).

Table 1. **Indicators of central hemodynamics**

Indicator	PLV	BVM	SBV	SI	CI	LVBM	VVBE	HR	BET	BEF	CEE
No	1	2	3	6	7	4	5	8	9	10	11
2 day	2.8 ± 0.3	4.9 ± 0.3	72 ± 3.7	46 ± 3.1	3.3 ± 0.3	57 ± 3.0	228 ± 5.0	74.0 ± 3.0	0.3 ± 0.01	63 ± 3.0	11.0 ± 2.0
21 day	3.2 ± 0.2	4.0 ± 0.2	61 ± 3.1	39 ± 3.0	2.8 ± 0.2	50 ± 3.0	200 ± 5.0	69.0 ± 3.0	0.3 ± 0.1	59 ± 2.0	10.9 ± 1.8
Delta (%)	14.3 ± 0.2	−18.4 ± 0.3	−15.3 ± 3.4	−15.2 ± 3.1	−15.2 ± 0.3	−12.3 ± 0.6	−12.3 ± 0.5	−6.8 ± 0.3	−6.3 ± 0.01	−6.3 ± 2.5	−0.9 ± 1.9

Indications: PLV — power of left ventricular, BVM — blood volume per minute, SBV — stroke blood volume, SI — shock index, CI — cardiac index, LVBM — linear velocity of blood movement, VVBE — volumetric velocity of blood ejection from the heart in aorta, HR — heart rate, BET — blood ejection time from left ventricle of the heart, BEF — blood ejection fraction, CEE — cardiac energy expenditure for blood pump. Indicators of central hemodynamics, results of recordings in experimental conditions

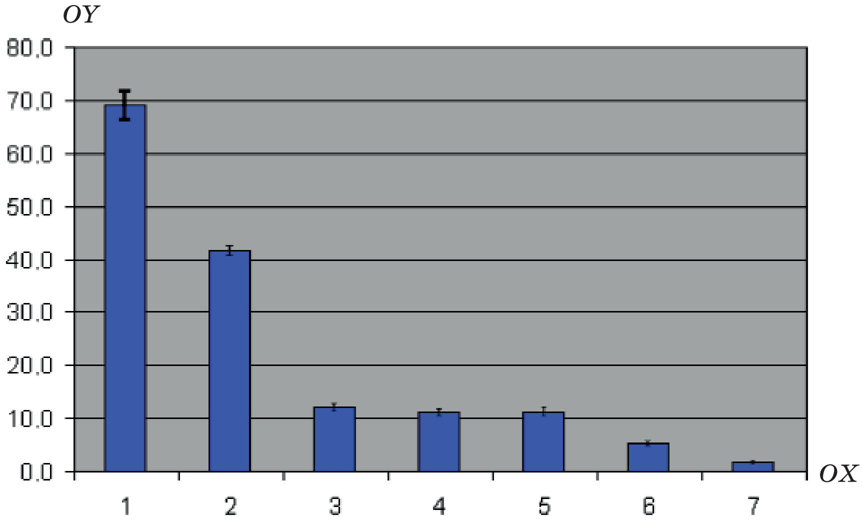

Fig. 2. **Functional diagram of red and white blood**
Note: see also the results in Table 2 on the 2nd and 21st day of stay at vil.Terskol at m. Elbrus slope (women, $n = 14$, 25–38 years old). Axes: *OX* — number of indicators; *OY* —Delta (in percentages)

