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MATHEMATICAL MODEL OF CONFLICT-CONTROLLED PROCESSES IN SELF-ORGANIZATION OF RESPIRATORY SYSTEM

***Introduction**. Various processes going in surrounding environment are controlled, i. e. their states are determined depending on the specific influence of controlling party. At the same time, it is natural to try to choose the optimal controlling influence that would be the best in comparison with other possible controlling methods. Intensive development of the theory of optimal solutions with computers use has obtained the ability to perform complex calculations and realize the rules of control due to the development of computational technology.*

The problem of identifying and studying of the nature of self-organization mechanisms of processes going in organism, the disclosure of the laws of control that operate in it actually arises during the investigation of living systems. Problem solution of self-organization process knowing for these controlled objects should be carried out using the methods of mathematical modeling. Peculiarities of setting problems of control for functionally-organized systems can be conveniently examined on the example of processes going in living organism when the achievement of certain goals is ensured.

The purpose *of the paper is to create the mathematical model of functional respiratory system for the investigation of self-organization mechanisms in human organism in response to extreme disturbances.*

Methods. *The usual nonlinear differential equations are used for process description; they describe the mass transfer and mass exchange of respiratory gases flowing along all their ways in organism.*

Results. *Mathematical model of functional respiratory system has been developed to study the current functional state and to predict the mechanisms of self-organization of respiratory system in adapting to the disturbing influences of external and internal environment based on the problem of optimal control and taking into account the conflict situation between the self-regulating organs — controlling and executing.*

Conclusions. *Mathematical model of functional self-organization of respiratory and blood circulatory systems is proposed, which takes into account the interaction and inter-influence of organism functional systems, conflict situations between controlling and executive elements of self-regulation; it is based on the assumption of optimal regulation of oxygen regimes. The model may be useful for solving a number of applied problems of physiology and medicine.*

Keywords: *Functional respiratory system, controlled dynamic system, self-organization of respiratory system, operators of continuous interaction system, disturbing influence of environment.*

INTRODUCTION

Mathematical modeling is a unique and powerful tool used for the investigation of physiological processes. It allows to deepen significantly our knowledge of studied phenomena, to form fundamentally new ideas about these phenomena, to identify a wide range of system responses during model parameters changing, to propose new hypotheses that could be studied experimentally and to identify new fundamental classes of phenomena. It can even be argued that along with experimental physiology, an independent branch of physiology is developing already — mathematical physiology, which is a specific source of a new knowledge about the nature of physiological processes. Even relevant textbooks have been written now on this subject [1]. Let's note that realistic computer models are the means of integrative description of a single subsystem and they take into account the relationships and interactions between different functional systems at different levels and time scales.

Taking into account as well that the possibilities of experimental approaches applying to the study of processes occurring in the respiratory and blood circulatory system are significantly limited, the development of effective software and algorithmic tools for numerical modeling and conducting of a full-scale computational experiment is particularly important.

Widespread computerization has substantiated the base for the development of theoretical bases for any phenomenon or process by simulating that phenomenon or process using computer. It is clear that the development of computer model follows the development of mathematical model. This is especially true for physiology and medicine. If in physics and chemistry the experimenter deals with inanimate objects with which any experiments could be carried out, then in addition to ethical norms, there are many other limitations associated with the impossibility of experimenting with various extreme perturbations and limitations of modern invasive methods. The complexity of the problem of mathematical models constructing for functional systems of organism is primarily due to the extreme complexity of examined biological system, the functioning of which nonlinearly depends on many factors, almost every element of living organism and these dependencies remain informal even at physiological level of description. Therefore, analytical methods of solutions have a rather narrow sphere of their use, and the main means for investigation of real problems linked with the respiratory and blood circulatory systems studying are computational methods of problems solving by computer.

PROBLEM STATEMENT

The determining factors for choosing and formulating a mathematical model are the object, purpose, method and means of modeling [2]. Methods of dynamic systems theory are used for mathematical modeling. Means are differential and difference equations, methods of qualitative theory of differential equations, computer simulation. The purposes of mathematical modeling of organism functional systems are represented on Fig.1.

The main principle of complex systems mathematical modeling is the principle of optimality [3]. In [4] works related to extreme principles in mathematical biology were observed.

According to [5], two approaches are used for mathematical analysis of physiological functions — data models and system models. In the first case, the task is to build a mathematical function that describes as accurately as possible a set of input data, like statistical data model. This does not take into account the physiological features of structural and functional organizations of modeled object.

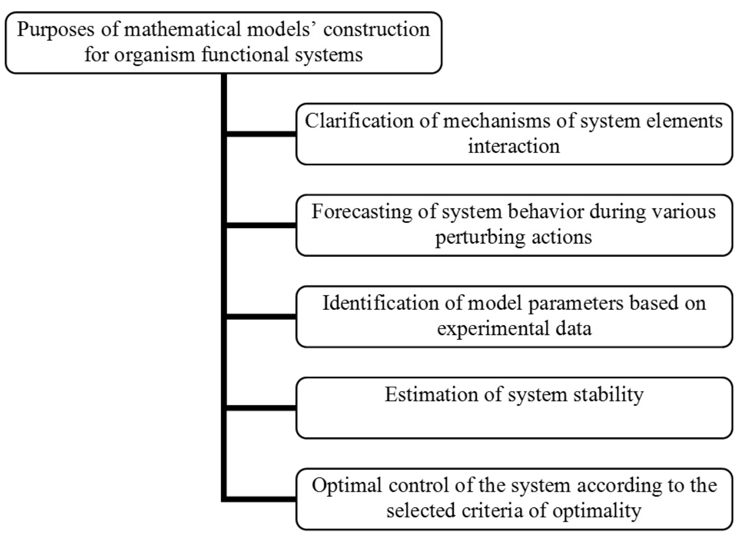

Fig. 1. Purposes of organism functional systems modelling

Models of the second type are based on physiological principles and hypotheses about the structural and functional organization of modeled object. The purpose of modeling is to check the physiological hypothesis in base of the model and to elucidate the physiological mechanisms that underlie studied phenomenon or process. It should be noted that usually the results of physiological experiment analysis with the construction of data models are used as initial data for the next stage of research — the system analysis of these data models and development of mathematical model of the system functioning; it is directed on studying of the fundamental physiological mechanisms put in base of its functioning.

We would like to emphasize the following item. It has been already mentioned above that there is a lot of publications linked with modeling of separated subsystems as well as a whole organism [1]. Following papers have been published recently concerning mathematical models of respiratory and blood circulatory systems [6–25]. However, all these studies were based on complex mathematical apparatus, that was very difficult in practical use. These studies were rather more theoretical and they could be attributed to recently formed field — mathematical physiology. An approach to modeling, which supposes the use of developed models to solve applied problems in physiology and medicine has been proposed in present article.

