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INTELLECTUAL SYSTEM FOR RESEARCHING FUNCTIONAL RELIABILITY OF FLIGHT CREW MEMBERS. Part II*

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The professional activity of a military pilot takes place in conditions of extreme disturbing influences, starting from changes in the qualitative composition of the gas environment and temperature regime to conditions of increased situational stress and circulatory hypoxia caused by overloads. Therefore, the issue of predicting the functional reliability of flight crew members in conditions of combined influence on their body of extreme external and internal disturbances is relevant. This opportunity is provided by mathematical models of functional systems of the body, on which one can simulate certain disturbances. Due to the fact that the functional respiratory system is the most sensitive to extreme environmental disturbances, it should be used as a base. This model should be supplemented with models that allow simulating other extreme disturbances of the body that occur during the professional work of pilots, for example, models that allow simulating changes in environmental temperature regimes, the impact of overload, etc. The proposed intellectual complex, which includes mathematical models of transport and mass exchange of respiratory gases, self-organization of the functional respiratory system, heat exchange and thermoregulation, adaptation and erythropoiesis, which interact with each other and influence each other through the circulatory system, allows predicting the regulatory reactions of the body of flight crew members when simulating extreme disturbances of the body that occur during professional military activities.

Keywords: functional reliability of pilots, mathematical model of regulation of oxygen regimes of the body, adaptation to extreme disturbances.

Introduction

In the first part of this publication [1], a complex of mathematical models is proposed that allow tracking the current characteristics of the functional state of flight personnel when they perform certain tasks on an aircraft simulator. This complex consists of a mathematical model of the pilot's behavioral reactions and a mathematical model of regulation of oxygen regimes of the body.

However, the capabilities of the flight simulator are quite limited, they do not allow to simulate extreme environmental disturbances that occur during a real flight. Examination on a flight simulator cannot answer the question of how much the body of a particular military pilot meets the physiological requirements that are imposed on flight crew members [1]. The physiological stress factors of attack aircraft pilots include the following: significant dynamic changes in the spatial position of the aircraft during the performance of combat missions, multidirectional pilot overloads, a strict time limit, circulatory hypoxia and hypoxic hypoxia, a change in the temperature regime of the environment (Fig. 1). The physiological stress factors of transport aircraft pilots include: a sharp change in the intensity of activity during maneuvers, hypoxic hypoxia [2].

From the point of view of labor physiology, we have the task of adapting the human body to the combined influence of extreme external (change in the gas composition of inhaled air, change in ambient temperature) and internal (circulatory hypoxia due to overload and conditions of increased situational stress) disturbing factors (Fig. 2).

There are a number of publications devoted to determining the functional reliability of flight crew members, their analysis is given in [3]. Also, publications devoted to the issues of reliability of operators of continuous interaction systems, to which flight crew members belong, in the context of adaptation to extreme environmental disturbances, are analyzed in [4]. In these publications, the functional reliability of pilots is associated with the state of their functional respiratory system. Also in [3] it is shown that if we consider the human body, from the point of view of reliability theory as a chain with a «weak link» [5], then such a «weak link» is the respiratory and circulatory system.