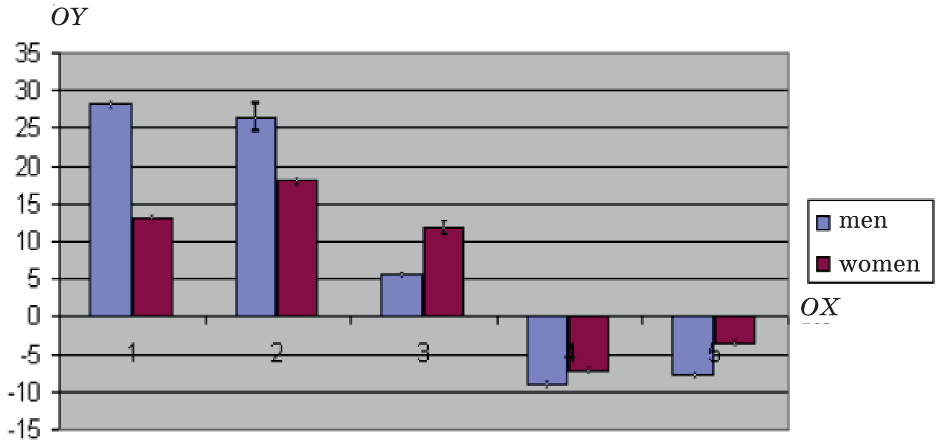

Fig. 3. **Functional diagram of the external breathing system**
in the process of adaptation to hypoxia in men ($n = 12$) and women ($n = 15$) in conditions of basic metabolism
Note: see also the results in Table 3. Axes: *OX* — numbers of indices for men (blue columns) and women (red columns); *OY* — gradient (in percentages)

Table 2. **Indicators of red and white blood**

Indicator **No**	**SDH** **7**	**InRe** **3**	**Pl** **6**	**Hb** **2**	**Er** **1**	**L** **5**	**ESR** **4**
2 day	5.8±0.4	0.60±.01	223±5.0	125±2.0	3.6±0.2	5.6±0.2	5.6±0.2
21 day	9.8±0.5	0.85±0.01	250±7.1	139±2.1	4.0±0.2	5.9±0.2	5.7±0.2
Delta (%)	69.0±0.5	41.7±0.01	12.1±6.1	11.2±2.0	11.1±0.2	5.4±0.2	1.8±0.2

Note: SDH — succinate dehydrogenase, InRe — erythrocyte resistance index, Pl — platelets, Hb — hemoglobin, Er — erythrocytes, L — leukocytes, ESR — erythrocyte sedimentation rate. Indicators of central hemodynamics, results of recordings in experimental conditions

Table 3. **Indicators of external breathing systems and hemodynamics**

	System Indicator No	**RV 1**	**External breathing systems**				**Hemodynamics system**				
			OERC 2	AV 3	SBA 4	BVM 5	OEHC 1	CO2A 2	OCB 3	HE 4	MBV 5
men	2 day	670 ± 18.0	19 ± 1.8	5.3 ± 0.2	33 ± 1.3	9.0 ± 0.4	3.6 ± 0.3	18.0 ± 1.8	20 ± 1.5	18.9 ± 1.8	4.4 ± 0.3
	21 day	860 ± 2.0	24 ± 1.3	5.6 ± 0.2	30 ± 1.4	8.3 ± 0.3	4.0 ± 0.3	19.7 ± 2.0	21 ± 1.4	17.1 ± 1.7	4.0 ± 0.2
	Delta (%)	28.4 ± 0.1	26.3 ± 1.6	5.7 ± 0.2	−9.1 ± 1.3	−7.8 ± 0.3	11.1 ± 0.3	9.4 ± 1.9	5.0 ± 1.4	-9.5 ± 1.7	−9.1 ± 0.2
women	2 day	415 ± 15.0	11 ± 0.4	3.4 ± 0.3	41 ± 1.5	5.6 ± 0.2	2.1 ± 0.1	14.6 ± 1.7	17.3 ± 1.8	27.5 ± 1.4	4.2 ± 0.3
	21 day	470 ± 16.0	13 ± 0.5	3.8 ± 0.3	38 ± 1.4	5.4 ± 0.2	2.4 ± 0.2	15.7 ± 1.7	18.6 ± 1.8	27.0 ± 1.5	3.6 ± 0.2
	Delta (%)	13.3 ± 0.1	18.2 ± 0.4	11.8 ± 0.3	−7.3 ± 1.2	−3.6 ± 0.2	14.3 ± 0.2	7.5 ± 1.7	7.5 ± 1.8	−1.8 ± 1.2	−14.3 ± 0.25