As a rule, biological systems are self-organized systems that have controlling subsystems developed in the process of evolution; which provide the normal course of processes occurring in the system and executing of their functions within appropriate limits of disturbances. Classical theory of control offers now the whole class of mathematical models that describe the type of control of moving objects, if there is known the ultimate goal of control to be achieved by these objects, limited region of control parameters, as well as criterion of quality of control.

The self-organized systems are distinguished in the class of controlled dynamical systems, i.e. the systems that have the ability to transform the system into a state in which this influence becomes insignificant in response to the disturbing influence. The biosystems and homeostatic systems belong to such systems. Stationary solutions of dynamic systems of such objects are asymptotically stable. And, although the optimality of such systems is denied by some authors, it is always possible to define the purpose of self-organization as the ability to maintain an equilibrium state during disturbances coming to this system.

PURPOSE OF THE PAPER

Purpose of the paper is to develop a mathematical model of functional systems of respiration and blood circulation; the model that take into account the interaction and inter-influence of organism functional systems, conflict situations between controlling and executive organs of self-regulation and based on the assumption about the optimality of regulation of organism oxygen regimes.

PROBLEM SOLUTION

Methods of the theory of optimal control of respiration have aroused the constant interest of researchers of physiological systems, primarily due to the ideas about perfection of regulatory mechanisms in living systems. The specificity of application of the methods of optimal control theory into the study of physiological systems is that the criteria for their optimality are unknown. The task of the study is to determine whether a given physiological system is an optimal control system and what is the criterion for its optimality. Accordingly, such studies include the following steps:

– selection of object under the control and creation of its mathematical model;

– selection of hypothetical criterion of optimality basing on the data of experimental studies;

– creation of mathematical model of the system of optimal control, which includes the controlling subsystem (optimizer) and object of control;

– examination of the model of control in order to verify its adequacy.

Significant difficulties appear at each stage they were both of experimental and theoretical nature.

Therefore, the number of the works on this issue is insignificant and they have appeared recently [26].

The criterion of optimality are most often the indicators that are somehow related to the energy of organism, because the efficiency of physiological functions is not in doubt in general case. The model of regulation of parameters of organism external respiration and blood supply developed by Yu. N. Onopchuk was based on the assumption of optimality in system regulation by organism oxygen regimes [27].

Let's observe a class of nonlinear dynamic systems, the structure of which contains m regions of utilization and creation of matter, linked with the system by transport pipeline network, which delivers this matter to the regions with special carrier. Usually, mathematical models that describe the processes that occur in such systems are balance-type models. It is assumed that in the pipeline system, the delivery of the substances, which can be both in dissolved form and chemically bound to other substances of the carrier, is carried out by forced convection. The transitions of the carrier to the region, or from the region to carrier are occurred by diffusion.

Let's denote by x the concentration of the substance in carrier, x_{i+1} in a given region (i — are negative indices), u_{i+1} — volumetric velocity of carrier in the region. Then the technological process of delivery and utilization of this substance in the chain "carrier-region" under consideration can be written by the system of differential equations [28]:

$$\frac{dx_i}{d\tau}=\frac{a_{1_i}u_i(y-x_i)+a_{2_i}u_i(\varphi(y)-\varphi(x_i))-a_{3_i}(x_i-x_{i+1})}{V_i\cdot(\alpha_i+\beta_i\cdot\varphi'(x_i))} \tag{1}$$

$$\frac{dx_{i+1}}{d\tau}=\frac{a_{3_i}(x_i-x_{i+1})-q^0_{i+1}q(x_{i+1})}{V_{i+1}\left(\alpha_{i+1}+\beta_{i+1}\phi'(x_{i+1})\right)}, \tag{2}$$

where V_i and V_{i+1} is the carrier volumes in the region; y is the concentration of the substance in the main pipeline; q_{i+1} is the maximum rate of substance utilization in the region; $q(x_{i+1})$ is a function that adjusts the intensity of utilization of the substance in the region, $\varphi(x_i)$, $\phi(x_{i+1})$ is the chemical activity of organic compounds to the substance under consideration in the carrier and region, $\alpha_{1_i}, \alpha_{2_i}, \beta_{1_i}, \beta_{2_i}, a_{1_i}, a_{2_i}, a_{3_i}$ are positive coefficients that characterize the solubility of the substance in the carrier and region, diffusion of the substance between the carrier and region, chemical properties of the compounds of the carrier and the environment of the region.

Let's suppose that $\varphi(z)$, $\phi(z)$ $q(z)$ — nonlinear functions of S type. In this case, let's assume that $\mu(z)$ — nonlinear function in the domain $z \geq 0$ refers to S type, if in this domain it is smooth, non-decreasing and

$$\lim_{z\to+0}\mu(z)=0, \quad \lim_{z\to+\infty}\mu(z)=1, \tag{3}$$

$$\lim_{z\to+0}\mu'(z)=0, \quad \lim_{z\to+\infty}\mu'(z)=1. \tag{4}$$

In addition, it is assumed that among m regions there is one region (for certainty, we assume that the first, i.e. the one for which $i=1$) which is responsible for ensuring the circulation of the carrier in closed network of magisterial pipelines with volumetric velocity

$$u=\sum_{i=1}^{m}u_i. \tag{5}$$

Let's assume as well that the utilization of the substance in the region is accompanied by a given amount of work performed in the region. So, it is natural to assume that the rate of utilization of the substance in the first region is a function of the rate provided by this region:

$$q_2^0=f(u) \tag{6}$$

and the rate of utilization of the substance q_{i+1}^0 ($i=3,5,....$) for other regions is constant, which corresponds to the given level of energy consumption in the region.

Thus, we suppose a system of regions connected by the network of pipelines to ensure the delivery of energetic substance, and utilization of this substance in the regions is carried out to perform their functions. The external perturbation for this system is the concentration of the substance in the main pipeline and ensuring the directional movement of the carrier in it is placed on the first region.

Models of this type describe many of technological, physical, chemical, environmental processes that are usually stable. The questions of the existence, unity and stability of the solutions of the model (1), (2) are practically important, especially at the stage when the idea of trust in the results of modeling of particular process or system is formed.

In article [29] the following properties of the solutions of the system (1), (2) at $\varphi(x), \phi(x), q(x)\in C^2[0,\infty)$, were proved, which satisfy (3), (4) under the conditions: $y=\text{const}>0$, $n_i=\text{const}>0$, $i=2k-1$, $k=\overline{1,m}$.

Under the given at initial time $\tau_0 x_i(\tau_0)=x_i^0\geq 0$, $\tau_0 x_{i+1}(\tau_0)=x_{i+1}^0\geq 0$, $i=2k-1$, $k=\overline{1,m}$ the system (1), (2) has a unique solution $x\left(\tau, x_i^0, x_{i+1}^0, i=2k-1, k=\overline{1,m}\right)$.