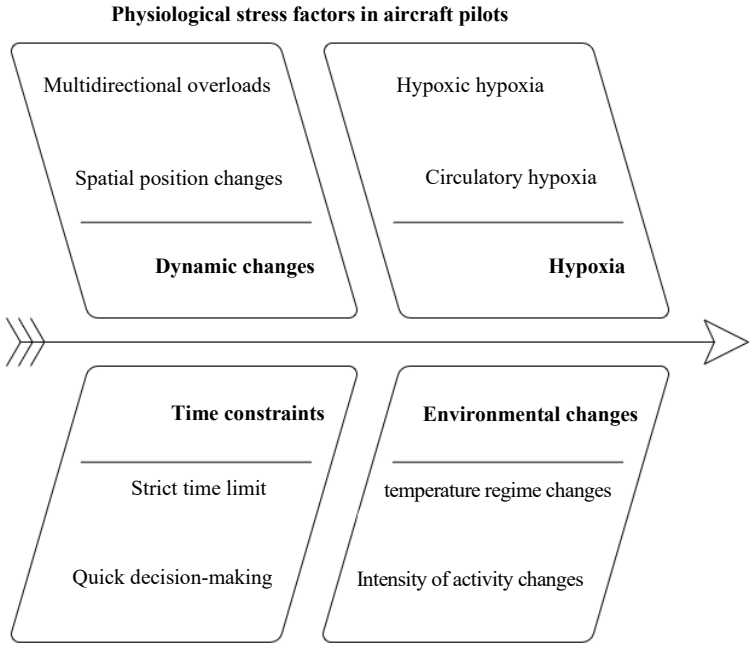

Fig. 1

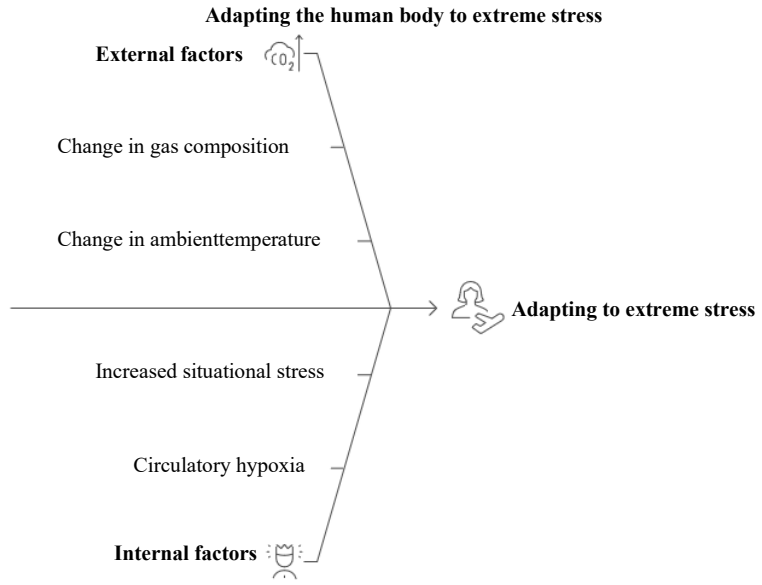

Fig. 2

Therefore, it is natural to choose mathematical models of the functional respiratory system for studying the functional reliability of flight personnel, their ability to perform professional activities in conditions of extreme disturbances. Due to the fact that one of the external disturbances is a change in temperature regimes, the mathematical model of the functional respiratory system should be supplemented with equations characterizing heat exchange and thermoregulation, which is associated with the respiratory system through the circulatory system. It is also natural to supplement these models with mathematical models of adaptation and erythropoiesis (Fig. 3).

Thus, the mathematical model of predicting adaptive capabilities can be presented as follows (Fig. 4).

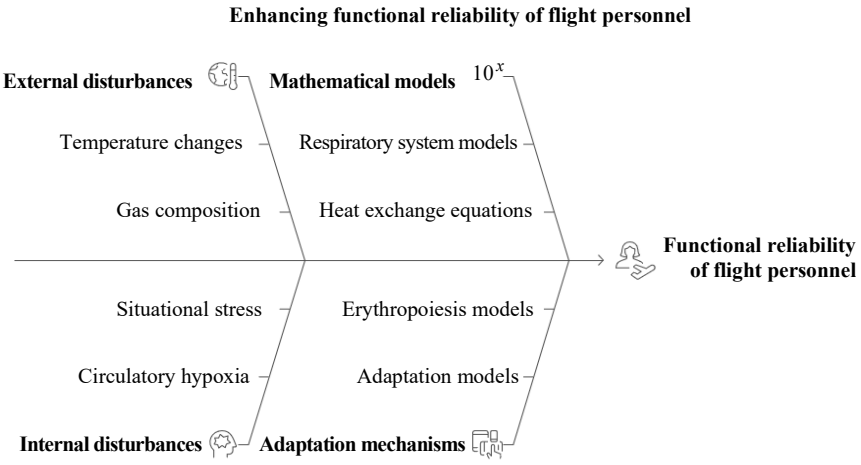

Fig. 3

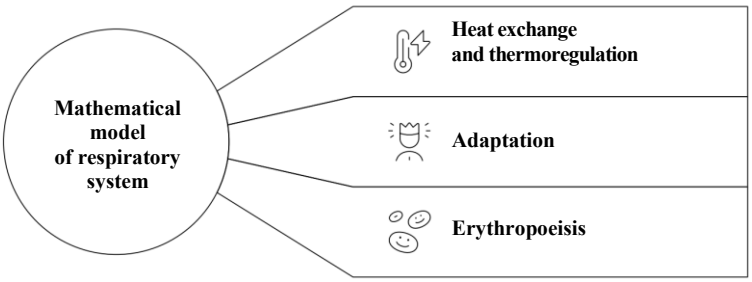

Fig. 4

Justification of the choice of model for research

Let us consider the mathematical model of the functional respiratory system, which describes the transport and mass exchange of respiratory gases in all areas of its movement in the body from the upper respiratory tract to the tissue level [3, 6, 7]. In this model, the process of breathing and blood circulation is presented as a controlled dynamic system in which the executive organs of self-organization direct their efforts to maintain a state of equilibrium with the tension of oxygen and carbon dioxide at a given level, disturbing the effect on the body. The unidirectionality of regulatory influences during physical and mental stress, the multidirectionality when a person is in a hypoxic or hyperbaric environment, and changes in temperature regimes can be explained by the hypothesis of a compromise solution to conflict situations at the intersystem and intrasystem levels while ensuring the stable development of these systems. Below are the main arguments that justify the choice of this particular model to support decision-making for optimizing the process of training flight personnel:

- the model describes the transport and mass exchange of respiratory gases in the body in the dynamics of the respiratory cycle, the process of tissue respiration;
- the model describes the self-organization of the functional respiratory system as a mechanism aimed at implementing the main function of the respiratory system — timely and adequate delivery of oxygen to the working organs and timely removal of carbon, which is a consequence of the course of metabolic processes in the body;

• the model is structured, its development is based on the idea of compartmental modeling;

• the model is developed for the body of an average person, whose functioning is based on the laws of modern normophysiology;

• in the presence of an array of data obtained during the functional study of a specific person.

In the model of the functional respiratory system, oxygen during the respiratory cycle is transported through the respiratory tract into the alveolar space of the lungs, and then through the alveolar-capillary membranes it enters the blood of the pulmonary capillaries. The circulatory system — arterial blood, branching into the system of tissue capillaries, delivers oxygen to the organs and tissues of the body. Oxygen is transferred from the blood to the tissue reservoir, where tissue respiration occurs. Carbon dioxide, which is a product of metabolism in the tissues, diffuses into the blood and is excreted by the venous blood to the lungs, where it is washed out of the body during exhalation (Fig. 5).

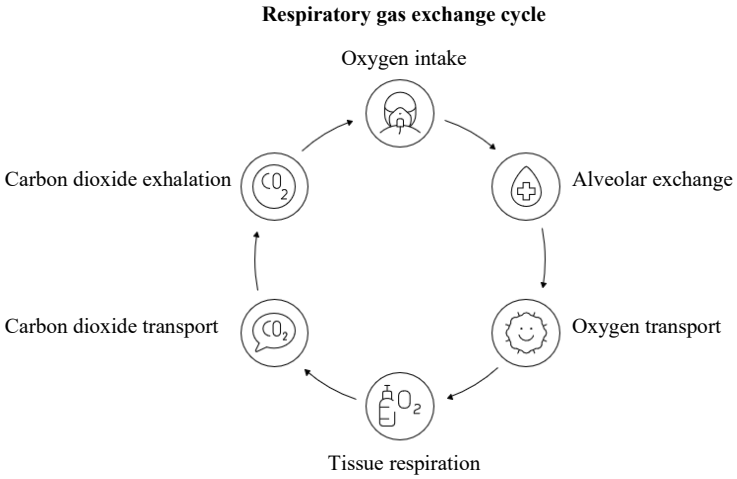

Fig. 5

The phase variables used to assess the state of the functional respiratory and circulatory systems are the partial pressures of respiratory gases of oxygen, carbon and nitrogen — in the respiratory tract, alveolar space and their tension in the blood and tissue capillary fluid. The dynamics of partial pressures and tensions of respiratory gases in the structures of the body are described by a system of ordinary differential equations. The principles of material balance and continuity of flow are used to construct them.

Mathematical model of transport and mass exchange of respiratory gases

Let P_{jD}, P_{jA} the partial pressure of gases of oxygen $(j=1)$, carbon dioxide $(j=2)$, and nitrogen $(j=3)$ in the respiratory tract (second subscript D) in the alveolar space (A), and P_{ja}, P_{jct}, $P_{j\bar{v}}$, P_{jt} — the tension of respiratory gases in the blood of pulmonary capillaries, arterial blood, blood of tissue capillaries, mixed venous blood and tissue fluid, respectively. Let P_1, P_2, P_3 denote the partial pressures of oxygen, carbon and nitrogen in the respiratory mixture, assuming that

$$B = P_1 + P_2 + P_3, \tag{1}$$

where B is the atmospheric pressure. Then the equation describing the dynamics P_{j2} in the respiratory tract can be presented in the form:

$$\frac{dP_{jD}}{d\tau} = \frac{\dot{V}}{V_D}[\tilde{P}_{jD} - \tilde{P}_{jA}], \quad j = 1, 2, 3, \tag{2}$$

where V_D is the volume of the respiratory tract, $\dot{V}$ is ventilation;