Note: RV — respiratory volume, OERC — oxygen effect of respiratory cycle, AV — alveolar ventilation, SBA — shift of buffer alkali, BVM — breathing volume per minute, OEHC — oxygen effect of heart contraction, CO_2A — oxygen content in arterial blood, OCB — oxygen capacity of blood, HE — hemodynamic equivalent, MBV — minute blood volume. Indicators of central hemodynamics, results of recordings in experimental conditions

Research using standard methods was conducted on athletes, healthy and sick representatives of population of mountainous regions, and members of special contingents. Various functional tests were used (in particular, a bicycle ergometric test), physical loads, "climbing" in pressure chambers; the changes in the process of adaptation to the conditions of mountain heights were studied as well [121, 122].

Created mathematical models and their analysis

During our research of structural-functional interdependencies, a number of mathematical models were created based on the obtained data, which analysis helped to understand the revealed phenomena. Analysis of the mathematical model of the functional respiratory system (FRS) during long-term hypoxia influence on the organism demonstrated that there are several mechanisms for compensation of hypoxic states [124–126]. The most important of them was related to more effective organization of tissue respiration. It is known that the oxygen delivered to the tissue reservoir is used to release the energy necessary to perform the direct function of this tissue, generation of heat and other types of energy. It can be assumed that functional component was not change at a given amount of work, and the thermal component decreases with sufficiently long exposure to hypoxia. Under these conditions, the rate of oxygen supply to the tissue region can be reduced. It consequently reduced the load on regulatory mechanisms and increased their resources during hypoxia.

With long-term exposure to hypoxia, the organism's sensitivity to it was changed. Ensuring the timely and effective delivery of oxygen to metabolizing tissues (the main function of respiratory system) caused conflict situations between the body organs under the regulation and oxygen consumers. Their compromise solutions were possible with increasing the mass (volume) of executive organs of regulation and, first of all, the mass of cardiac muscle as the most vulnerable of all executive organs of regulation. Besides, with prolonged exposure to hypoxia, the process of erythropoiesis begins. Many researchers linked the number of red blood cells produced by the bone marrow with the increase of the mass of bone tissue, which also evidenced the structural and morphological changes in organism. These dependencies, demonstrated on mathematical models, coincided with the results obtained experimentally [122, 124–126].

So, the mathematical analysis of the model of functional respiratory system during long-term hypoxia influence on the organism makes it possible to recognize links between functional, structural and morphological changes in the organism at systemic level. It also enabled to estimate qualitatively and quantitatively the hypoxic states of organism in various periods during the long-term adaptation.

Practical activities based on the studied structural-functional interdependencies: training of alpinists groups to climb Everest

The practical use of theoretical research at EMBS was carried out during the implementation of various important projects, for example, for the space-research project of modeling of astronauts landing on the Moon [161]. Among other important projects, we have to describe in more details the selection and training of a student team of alpinists to climb the highest peak in the world Everest (8848 m). The examinations of the members of that team were complex and were held in three stages during the course of two years. It was started from the first familiarization meeting with further ascent to the top of Elbrus. Because the levels of adaptation of the team members to the conditions of mountain heights were insufficient, it was decided to exclude the barometric chamber survey at the "altitude" of 7500 m a.s.l. and they were advised before leaving for the Himalayas to hold two more adaptation meetings with trainings. Individual recommendations were given to each participant of these Elbrus meetings, aimed at the conducting of additional specific medical examinations, complex strengthening measures that harden the organism (with general or local effects), increase aerobic and anaerobic capacity. Depending on the purpose, this was done at the states of rest and during various functional tests (physical and mental stress, "climbing" in a pressure chamber, climbing to the top of Elbrus, cold test, holding of the breath for 45 seconds, forced exhalation, maximum lung ventilation, etc.). For examined athletes the states of higher nervous activity, the state of the vegetative, respiratory, cardiovascular systems, physical and mental capacity (at "altitudes" of 2100, 5600, 7500 m a.s.l. in barochamber tests) were estimated.