The solution of the system (1), (2) is non-negative under non-negative initial conditions.

The solution of the system (1), (2) with non-negative initial data is limited from above.

The system (1), (2) has a single stationary solution $\{\overline{x}_i, \overline{x}_{i+1}, i = 2k-1, k = \overline{1,m}\}$.

The stationary solution (1), (2) is asymptotically stable.

The dynamic system (1), (2) can be considered as controlled, if the control effects cause the volumetric velocities u_i, $i = \overline{1, 2m-1}$ of the carrier in the pipeline system.

Concerning the system (1), (2), we should not talk about controllability, but about the self-organization of the system, which is aimed at maintaining of some states of the system. The choice of u_i in this type of systems should cause the compensation of disturbing effects on the system, to its transfer to some other stationary motion, which corresponds to influences on the system.

Let's write the conditions of stationarity for the system (1), (2). Any stationary trajectory satisfies the condition

$$x_i - x_{i+1} = \frac{q^0}{a_{3_i}} q_{i+1}(x_{i+1}), \quad i = \overline{1, 2m-1},$$

which means that the positive difference $x_i - x_{i+1}$ in stationary motion is set in accordance with the level of utilization of the substance in this region. Therefore, any change in the value of q^0_{i+1} should be perceived as perturbation influence on the system, and the problem of control can be considered as a problem of optimal (for example, in time) response of the system to the transition to a new stationary motion. The change in the concentration of the substance y in the main pipeline can be interpreted similarly.

To solve the control problem in practice, it suffices to require that in the presence of perturbations the system (1), (2) to be transited into such a motion (close to stationary), which is determined by the set $M(t)$ that for all $\tau > t$ for all τ at the same time the condition below was satisfied

$$\frac{q^0_{i+1}}{a_{3_i}} q_{i+1}(x_{i+1}) - \varepsilon < x_i(\tau) - x_{i+1}(\tau) \le \frac{q^0_{i+1}}{a_{3_i}} + \varepsilon. \tag{7}$$

It can be shown [30] that under the influence of constant perturbations $q^0_{i+1} > 0$, $y > 0$ on the system (1), (2), any set $n_i > 0$ will transform the system in $M(t)$ for a finite time.

In process of examination of physiological and biological processes, it is advisable as a criterion for quality of control to choose an integrated criterion of following type

$$I(u) = \int_{\tau}^{\infty} \sum_i \sigma_i [a_{3_i}(x_i - x_{i+1}) - q^0_{i+1} q(x_{i+1})]^2 \, d\tau \tag{8}$$

and to solve the optimization problem with simple constraints for the control:

$$\underline{n}_i \le n_i \le \overline{n}_i . \qquad (9)$$

The coefficients σ_i in (8) can be considered as the values of sensitivity of the region to deficit or excess of the substance, because in square brackets there is the expression of the differences between the rates of entry and utilization of the substance in the region.

Since the control task is to output the perturbations of the system in the ε -tube of stationary trajectory, the upper limit in (8) can be replaced by a finite number T .

Let's suppose that in the system with forced ventilation there are the mass transfers of three substances. One of them was utilized in the region, and the others were produced. The concentration of these three substances transported in the dispersed medium of main channel is maintained at constant levels. The dispersed medium contains two carriers-adsorbents, which form the dispersed phase of circulating mixture. One carrier carries only one substance, the other one — two substances simultaneously.

The third substance is transported only in dissolved form. All three substances can diffuse through the phase distribution surface. Sorbent located in a region, can bind a substance that is carried by only one carrier in regional channel, and that is utilized in parallel with the production of another substance. One example of such a system may be the blood gas transfer system to the tissues.

Let's consider the blood of regional channels as circulating mixture — generalized tissue capillaries, in regions — tissue cylinders, substances that transport oxygen, carbon dioxide and nitrogen. So, the state of this system will be characterized by the levels of partial pressures of these gases in dispersed medium, i.e. blood plasma and tissue reservoirs, which depending on the rate of oxygen utilization can be regulated under the given conditions of internal or external environment by changing the volumetric flow rate of the circulating mixture (blood in the main and regional channels). Experimental studies have demonstrated that in some disturbances of the environment — reducing the partial pressure of gases, increasing the rate of oxygen utilization and etc. — the role of mechanisms that regulate circulation, in stabilizing the system parameters is the main. The methods of mathematical modeling and apparatus of the theory of automatic regulation are successfully used in studying the rules of these mechanisms functioning under the different conditions. Studies also have shown that any of known basic regulatory schemes cannot explain the compensating reaction, regulation of self-organization of processes occurring in the system — direct or feedback control, perturbation control and etc.

In general, the equations of the dynamics of partial pressures and stresses of respiratory gases pO_2, pCO_2 and pN_2 in respiratory tract, alveolar space, arterial and mixed venous blood, blood tissue capillaries and tissues were built on the principles of material balance and continuity of flow are as follows [31] – [33]:

$$\frac{dp_iO_2}{d\tau} = \varphi(p_iO_2, p_iCO_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}O_2, q_{t_i}O_2) \qquad (10)$$

$$\frac{dp_iCO_2}{d\tau} = \psi(p_iO_2, p_iCO_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}CO_2, q_{t_i}CO_2), \qquad (11)$$

where the functions φ and ψ were described in detail in [31] – [33]; $\dot{V}$ is the ventilation; η is the degree of oxygen saturation of hemoglobin; Q is the volumetric rate of systemic and Q_{t_i} local blood circulation; $q_{t_i}O_2$ is the rate of oxygen consumption by ith tissue reservoir; $q_{t_i}CO_2$ is the rate of carbon dioxide release in ith tissue reservoir. The flow rate $G_{t_i}O_2$ of oxygen from the blood into the tissue, and $G_{t_i}CO_2$ carbon dioxide from the tissue into the blood is determined by the ratio

$$G_{t_i} = D_{t_i}S_{t_i}(p_{ct_i} - p_{t_i}),$$

where D_{t_i} is the gas permeability coefficients through the air barrier, S_{t_i} is the gas exchange surface area.

The participation of biochemical structures — hemoglobin, myoglobin and buffer bases in processes of mass transfer of gases add significant nonlinearity in the system of differential equations. Naturally that all these cause serious difficulties for mathematical analysis of dynamic system, but there is very powerful mechanism for maintaining of gas homeostasis of organism, and from the standpoint of theory of control — the mechanism of control.

All the values that characterize the process of mass transfer of gases in living organism are non-negative and limited, moreover, the limits of changes of some of them are quite narrow. The theory of mathematical modeling requires usually a qualitative study of the models to determine the area of adequate description of the studied process. We need to be sure in the existence and unity of the solutions of the system of equations and to study the nature of these solutions.