$$\dot{V} = \begin{cases} \frac{D \bullet \tau}{T_a} \sin \frac{\tau - \tau_0}{T_a} n_i, \text{ during the respiratory act (inspiration and expiration)} \\ 0, \qquad \text{during the respiratory pause} \end{cases} \tag{3}$$

and

$$\tilde{P}_{jD} = \begin{cases} P_j, \text{ при } \dot{V} > 0, \\ P_{jD}, \text{ при } V \le 0, \end{cases} \tag{4}$$

$$P_{jA} = \begin{cases} P_{jD}, \text{ при } \dot{V} > 0, \\ P_{jA}, \text{ при } \dot{V} \le 0, \end{cases} \tag{5}$$

where T_a is the duration of the respiratory act, τ_0 is the time of its beginning, D is the respiratory volume. Using the same principles of material balance and continuity, we write the equation for the dynamics of respiratory gases in alveolar air:

$$\frac{dP_{jA}}{d\tau} = \frac{1}{n_j (V_L - V_D)} \left[n_j \tilde{P}_{jA} \tilde{V} - G_{jA} - n_j P_{jA} \frac{dV_L}{d\tau} \right], \tag{6}$$

where G_{jA} is the gas flow through the alveolar-capillary membrane, V_L is the lung volume, and n_j is the conversion coefficients. For G_{jA} an algebraic analogue of Fick's law is used:

$$G_{jA} = k_j n_j S(P_{jA} - P_{jCL}), \tag{7}$$

where k, n — gas permeability coefficients through the membrane, S — mass exchange surface area.

Let us give an equation characterizing changes in respiratory gas tensions in the blood of tissue capillaries and tissue fluid of the organ:

$$\frac{dP_{1cti}}{d\tau} = \frac{1}{V_{cti}\left(\alpha_1 + \gamma Hb \frac{\partial \eta_{cti}}{\partial P_{1cti}} \right)} (\alpha_1 Q_{t_i} (P_{1a} - P_{1ct_i}) + \gamma HbQ_{t_i} (\eta_a - \eta_{ct_i}) - G_{1t_i}), \tag{8}$$

$$\frac{dP_{2ct_i}}{d\tau} = \frac{1}{V_{ct_i}\left(\alpha_2 + \gamma_{BH} BH \frac{\partial z_{ct_i}}{\partial P_{2ct_i}} \right)} \left(\alpha_2 Q_{t_i} (P_{2a} - P_{2ct_i}) - G_{2t_i} + \right.$$

$$\left. + Q_{t_i} BH \gamma_{BH} HbQ_{t_i} z_a - (1 - \eta_{ct_i}) \gamma_{Hb} HbV_{ct_i} \frac{\partial \eta_{ct_i}}{\partial \tau} \right), \tag{9}$$

$$\frac{dP_{3ct_i}}{d\tau} = \frac{1}{\alpha_3 V_{ct_i}} (\alpha_3 P_{3a} Q_{t_i} - \alpha_3 P_{3ct_i} Q_{t_i} - G_{3t_i}), \tag{10}$$

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$$\frac{dP_{1t_i}}{d\tau} = \frac{1}{V_{t_i}\left(\alpha_{t_i} + \gamma_{Mb} Mb \frac{\partial \eta_{t_i Mb}}{\partial P_{1t_i}}\right)} (G_{1t_i} - q_{1t_i}), \tag{11}$$

$$\frac{\partial P_{2t_i}}{\partial \tau} = \frac{G_{2t_i} + q_{2t_i}}{\alpha_{2t_i} V_{2t_i}}, \tag{12}$$

$$\frac{\partial P_{3t_i}}{\partial \tau} = \frac{G_{3t_i}}{\alpha_{3t_i} V_{t_i}}, \tag{13}$$

where

$$\eta_{ct_i} = 1 - 1,75\exp(-0,052 m_{ct_i} P_{1ct_i}) + 0,75\exp(-0,12 m_{ct_i} P_{1ct_i}), \tag{14}$$

$$m_{ct_i} = 0,25(pH_{ct_i} - 7,4) + 1, \tag{15}$$

$$pH_{ct_i} = 6,1 + \lg\frac{BH}{\alpha_2 P_{2ct_i}}, \tag{16}$$

$$z_{ct_i} = \frac{P_{2ct_i}}{P_{2ct_i} + 35}. \tag{17}$$

In (8)–(17) $\alpha_1, \alpha_2, \alpha_3, \alpha_{1t_i}, \alpha_{2t_i}, \alpha_{3t_i}$ are the solubility coefficients of respiratory gases in blood and tissue fluid, Q_{t_i} — the volumetric velocity of blood circulation in the capillary bed of the tissue reservoir t_i, V_{ct_i}, V_{t_i} — the volume of blood and tissue fluid, respectively.