From the hematological indicators there were studied the content of hemoglobin, the number of erythrocytes, leukocytes, platelets, and the rate of sedimentation of erythrocytes. In the smears, the formulas of leukocytes and lymphocytes were calculated, the count of erythrocytes and the degree of deformation of their membranes, as well as qualitative changes of leukocytes and platelets were determined. Elevation in a pressure chamber to the "heights" of 5600 m or 7500 m a.s.l. was carried out at a rate of 15–20 m/s with "plateaus" at the "heights" of 3500, 5500, 6500 m a.s.l. for 5 minutes. The one-time composition of the team members did not exceed 5 people (including the doctor who used the oxygen device). A functional test (20 squats in 30 seconds) or gradually increasing functional test (bicycle ergometry) was performed at the altitudes 5600 m and 7500 m a.s.l. According to the doctor' decision, the test was immediately stopped if the team member lost consciousness, with appearance of acute pain of any localization (heart, dental, with flatulence, etc.), with sharp increase of pulse frequency (over 170) or decrease of the pulse, with the appearance of arrhythmias, with a strong cough and other objective signs of health deterioration.

The selection and training of alpinists and other special contingents for the successful performance of works in conditions of reduced oxygen partial pressure (hypoxybaria) were done in several mandatory stages: 1 — dispensary examination, 2 — special clinical and physiological examination during the "elevation" in a pressure chamber and carrying out stress tests, 3 — clinical and physiological examination in the process of adaptation to mountain heights conditions, 4 — use of mathematical models of hypoxic states to assess speed and economy of oxygen transport, as well as the distribution of its tension in the tissues of the heart, muscles, brain, lungs, etc. Particular attention was paid to determining the level of stress, mental and physical capacity, cold resistance, and evaluation of the efficiency of transport and oxygen utilization systems, as well as adaptability. A special ranking system was developed taking into concideration the importance of each parameter in the provision of ROF in extreme conditions, firstly with determination of the level of functioning of any separate system, and secondly - of the entire organism. This approach made it possible to predict behavior, work ability, and stability in extreme environmental conditions. The effectiveness of this approach has previously been confirmed by successful expeditions to the highest mountains ("eight-thousanders") in the Himalayas [121].

In particular, we had demonstrated the application of one of created mathematical models that allowed calculating pO_2 and pCO_2 in tissues of functioning organs [124-126]. To do this, the data on OC (oxygen consumption), RV, Hb (hemoglobin content), body weight, duration of the respiratory cycle and its components were input into this our model [124–126]. Calculations showed that, in the initial period of adaptation, the oxygen tension in arterial blood was 79.7±3.0 mm Hg, 30.9±2.0 in the brain, 25.15±2.0 in the heart, 25.65±2.3 in skeletal muscles, 34.5±2.3 in venous blood. During the second examination in the village Terskol (2500 m a.s.l., after a ten-day adaptation and climbing to the top of Elbrus), the level of PO_2 in the arterial blood increased to 84.18±2.54 mm Hg, 33.3±0.8 in the brain tissues, up to 27.9±1.6 in the heart, up to 27.29±1.46 in skeletal muscles, up to 36.46±1.97 in venous blood.

Conclusions

Thus, in present article we had observed and characterized the research results of structural and functional interdependencies of organisms in high mountain conditions. Contrary to [1–120, 134–155], we did complex analysis of structural and functional interrelations at different levels of the organism's organization: molecular (biochemical level), cellular, organ and whole organism. We had confirmed significant role of quantitative and qualitative changes in the erythrocyte formation system (erythron), in provision of reliability of organism' functioning (ROF) at the extreme highland conditions. It was demonstrated as well that the changes in red and white blood cells largely reflect the relationships between the organism's reactivity and resistance.

Dependencies on the degrees of rarefaction of the air, the modes of elevation, the reactions of training, activation or stress were revealed [122]. The adaptive hemolysis of erythrocytes was demonstrated: biologically active substances released from blood cells and acted as triggers, which were able to change cell metabolism, and they played significant role for ROF providing in extreme conditions.

When adapting to hypoxia, the human organism behaves like ultrastable system. It has been found that the effects of other factors (for example, cold) were potentiated against the background of the main stimulus; and that can lead to increase of the main stimulus effect [125, 126].