In article [30] the following statements were proved.

1) For given at the initial moment of time τ_0 $p_{j_{ct_i}}(\tau_0) = p^0_{j_{ct_i}} > 0$, $p_{j_{t_i}}(\tau_0) = p^0_{j_{t_i}} > 0$, $j = \overline{1,3}$, $i = \overline{1,m}$ there is only one solution of the system (10), (11) $p(\tau, p^0_{j_{ct_i}}, p^0_{j_{t_i}}, j = \overline{1,3}, i = \overline{1,m}$.

2) If $\lim\limits_{p_{j_{t_i}} \to 0} q_{j_{t_i}} = 0$, $q_{j_{t_i}} = 0$, when $p_{j_{t_i}} = 0$ then the solution of the system (10), (11) is positive under positive initial conditions.

3) The solution of system (10), (11) is limited from above in the conditions of statement 1.

4) The system (10), (11) has a unique stationary solution for $p_{j_a} = \text{const}$, $j = \overline{1,3}$, $Q_i = \text{const}$, $i = \overline{1,m}$.

5) The stationary solution of the system (10), (11) is asymptotically stable.

There are two main types of models of regulation of blood circulation are possible to be selected [27], [29]. To the first one it is expedient to relate those models at which construction the principles of the theory of automatic regulation were used. The choice of values of systemic and local blood circulation as control parameters is aimed on the eliminating of respiratory gas stresses deviations from the "setpoint" values that occur when the system is disturbed. It is necessary to know these values for each specific type of environmental conditions, the level of functional loading etc. Such models are effective in practice, but they do not allow revealing the causal-consequential links of regulation. The second type of models includes more general models of gas dynamics control in organism using the principle of maximum by Pontryagin [34].

However, the calculated data differed from those obtained experimentally. In addition, the calculated data did not answer a number of theoretical and applied questions. For example, they did not explain the reasons of tissue hypoxia during muscle work of low intensity, staying in hypoxic environment (when the reserves for the growth of systemic circulation are present still), the role of hypercapnic regulatory stimulus at hypoxia of loading known in physiology, hypoxic hypoxia etc.

The model proposed in [31] – [33] and developed for these problems solutions was based on following principles:

– modeled system is considered as self-organized, respectively, the model was also formulated as a model of blood circulation self-organization. Self-organization means the ability of the model when the perturbations to change the system parameters were such as, that the effect of perturbations was insignificant. At the same time, certain quality criteria should be minimized.

– the control in such systems should be carried out with the resolution of conflict situations of various natures that appear.

We formulate the problem of system control (10), (11) as follows. It is necessary to transmit the perturbed dynamical system (10), (11) into the multitude

$$M(\tau)=\begin{cases} \dfrac{\dot{q}_{t_i}\mathrm{O}_2\cdot\tau-\varepsilon_i^{\mathrm{O}_2}}{n_{t_i}\mathrm{O}_2\cdot k_{t_i}\mathrm{O}_2\cdot S_{t_i}}\le\displaystyle\int_{\tau_0}^{\tau_0+\tau}(p_{ct_i}\mathrm{O}_2-p_{t_i}\mathrm{O}_2)d\xi\le\dfrac{\dot{q}_{t_i}\mathrm{O}_2\cdot\tau+\varepsilon_i^{\mathrm{O}_2}}{n_{t_i}\mathrm{O}_2\cdot k_{t_i}\mathrm{O}_2\cdot S_{t_i}}, \\ \dfrac{\dot{q}_{t_i}\mathrm{CO}_2\cdot\tau-\varepsilon_i^{\mathrm{CO}_2}}{n_{t_i}\mathrm{CO}_2\cdot k_{t_i}\mathrm{CO}_2\cdot S_{t_i}}\le\displaystyle\int_{\tau_0}^{\tau_0+\tau}(p_{ct_i}\mathrm{CO}_2+p_{t_i}\mathrm{CO}_2)d\xi\le\dfrac{\dot{q}_{t_i}\mathrm{CO}_2\cdot\tau+\varepsilon_i^{\mathrm{CO}_2}}{n_{t_i}\mathrm{CO}_2\cdot k_{t_i}\mathrm{O}_2\cdot S_{t_i}}, \\ -\varepsilon_i^{N_2}\le\displaystyle\int_{\tau_0}^{\tau_0+\tau}(p_{ct_i}N_2-p_{t_i}N_2)d\xi\le\varepsilon_i^{N_2}, \end{cases} \quad (12)$$

with minimum of functional:

$$I=\int_{\tau_0}^{\tau_0+T}\sum_{i=1}^{m}[\rho_1\lambda_1(G_{t_i}O_2-q_{t_i}O_2)^2+\rho_2\lambda_2(G_{t_i}O_2+ \\ q_{t_i}CO_2)^2+\rho_3\lambda_3(G_{t_i}N_2)^2]d\tau, \quad (13)$$

where ρ_1,ρ_2,ρ_3 are coefficients that characterize the sensitivity of particular organism to oxygen deficiency, excess of carbon dioxide, and increase of nitrogen concentration, respectively; λ_t are coefficients that reflect the functional and morphological features of particular region.

Restrictions are imposed on control parameters:

$$0 \le Q_i \le Q, \quad i = \overline{1,m}. \tag{14}$$

The multitude $M(\tau)$ is a terminal multitude of states of the system, which has a homeostatic property — gas stresses were set at certain level, the rates of oxygen utilization and carbon dioxide removal corresponded to the rates of oxygen utilization and carbon dioxide removal in all tissue regions of organism. In this case, the moment of time τ is precisely the moment at which this homeostatic property of the system is manifested. Functional (13) is a quality criterion of accepted law of control.

In this problem's formulation of the process of gases mass transfer regulating, we can speak about the optimal choice of volumetric velocity of organism blood circulation in relation to criterion (13). The accepted form of setting the problem of control is consistent with the conceptual models that currently exist in contemporary respiratory physiology. It is important to make sure that the set of solutions to formulated problem is not empty. Also in [30] it was proved that when the system (10), (11) is affected by constant perturbations $\dot{q}_{t_i}\,O_2$, $\dot{q}_{t_i}\,CO_2$, $p_a\,O_2$, $p_a\,CO_2$, $p_a\,N_2$ a number of constants $\dot{Q}_i$, $i = \overline{1,m}$, which satisfy (14) will deduce the trajectories of the system in $M(\tau)$ during finite period of time.

$$q_{ск.м} = \sigma \dot{Q} \gamma, \tag{15}$$

where $\sigma, \gamma > 0$.