Tissue blood, which has partially given up oxygen and is saturated with carbon, is collected in the venous bed and, due to circulation, returns to the lungs, where it is enriched with oxygen and washed out of carbon during the next respiratory cycle:

$$\frac{dP_{1\bar{v}}}{d\tau} = \frac{1}{V_{\bar{v}}\left(\alpha_1 + \gamma_{Hb} Hb \frac{\partial \eta_{\bar{v}}}{\partial P_{1\bar{v}}}\right)} \left[\alpha_1 \left(\sum_{t_i} Q_{t_i} P_{1ct_i} - Q P_{1\bar{v}}\right) - \gamma Hb Q \eta_{\bar{v}}\right], \tag{18}$$

$$\frac{dP_{2\bar{v}}}{d\tau} = \frac{1}{V_{\bar{v}}\left(\alpha_2 + \gamma_{BH} BH \frac{\partial z_{\bar{v}}}{\partial P_{2\bar{v}}}\right)} \left[\alpha_2 \left(\sum_{t_i} Q_{t_i} - Q P_{2\bar{v}}\right) + \right.$$

$$+ \left(\sum_{t_i} \gamma_{BH} BH_{ct_i} Q_{t_i} z_{2ct_j} - \gamma_{BH} BHQ z_{2\bar{v}}\right) +$$

$$\left. + \left(\sum_{t_i} (1 - \eta_{ct_i}) \gamma_{Hb} HbQ z_{\bar{v}} - (1 - \eta_{\bar{v}}) \gamma_{Hb} HbQ z_{\bar{v}}\right)\right] + \sum_{t_i} \gamma_{Hb} Hb_{ct_i} V_{ct_i} \frac{\partial \eta_{ct_i}}{\partial \tau}, \tag{19}$$

$$\frac{dP_{3\bar{v}}}{d\tau} = \frac{1}{\alpha_3 V_{\bar{v}}} \left(\sum_{t_i} \alpha_3 Q_{t_i} P_{3ct_i} - \alpha_3 Q P_{3\bar{v}}\right). \tag{20}$$

System (1)–(20) at given $\dot{V}, Q, Q_{t_i}, i=\overline{1,m}, D, q_{t_i}$ and T_a describes changes in partial pressures and tensions of respiratory gases in blood and tissue fluids of regions and organs on respiratory cycle.

Mathematical model of mechanisms of regulation of the main function of respiratory system

In [8] it was proposed to consider process of breathing described by equations (1)–(20) as the controlled dynamic system. There is enough experimental data that in response to disturbance — external (changes of barometric pressure, qualitative changes of composition of the inhaled mixture) and/or internal (changes of intensity of metabolic processes in tissues, characterized by rate of oxygen utilization), the value of alveolar ventilation $\dot{V}$, volumetric velocity of systemic blood flow Q, vasodilation (vasoconstriction) of tissue vessels significantly increases (decreases) and, as a result, the volumetric velocity of blood Q_{t_i} in them changes. That is why the parameters $\dot{V}, Q, Q_{t_i}$ in mathematical modeling are considered as control parameters, and the respiratory muscles, cardiac muscles and vascular smooth muscles, whose work provides the necessary values for stabilizing the basic function of respiration, the value of these parameters in a disturbed system as executive organs of active regulation. The system of equations (1)–(20) is asymptotically stable, therefore it can be assumed that the purpose of regulation is to bring the disturbed system into a relatively equilibrium state, which occurs when

$$\left|G_{1t_i}-q_{1t_i}\right| \le \varepsilon_1,\ \left|G_{2t_i}+q_{2t_i}\right| \le \varepsilon_2,\ \left|G_{3t_i}\right| \le \varepsilon_3, \tag{21}$$

where $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are arbitrarily small positive numbers. The set of system states for which (21) is satisfied will be defined as the terminal set M of the dynamic system control problem. It is natural to assume that the control parameters are bounded

$$\dot{V}_{\min} \le V \le V_{\max},\ Q_{\min} \le Q \le Q_{\max},\ Q_{t_i\min} \le Q_{t_i} \le Q_{t_i\max},\ \sum_{t_i} Q_{t_i} = Q. \tag{22}$$

The control problem of outputting a perturbed dynamic system to a set M under constraints (22) has a solution, since the conditions of Filipov's theorem [9] are fulfilled.