ROF was realized at various levels of organism, — from the whole organism level to the cellular, subcellular, and even molecular level. The latter levels are rather popular in contemporary studies [134–155]. The difference of our work is in the comparison and finding relations between the effects at those lower levels of organization and the level of organs and whole organism.

Elevation to heights above 8000 m a.s.l. was possible both due to the adaptation to hypoxia as well as due to the initiation of metabolic program that was "hided" at the genetic level after birth and could be activated in critical situations [122]. Adaptation to the conditions of mountain heights was possible up to the level of 5500 m a.s.l., however, at higher levels, the economization of the body functions did not occur. The individual features of adaptability, genetically determined mechanisms, possibilities of their correction using methods of hypoxytherapy, cold effects, vitamin therapy, diet therapy, etc., were very important in ROF determining. [122, 124–126].

The authors of this article in process of their researches had invented, perfected and applied some biotechnological methods, devices with specific detectors, and bioinformation systems [128–131] linked with databases with different biological information of different levels of biological organisms, their organs, molecular and biochemical peculiarities, etc. [128, 130, 131].

We had already published briefly the results of mathematical modeling of structural and functional interdependencies of organisms in extreme conditions [125, 126]. In this publication we suggest more information about all fulfilled investigations of structural and functional interdependencies of organisms in high mountain conditions and their analysis. Results of mathematical modeling coincide with the results obtained in experiments and observations.

The best confirmation of the effectiveness of the proposed methods of selection and preparation of alpinists, and correction of their training process was 100% result of successful ascent to the highest peak in the world by all ten athletes selected at the EMBS and included to the Himalayan expedition on 1999. This unique success was ensured in great degree by full mutual understanding between all participants of the expedition, high professionalism of the members of complex scientific group and coaching council, as well as due to the successful implementation of agreed medical and coaching recommendations during three years. This practical application of the proposed method of structural and functional analysis can be useful also in order to find the most optimal solution to problems that require coordination, control, and cross-functional interaction of all links of processes in some systems where biological and technical components were unite combined.

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СТРУКТУРНО-ФУНКЦІОНАЛЬНІ ВЗАЄМОЗАЛЕЖНОСТІ В ОРГАНІЗМАХ ЗА ЕКСТРЕМАЛЬНИХ УМОВ

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Дослідження адаптації до різноманітних екстремальних факторів надзвичайно важливі.

Мета. Охарактеризувати та проаналізувати результати дослідження структурно-функціональних взаємозалежностей організмів в екстремальних умовах.

Методи. Порівняльний аналіз зареєстрованих біохімічних, фізіологічних характеристик, математичне моделювання на їх основі; інформаційно-комп'ютерні технології.

Результати. Зміни у функціях організмів в процесі адаптації спричиняли зміни деяких їхніх структур. Підтверджено значну роль кількісних і якісних змін системи еритроцитоутворення в надійності забезпечення життєдіяльності організму в екстремальних умовах високогір'я. Зміни еритроцитів і білих кров'яних тілець значною мірою відображають зв'язок між реактивністю і резистентністю організму. Виявлено залежності від ступеня розрідження повітря, режиму підйому, реакцій під час тренування та ін. Адаптивний гемоліз еритроцитів — біологічно активні речовини, що вивільняються з клітин крові, виступають як месенджери, тригери, здатні змінювати клітинний метаболізм. Вони відігравали значну роль у надійності функціонування організму. Розроблено набір програмних моделей для підготовки спортсменів до високогірного сходження.

Висновки. Проаналізовано результати дослідження структурно-функціональних взаємозалежностей організмів в екстремальних умовах. Результати математичного моделювання збіглися з результатами, отриманими в процесі досліджень і спостережень. У процесі адаптації до гіпоксії організм людини поводився як ультрастабільна система. Отримані результати можуть бути застосовані на практиці, наприклад, для контролю біотехнологічних процесів.

Ключові слова: структурно-функціональні взаємозалежності організмів; теоретичний аналіз; порівняльний аналіз; математична модель; адаптація; гіпоксичний стан.