Let's note that the formulation of the optimal control problem (10), (11), (9), (12), (13) is such that gas homeostasis is understood as the relative constancy of oxygen, carbon dioxide and nitrogen stresses. It consists on the compromise formation of corresponding homeostasis levels to the disturbance in resolution of conflicts of both regional and systemic nature. The Fick ratio can be used to calculate how much it is necessary to increase the volume of blood circulation through the working skeletal muscles in order to maintain oxygen tension in them at constant level. When comparing the calculated data with the experimental ones, it was appeared that the first ones exceed the experimental values significantly. According to the proposed model, this is due to ignoring the nature of conflict that arises in organism between the groups of functioning tissues and the heart muscle, which provides the necessary cardiac output. In fact, such situations occur every time with the changes of organism living conditions. An increase in muscle intensity requires corresponding increase in blood circulation in muscles (otherwise there will be oxygen deficiency in the muscles) and it can be achieved by changing the systemic circulation or its redistribution. In the first case, the intensity of the heart muscle increases (because oxygen deficiency arise in it), in the second — the decrease in blood circulation in tissue reservoirs of other organs appears, which at a constant rate of oxygen consumption causes hypoxia development in tissue. Thus, changing the conditions of external or internal environment to maintain gas homeostasis in one muscle group requires the blood circulation increase, which is contrary to the interests of other tissues, because it causes oxygen deficiency. This conflict resolution is in finding a compromise, in which all tissues, on average, feel oxygen deficiency, and their average oxygen tensions decrease. In the model, this is represented by introduction of heart muscle oxygen consumption rate dependence on the volumetric rate of systemic circulation

$$q_{sc.m} = \sigma \dot{Q} \gamma , \tag{16}$$

where $\sigma, \gamma > 0$. The dependence of the rate of oxygen consumption in tissues of brain, kidneys, liver is determined by Michaelis–Menten ratio

$$q_t \, O_2(\tau) = q_t^0 \, O_2 \frac{p_t \, O_2}{k + p_t \, O_2}, \tag{17}$$

where k is Michaelis constant.

In skeletal muscles, including peripheral tissues, the oxygen consumption rate is determined by the ratio

$$q_t \, O_2(\tau) = q_t^0 \, O_2 \frac{\eta(\tau)}{\eta}, \tag{18}$$

where $q_t^0 \, O_2$ is a rate of oxygen consumption under normal environmental conditions at known intensity of physical activity; η is the degree of saturation of hemoglobin with oxygen in these conditions; $\eta(\tau)$ is the degree of saturation of hemoglobin with oxygen under altered experimental conditions.

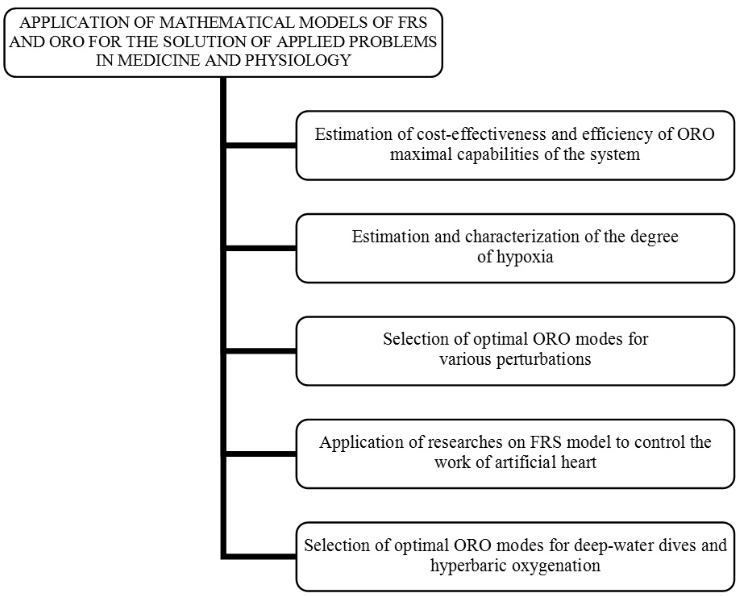

Fig. 2. Application of mathematical models of respiratory system self-organization for the solution of applied problems in medicine and physiology

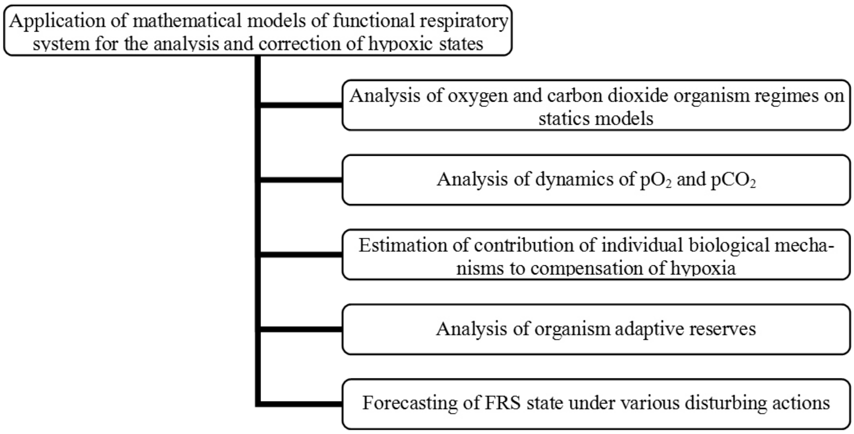

Fig. 3. Application of mathematical models of FRS for analysis and correction of hypoxic states

This model also permits the resolution of conflicts that arise between organism subsystems, which provide hypercapnic, hyperazotic stimulation of respiration due to the quality criterion in the form of criterion (13), which provides a compromise minimization of inconsistencies in flows and utilization (release) of gases in tissues.

This approach to the problem of optimal control for the investigation of self-organization process of the functional respiratory system in adaptation to extreme disturbances has been widely used to solve practical problems in occupational medicine and sports (Fig. 2). In particular, in the authors' investigations with determining the parameters of self-organization of mountain rescuers respiratory systems at mid-term and short-term adaptation to hypoxic hypoxia [35] – [37], and athletes specialized in combat sports [38], [39]. Also, the proposed models could be used for the analysis and correction of hypoxic states as well (Fig. 3).

CONCLUSIONS

The mathematical model of functional system self-organization, which is based on the taking into account the conflict situation between the controlling and executive organs of self-regulation is described in present article. The purposes of the functioning, resource of control, criteria of effective self-organization are defined in present study. This approach has made it possible to solve a number of problems in occupational medicine and sports of the highest achievements, related to the prediction of parameters of self-organization of respiratory and blood circulatory systems in adaptation to extreme environmental disturbances.