Of all the solutions to the optimal parameter $\dot{V}_{opt}, Q_{opt}, Q_{t_i opt}$ control problem, we will consider those that provide a minimum of the functional on the trajectory of the state change of the dynamic system

$$\dot{I} = \int_{\tau_0}^{T} \left[\rho_1 \sum_{t_i} \lambda_{t_i} (G_{1t_i} - q_{1t_i})^2 + \rho_2 \sum_{t_i} \lambda_{t_i} (G_{2t_i} + q_{2t_i})^2 + \rho_3 \sum_{t_i} \lambda_{t_i} G_{3t_i} \right] d\tau, \tag{23}$$

where ρ_1, ρ_2, ρ_3 — coefficients of the body's sensitivity to hypoxia, hypercapnia and excess nitrogen; λ_{t_i} — coefficients characterizing the importance of a particular organ or tissue for life. Coefficients λ_{t_i} are formed through evolution. It is known that damage to the heart muscle, brain tissue, liver, and kidneys leads to loss of life and, perhaps, that is why the density of capillaries in them is quite high. In mathematical modeling, the dependence

$$\lambda_{t_j} = \omega\left(\frac{V_{C_j}}{V_{t_j}}\right),\ j=\overline{1,m}. \tag{24}$$

The quadratic function ω characterizes the degree of blood filling of a unit volume of the tissue reservoir. Even with such a simple form of dependence, it becomes obvious that the more blood in the tissues of the organ and the smaller its volume, the more acutely the tissues feel a lack of oxygen and hypercapnia.

Mathematical models of heat exchange and thermoregulation

The heat exchange system is most closely related to the functional system of respiration and blood circulation, thermal energy is the result of tissue metabolism and also, like the respiratory gases of the respiratory mixture, receives additional heat from the environment. Like the respiratory mixture, heat is distributed in the body by circulating blood. But when building a mathematical model of heat exchange and thermoregulation, it is necessary to take into account the differences — if oxygen enters the body through the respiratory tract and carbon is excreted in the same way, then heat evaporates mainly through the skin and is distributed not only by blood, but also convectively from one region to another.

We present a mathematical model of heat exchange and thermoregulation as follows [10]. Let $T_A, T_{LC}, T_a, T_{ct_i}, T_{t_i}, T_{\bar{v}}$ are the average temperature a in the alveolar space, blood of pulmonary capillaries, arterial blood, blood of tissue capillaries of the t_i tissue reservoir, tissue fluid and mixed venous blood — characterize the state of the heat exchange system.

Let c, ρ are the specific heat capacity and density of blood in individual structures, $c_{t_i}, \nu_{t_i}, \mu_{t_i}$ — respectively, the specific heat capacity, mass and rate of change of heat production for the t_i tissue reservoir, γ_{t_i} — the coefficient of thermal conductivity between the volumes of blood and tissue, S_{t_i} — the surface area on which heat exchange takes place in the «blood — tissue» system. Let $D_{t_i,t_i-1}(\tau)$, $D_{t_i,t_i+1}(\tau)$ are the heat flows that form the heat transfer between t_i and tissue volumes t_{i-1} and t_{i+1}, adjacent along the length of the generalized capillary, and Q_{t_i} — the volumetric velocity of blood in tissue capillaries.

Then the equation for the change in arterial blood temperature can be represented as:

$$c\rho V_a \frac{dT_a(\tau)}{d\tau} = c\rho(Q_{LC}T_{LC}(\tau) + Q_{Sh}T_{\bar{v}}(\tau) - Q_a T_a(\tau)), \tag{25}$$

where Q_{Sh} — volumetric blood velocity in the pulmonary shunt.

The temperature change in tissue blood — tissue structures is described by a system of ordinary differential equations

$$c\rho V_{ct_i} \frac{dT_{ct_i}(\tau)}{d\tau} = c\rho Q_{t_i}(T_a(\tau) + T_{ct_i}(\tau)) + G_{ti}(T(\tau)), \tag{26}$$

$$c_{t_i} V_{t_i} \frac{dT_{t_i}}{d\tau} = \mu_{t_i} - G_{t_i}(T(\tau)) - D_{t_i,t_{i-1}}(\tau) + D_{t_i,t_{i+1}}(\tau), \tag{27}$$

$$G_{t_i}(T(\tau)) = \gamma_{t_i} S_{t_i}[T_{t_i}(\tau) - T_{ct_i}(\tau)], i = \overline{1,n}. \tag{28}$$

The equations for the temperature changes of mixed venous blood and pulmonary blood are written as:

$$c\rho V_{\bar{v}} \frac{dT_{\bar{v}}(\tau)}{d\tau} = c\rho\left(\sum_{t_i} Q_{t_i} T_{t_i}(\tau) - QT_{\bar{v}}(\tau)\right), \tag{29}$$

$$c\rho V_{LC}\frac{dT_{LC}(\tau)}{d\tau}=c\rho Q_{LC}(T_{\bar{v}}(\tau)-T_{LC}(\tau))-G_{\mathrm{Re}s}, \tag{30}$$

where $Q=\sum_{t_i}Q_{t_i}=Q_{Sh}+Q_{LC}$, $G_{\mathrm{Re}s}$ — the value of the heat flow, which represents heat losses to the surrounding environment through the respiratory tract.