REFERENCES

1. Keener J., Sneyd J. Mathematical physiology. Springer-Verlag New York, 1998.
2. Anokhin P.K. Fundamental questions of general theory of functional systems. The principles of systemic organization of the functions. Moscow: Nauka, 1973, 258 p. [In Russian]
3. Balanter B.I. Introduction to mathematical modeling of pathological processes. M .: Medicine, 1980, 262 p. [In Russian]
4. Fursova I.V. Extreme principles in mathematical biology. *Advances in contemporary biology.* 2003,123, 2, pp. 115–117. [In Russian]

5. Mesentseva L.V., Pertsov S.S. Mathematical modeling in biomedicine. *Journal of new medical technologies*. 2013, XX, 1, pp.11–14.
6. Diekman C.O., Thomas P.J., Wilson, C.G. Eupnea, tachypnea, and autoresuscitation in a closed-loop respiratory control model. *J. Neurophysiol*. 2017, 118, pp. 2194–2215. doi:10.1152/jn.00170.2017
7. Duffin, J. Model validation and control issues in the respiratory system. *Mathematical Modeling and Validation in Physiology Lecture Notes in Mathematics*, eds J. J. Batzel, M. Bachar, F. Kappel (Berlin; Heidelberg; Springer), 2013, pp.133–162.
8. Fincham W. F., Tehrani F. T. A mathematical model of the human respiratory system. *J. Biomed. Eng*. 1983, 5, pp. 125–133. doi: 10.1016/0141-5425(83)90030-4
9. Serna Higuita L.Y., Mañanas M.A., Hernández A.M., Marína Sánchez J., Benito S. Novel modeling of work of breathing for its optimization during increased respiratory efforts. *IEEE Syst. J.* 2014, 10, pp. 1003–1013. doi: 10.1109/JSYST.2014.2323114
10. Serna L.Y., Marín J., Hernández A.M., Mañanas, M.Á. Optimization techniques applied to parameter estimation in respiratory control system models. *Appl. Soft Comput*. 2016, 48, pp. 431–443. doi: 10.1016/j.asoc.2016.07.033
11. Tsai N. C., Lee R. M. Interaction between cardiovascular system and respiration. *Appl. Math. Model*. 2011, 35, pp. 5460–5469. doi: 10.1016/j.apm.2011.04.033
12. Serna L.Y., Mañanas M.A., Hernández A.M., Rabinovich R.A. An Improved Dynamic Model for the Respiratory Response to Exercise. *Front. Physiol*. 2018, 9.69. DOI: 10.3389/fphys.2018.00069
13. Ellwein Fix L., Khoury J., Moores R.R.Jr., Linkous L., Brandes M., Rozycki H.J. Theoretical open-loop model of respiratory mechanics in the extremely preterm infant. *PLoS ONE* .2018, 13(6): e0198425. https://doi.org/10.1371/journal.pone.0198425
14. Ebrahimi Nejad S., Carey J.P., McMurtry M.S., Hahn J.-O. Model-based cardiovascular disease diagnosis: a preliminary in-silico study. *Biomech Model Mechanobiol.* 2017, 16, pp. 549–560 (2017). https://doi.org/10.1007/s10237-016-0836-8
15. Quarteroni A, Formaggia L. Mathematical modelling and numerical simulation of the cardiovascular system. *Handb Numer Anal.* 2004, 12:7–9. DOI: 10.1016/S1570-8659(03)12001-7
16. Quarteroni A., Manzoni A., Vergara C. The cardiovascular system: mathematical modelling, numerical algorithms and clinical applications. *Acta Numer.* 2017.26.365–590. DOI: https://doi.org/10.1017/S0962492917000046
17. Capoccia M., Marconi S., Singh S.A., Pisanelly D.M., De Lazzari C. Simulation as a preoperative planning approach in advanced heart failure patients. A retrospective clinical analysis. *BioMed Eng OnLine.* 2018, 17, 52 . https://doi.org/10.1186/s12938-018-0491-7
18. Korobov A.A., Frolov S.V., Aliyev N.E., Rodionova I.E. Dual-contoured model of cardiovascular system regulation. *J. Phys.: Conf. Ser.* 2020, 1553 012006 DOI:10.1088/1742-6596/1553/1/012006
19. Albanese A., Cheng L., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model development. *Am J Physiol Heart Circ Physiol.* 2016, Apr 1;310(7):H899-921. doi: 10.1152/ajpheart.00230.2014.
20. Cheng L., Albanese A., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model validation under hypercapnia and hypoxia. *Am J Physiol Heart Circ Physiol.* 2016, Apr 1;310(7):H922-37. DOI: 10.1152/ajpheart.00923.2014
21. Sarmiento C.A., Hernández A.M., Serna L.Y., Mañanas M.Á. An integrated mathematical model of the cardiovascular and respiratory response to exercise: model-building and comparison with reported models. *Am J Physiol Heart Circ Physiol.* 2021, Apr, 1;320(4):H1235-H1260. doi: 10.1152/ajpheart.00074.2020.
22. Trenhago P.R., Fernandes L.G., Müller L.O., Blanco P. J., Feijóo R.A. An integrated mathematical model of the cardiovascular and respiratory systems. *Int. J. Numer. Methods Biomed. Eng.* 32 2016, no. 1, e02736, 25 pp.
23. Zhou S, Xu L, Hao L, Xiao H, Yao Y, Qi L, Yao Y. A review on low-dimensional physics-based models of systemic arteries: application to estimation of central aortic pressure. *Biomed Eng Online.* 2019, Apr 2;18(1):41. doi: 10.1186/s12938-019-0660-3.