The main heat flows of exchange with the surrounding environment are carried out through the skin — therefore, the mathematical model of heat exchange must include the equation of temperature change in the skin:

$$c_kV_k\frac{dT_k}{d\tau}=\mu_k-G_k(\tau)-D_{k,k-1}(\tau)+D_{k,k+1}(\tau)-G_{KON\bar{v}}(\tau)-G_{RAD}(\tau)-G_{EV}(\tau), \tag{31}$$

where the index k corresponds to the tissue region is the skin, and $G_{KON\bar{v}}$, G_{RAD}, G_{EV} — the flows that form the heat exchange with the external environment, convection, radiation and evaporation from the surface of the human skin, respectively.

Like the functional respiratory system, the heat exchange system in the body is represented in the modeling as a regulated system. Unlike models in which the goal of regulation is to maintain the temperature of the internal environment of the body or individual organs (in particular – the brain) at a given level, in the model proposed below it is assumed that the goal of regulation is to bring the disturbed heat exchange system to a certain equilibrium state, in which the relationship is satisfied for all tissue regions

$$\theta(\tau)=\mu_{t_i}-G_{t_i}(T(\tau))-D_{t_i,t_{i-1}}(\tau)+D_{t_i,t_{i+1}}(\tau)=0. \tag{32}$$

In this case, the effector physiological reactions act as regulation parameters:

- evaporation $G_{EV}(\tau)$ from the skin surface, as the main action of the body, which protects it from overheating;
- the rate of heat production in the muscles μ_{t_i}, taking into account the effect of thermal shivering;
- volumetric velocities of tissue blood flows Q_{t_i}, $i=\overline{1,m}$.

The quality of the heat exchange system control processes can be assessed by the system's ability to provide a minimum of functionality

$$\dot{J}=\int_{\tau_0}^{\tau^*}\left[\sum_{t_i}\lambda_{t_i}\theta_{t_i}^2(\tau)+\sum_{t_i}\omega_{t_i}(\mu_{t_i}(\tau)-\mu_{t_i}^N)^2\right]d\tau, \tag{33}$$

where the first term in the integrand characterizes the violation of heat balance in all tissue regions under consideration, and the second term is the energy expenditure of the organism. In (33) λ_{t_i} are the coefficients that determine the sensitivity of different tissues to thermal imbalance, and ω_{t_i} — sensitivity to imbalance and energy expenditure.

If we model the heat exchange and thermoregulation system in isolation from the respiratory system, then all the regulation parameters listed above really turn out to be significant. But we can assume that evaporation from the skin is one of the main functions of this tissue, which requires, under certain disturbances, internal (intensive unskilled low-productivity work) or external (change in temperature regime) changes in the intensity of the metabolic process. Similarly, the rate of heat production is a component of the rate of energy release as a result of tissue metabolism, perhaps slightly exceeding the required level when cold shivering occurs. The above allows us to consider the respiratory, circulatory and heat exchange systems in interaction and to present the

problem of regulating these systems as the output of dynamic systems (1)–(20), (25)–(32) from a disturbed state to a balanced one, and the optimal parameters of regulation $\dot{V}, Q, Q_{t_i}$ are considered to be such and possibly component parts μ_{t_i} that deliver a minimum of functionality $\dot{I} + \dot{J},$ which are determined by the relations (23) and (33).

With the joint functioning of the respiratory, circulatory and heat exchange systems, conflict situations arise between the systems, since maintaining a stable state in these systems is ensured by the same active executive mechanisms of regulation – respiratory muscles, cardiac muscle, vascular smooth muscles, and heat removal by evaporation and radiation is added.

Since this work deals with the justification of mathematical models, it should be recalled that in order to confirm the adequacy of models to real processes that they reflect, it is necessary that [11]:

- there exists and at the same time a unique solution to the Cauchy problem for the system of equations (1)–(20), (25)–(31) over the entire time interval of modeling;
- based on the nature of physical quantities, partial pressures and stresses of gases, as well as body temperatures, must be non-negative and bounded from above;
- stationary solutions of the system of equations must be asymptotically stable;
- there must exist a solution to the problem of optimal control of the respiratory, circulatory and heat exchange systems by deriving perturbed systems in a balanced state (Fig. 6).