24. Maury B. The Respiratory System in Equations. Springer. 2013, 278 p. DOI:10.1007/978-88-470-5214-7
25. Fouchet-Incaux, J. Artificial boundaries and formulations for the incompressible Navier–Stokes equations: applications to air and blood flows. *SeMA*. 2014, 64, pp.1–40. https://doi.org/10.1007/s40324-014-0012-y
26. Bobryakova I. L., "Sensitivity of mathematical model and optimality of regulation of the functional respiratory system," *diss. Candidate of Physical and Mathematical Sciences Sciences*, Kyiv, 2000, 179 p. [In Russian]
27. Onopchuk Yu.N. About one scheme of regulation of external respiration modes, minute blood volume and tissue blood flow at oxygen request. *Cybernetics*. 1980, No. 6, pp. 110–115 [In Russian]
28. Onopchuk Yu.N. On the construction of model for optimal distribution of blood flow in human tissues and organs — In the book: *Theory of optimal solutions.* Kyiv, 1979, pp. 80–86 [In Russian]
29. Onopchuk Yu.N. Controlled models of organism gas dynamics and their numerical analysis. Dis ... ..doct. phys.-mat. sciences. Kyiv, 1984, 208 p. [In Russian]
30. Onopchuk Yu. N., "Equilibrium states and transients in the systems of external respiration and blood circulation. Research on a mathematical model," *Cybernetics*. 1981, no. 1, pp. 136–139. [In Russian]
31. Onopchuk Yu. N. Homeostasis of functional respiratory system as a result of intersystem and system-medium informational interaction. *Bioecomedicine. Uniform information space. Ed. by V. I. Gritsenko*. Kyiv, 2001, pp. 59–84. (In Russian).
32. Onopchuk Yu. N. Homeostasis of the functional circulatory system as a result of intersystem and system-medium informational interaction. *Bioecomedicine. Uniform information space. Ed. by V. I. Gritsenko.* Kyiv, 2001, pp. 85–104. (In Russian).
33. Aralova N. I. Mathematical models of functional respiratory system for solving the applied problems in occupational medicine and sports. Saarbrücken: LAP LAMBERT Academic Publishing GmbH&Co, KG. 2019, 368 p. (In Russian). ISBN 978-613-4-97998-6
34. Pontryagin L.S., Boltyansky V.G., Gamkrelidze R.V., Mishchenko E.F., Mathematical theory of optimal processes. Moscow: Nauka. 1983, 392 p.
35. Aralova N. I. Mathematical model of the mechanism short- and medium-functional adaptation of breath of persons work in extreme conditions high. *Kibernetika i vychislitelnaya tekhnika.* 2015, V. 182, pp. 15–25.
36. Onopchuck Y. N., Beloshitsky P. V., Aralova N. I. To problem of reliability of functional systems in organism. *Kibernetika i vychislitelnaya tekhnika.*1999, V. 122, pp. 72–82. ISSN - 0454-9910. (In Russian).
37. Beloshitsky P. V., Onopchuk Yu. M., Aralova N. I. Mathematical methods for the investigation of the problem of organism functioning reliability at extreme high mountains conditions. *Physiol. Journal.*2003,V. 49, № 3, pp. 47–54 (in Russian).
38. Aralova N. I. Information technologies of decision-making support for rehabilitation of sportsmen engaged in combat sport. *J. Automation Information Sci.* 2016, V. 3, pp. 160–170. https://doi:10.1615 / JAutomatInfScien.v48. i6.70
39. Onopchuk Yu.N., Aralova N.I., Beloshitsky P.V., Podlivaev B. A., Mastycash Yu. I. Forecasting of wrestler' state in the combat on the base of mathematic model of functional respiratory system. *Computer mathematics.* 2005, № 2, pp. 69–79 (In Russian)

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ЛІТЕРАТУРА

1. Keener J., Sneyd J. Mathematical physiology. Springer-Verlag New York, 1998.
2. Анохин П.К. Принципиальные вопросы общей теории функциональных систем. Принципы системной организации функций. М.: Наука, 1973. 258 с.
3. Балантер Б.И. Введение в математическое моделирование патологических процессов. М.: Медицина, 1980. 262 с.
4. Фурсова И.В. Экстремальные принципы в математической биологии. *Успехи современной биологии.* 2003. 123, 2. С. 115–117.

5. Мезенцева Л.В., Перцов С.С.Математическое моделирование в биомедицине. *Вестник новых медицинских технологий.* 2013. XX, 1. С.11–14.
6. Diekman C.O., Thomas P.J., Wilson C.G. Eupnea, tachypnea, and autoresuscitation in a closed-loop respiratory control model. *J. Neurophysiol*. 2017.118. C. 2194–2215. DOI: 10.1152/jn.00170.2017
7. Duffin, J. Model validation and control issues in the respiratory system. *Mathematical Modeling and Validation in Physiology Lecture Notes in Mathematics*, eds J. J. Batzel, M. Bachar, F. Kappel (Berlin; Heidelberg; Springer). 2013. C. 133–162.
8. Fincham W. F., Tehrani F. T. A mathematical model of the human respiratory system. *J. Biomed. Eng*. 1983.5. C. 125–133. doi: 10.1016/0141-5425(83)90030-4
9. Serna Higuita L.Y., Mañanas M.A., Hernández A.M., Marína Sánchez J., Benito S. Novel modeling of work of breathing for its optimization during increased respiratory efforts. *IEEE Syst. J.* 2014. 10. C. 1003–1013. doi: 10.1109/JSYST.2014.2323114
10. Serna L.Y., Marín J., Hernández A.M., Mañanas, M.Á. Optimization techniques applied to parameter estimation in respiratory control system models. *Appl. Soft Comput*. 2016. 48. C. 431–443. doi: 10.1016/j.asoc.2016.07.033
11. Tsai N. C., Lee R. M. Interaction between cardiovascular system and respiration. *Appl. Math. Model*. 2011. 35. C. 5460–5469. doi: 10.1016/j.apm.2011.04.033
12. Serna L.Y., Mañanas M.A., Hernández A.M., Rabinovich R.A. An Improved Dynamic Model for the Respiratory Response to Exercise. *Front. Physiol*. 2018. 9.69. DOI: 10.3389/fphys.2018.00069
13. Ellwein Fix L., Khoury J., Moores R.R.Jr., Linkous L., Brandes M., Rozycki H.J. Theoretical open-loop model of respiratory mechanics in the extremely preterm infant. *PLoS ONE 2018*. 13(6): e0198425. https://doi.org/10.1371/journal.pone.0198425
14. Ebrahimi Nejad S., Carey J.P., McMurtry M.S., Hahn J.-O. Model-based cardiovascular disease diagnosis: a preliminary in-silico study. *Biomech Model Mechanobiol.* 2017. 16. C. 549–560. https://doi.org/10.1007/s10237-016-0836-8
15. Quarteroni A, Formaggia L. Mathematical modelling and numerical simulation of the cardiovascular system. *Handb Numer Anal.* 2004.12:7–9. DOI:10.1016/S1570-8659(03)12001-7
16. Quarteroni A., Manzoni A., Vergara C. The cardiovascular system: mathematical modelling, numerical algorithms and clinical applications. *Acta Numer.* 2017.26.365–590. DOI: https://doi.org/10.1017/S0962492917000046
17. Capoccia M., Marconi S., Singh S.A., Pisanelly D.M., De Lazzari C. Simulation as a preoperative planning approach in advanced heart failure patients. A retrospective clinical analysis. *BioMed Eng OnLine.* 2018. 17. 52 . https://doi.org/10.1186/s12938-018-0491-7
18. Korobov A.A., Frolov S.V., Aliyev N.E., Rodionova I.E. Dual-contoured model of cardiovascular system regulation. *J. Phys.: Conf. Ser.* 2020. 1553 012006 DOI:10.1088/1742-6596/1553/1/012006
19. Albanese A., Cheng L., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model development. *Am J Physiol Heart Circ Physiol.* 2016. Apr 1. 310(7):H899-921. doi: 10.1152/ajpheart.00230.2014.
20. Cheng L., Albanese A., Ursino M., Chbat N.W. An integrated mathematical model of the human cardiopulmonary system: model validation under hypercapnia and hypoxia. *Am J Physiol Heart Circ Physiol.* 2016. Apr 1. 310(7):H922-37. doi: 10.1152/ajpheart.00923.2014
21. Sarmiento C.A., Hernández A.M., Serna L.Y., Mañanas M.Á. An integrated mathematical model of the cardiovascular and respiratory response to exercise: model-building and comparison with reported models. *Am J Physiol Heart Circ Physiol.* 2021. Apr 1. 320(4):H1235-H1260. doi: 10.1152/ajpheart.00074.2020.
22. Trenhago P.R., Fernandes L.G., Müller L.O., Blanco P. J., Feijóo R.A. An integrated mathematical model of the cardiovascular and respiratory systems. *Int. J. Numer. Methods Biomed. Eng.* 2016. 32. no. 1, e02736, 25 pp.
23. Zhou S, Xu L, Hao L, Xiao H, Yao Y, Qi L, Yao Y. A review on low-dimensional physics-based models of systemic arteries: application to estimation of central aortic pressure. *Biomed Eng Online.* 2019. Apr 2. 18(1):41. doi: 10.1186/s12938-019-0660-3.

24. Maury B. The Respiratory System in Equations. Springer. 2013. 278 c. DOI: 0.1007/978-88-470-5214-7
25. Fouchet-Incaux, J. Artificial boundaries and formulations for the incompressible Navier–Stokes equations: applications to air and blood flows. *SeMA* 64. 2014. C. 1–40. https://doi.org/10.1007/s40324-014-0012-y
26. Бобрякова И.Л. Чувствительность математической модели и оптимальность регуляции функциональной системы дыхания. дисс. канд.физ.-мат. наук, Киев, 2000. 179 с.
27. Онопчук Ю.Н. Об одной схеме регуляции режимов внешнего дыхания, минутного объема крови и тканевого кровотока по кислородному запросу. *Кибернетика.*1980. № 6. С. 110–115.
28. Онопчук Ю.Н. К вопросу о построении модели оптимального распределения кровотока по тканям и органам человека. В кн.: Теория оптимальних решений. Киев, 1979, с. 80–86.
29. Онопчук Ю.Н. Управляемые модели газовой динамики организма и их численный аналіз Дис…..докт. физ.–мат. наук. Киев, 1984. 208 с.
30. Онопчук Ю.Н. Равновесные состояния и переходные процессы в системах внешнего дыхания и кровообращения. Исследования на математической модели.*Кибернетика.* 1981, № 1. С. 136–139.
31. Онопчук Ю.Н. Гомеостаз функциональной системы дыхания как результат внутрисистемного и системно-средового информационного взаимодействия. *Биоэкомедицина. Единое информационное пространство.*Киев. 2001. С. 59–81.
32. Онопчук Ю.Н. Гомеостаз функциональной системы кровообращения как результат внутрисистемного и системно-средового информационного взаимодействия *Биоэкомедицина. Единое информационное пространство.* Киев.2001. С. 82–104.
33. Аралова Н.И. Математические модели функциональной системы дыхания для решения прикладных задач медицины труда и спорта. Saarbrücken: LAP LAMBERT Academic Publishing GmbH&Co, KG. 2019. 368 с.ISBN 978-613-4-97998-6
34. Понтрягин Л.С., Болтянский В.Г., Гамкрелидзе Р.В., Мищенко Е.Ф. Математическая теория оптимальных процессов. М.: Наука. 1983.392 с. ИБ № 12370.
35. Аралова Н.И. Математическая модель механизмов краткосрочной и среднесрочной адаптации функциональной системы дыхания лиц, работающих в экстремальных условиях Кибернетика *и вычислительная техника.* 2015. Вып. 182. С. 15–25.
36. Онопчук Ю.Н., Белошицкий П.В, Аралова Н.И. К вопросу о надежности функциональных систем организма. *Кибернетика и вычислительная техника.*1999. Вып. 122. С. 72–82.
37. Білошицький П.В., Онопчук Ю.М., Аралова Н.І. Математичні методи дослідження проблеми надійності функціонування організму за екстремальних умов високогір’я *Фізіол.журнал.* 2003.Т. 49. № 3. С. 47–54.
38. Aralova N. I. Information technologies of decision-making support for rehabilitation of sportsmen engaged in combat sport. *J. Automation Information Sci.* 2016. V. 3. P. 160–170. https://doi:10.1615 / JAutomatInfScien.v48. i6.70
39. Онопчук Ю.Н., Аралова Н.И., Белошицкий П.В., Подливаев Б.А., Мастыкаш Ю.И. Прогнозирование состояния борца в процессе поединка на основе математической модели функциональной системы дыхания. *Компьютерная математика.* 2005. № 2. С. 69–79.

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МАТЕМАТИЧНА МОДЕЛЬ КОНФЛІКТНО-КЕРОВАНИХ ПРОЦЕСІВ ПРИ САМООРГАНІЗАЦІЇ СИСТЕМИ ДИХАННЯ

Вступ. Різноманітні процеси, які відбуваються в середовищі, є керованими, тобто їх стан визначається в залежності від конкретного впливу системи, яка керує. Водночас природним є намагання вибрати оптимальний керуючий вплив, найкращий у порівнянні з іншими можливими способами керування. Розв'язок проблеми пізнання процесу самоорганізації цих об'єктів керування має здійснюватися за допомогою методів математичного моделювання на прикладі перебігу процесів у живому організмі у разі забезпечення досягнення заданих цілей.

Метою роботи є побудова математичної моделі функційної системи дихання для дослідження механізмів самоорганізації організму людини при екстремальних збуреннях.

Методи. Процес транспорту та масообміну респіраторних газів на їх шляху в організмі описується за допомогою системи звичайних нелінійних диференційних рівнянь.

Результати. Розроблено математичну модель функційної системи дихання для дослідження поточного стану та прогнозування параметрів самоорганізації системи дихання при адаптації до збурюючих впливів зовнішнього та внутрішнього середовищ, яка ґрунтується на задачі оптимального керування з урахуванням конфліктних ситуацій між керуючими та виконавчими органами саморегуляції.

Висновки. Запропоновано математичну модель функційної самоорганізації системи дихання та кровообігу, яка враховує взаємодію та взаємовплив функційних систем організму, конфліктність ситуацій між керуючими та виконавчими органами саморегуляції, яка ґрунтується на припущенні щодо оптимальності регуляції кисневих режимів організму та дозволяє прогнозувати параметри самоорганізації організму людини при екстремальних збурюючих впливах. Модель може виявитися корисною для розв'язку прикладних задач фізіології та медицини.

Ключові слова: *функційна система дихання, керована динамічна система, самоорганізація системи дихання, збурюючий вплив середовища.*