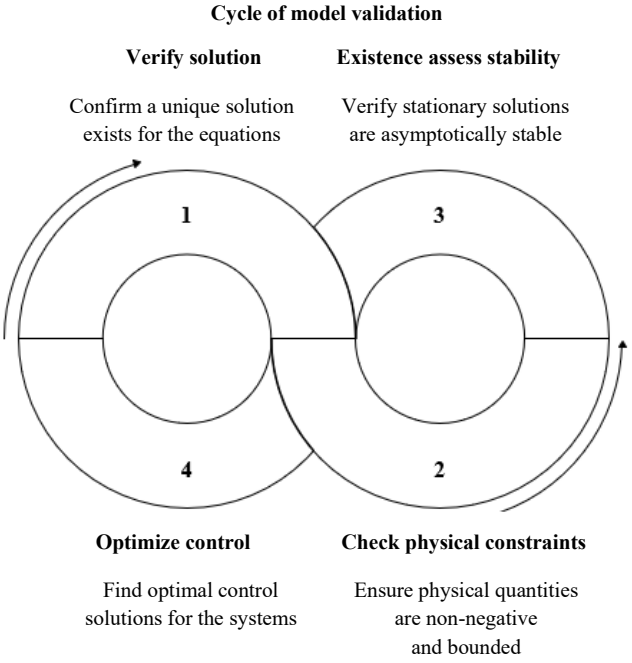

Fig. 6

In [12] it is shown that a unique positive and bounded from above solution of the systems of differential equations under consideration exists when

$$\lim_{P_{t_1} \to +0} \eta = 0, \tag{34}$$

$$\lim_{P_{1ct_i} \to +0} \eta_{ct_i} = 0, \tag{35}$$

$$\lim_{P_{1t_i}\to+0} q_{t_i} = 0, \quad \lim_{P_{1t_i}\to+0} \dot{q}_{1t_i} = 0, \tag{36}$$

for all tissue regions t_i.

The relation (14) for the function η guarantees the fulfillment of conditions (34), (35). It is necessary to require the fulfillment of conditions (36). However, (36) reflects nothing more than hypometabolism: on a monotonically decreasing sequence of oxygen tensions, the limiting value of which is $+O$, and in such a way that the sequence of derivative values also has its limit $+O$.

Mathematical model of adaptation

We will set:

— initial state of the system: $p_{RP}O_2$, $p_{RP}CO_2$, p_AO_2, p_ACO_2, which are characterized by the partial pressures of oxygen and carbon dioxide in the respiratory tract and alveolar space $p_{LC}O_2$, $p_{LC}CO_2$, p_aO_2, p_aCO_2, $p_{C_j}O_2$, $p_{C_j}CO_2$, $p_{t_j}O_2$, $p_{t_j}CO_2$, $j=\overline{1,m}$, $p_{\bar{v}}O_2$, $p_{\bar{v}}CO_2$, which characterize the tensions of oxygen and carbon dioxide in the blood of the pulmonary capillaries, τ_0 the time of the onset of the disturbance;

— areas of change of control parameters:

$$\left.\begin{aligned} &\dot{V}_{\min} \le \dot{V} \le \dot{V}_{\max} \\ &Q_{\min} \le Q \le Q_{\max} \\ &Q_{C_j\min} \le Q_{C_j} \le Q_{C_{\max}\max},\ j=\overline{1,m} \\ &\sum_{j=1}^{m} Q_{C_j} \le Q \end{aligned}\right\}, \tag{37}$$

— the terminal set of states, determined by the relations:

$$\left.\begin{aligned} &\left| G_{t_j}O_2 - q_{t_j}O_2 \right| \le \varepsilon_{t_j}O_2, \qquad j=\overline{1,m} \\ &\left| G_{t_j}CO_2 - q_{t_j}CO_2 \right| \le \varepsilon_{t_j}CO_2,\ j=\overline{1,m} \end{aligned}\right\}, \tag{38}$$

where $\varepsilon_{t_j}O_2$, $\varepsilon_{t_j}CO_2$, $j=\overline{1,m}$, are sufficiently small positive values.

The solution to the problem of short-term adaptation, formulated in this way, will be any set of values of the control parameters $\bar{V}$, Q, Q_{C_j}, $j=\overline{1,m}$, from equation (43), i.e. these parameters will, after some time, transfer the disturbed system, characterized by conditions (38). In this case, the degree of oxygen deficiency or carbon dioxide accumulation will be reliable. Let us present the problem of short-term adaptation as a problem of optimal self-regulation. Let us assume that the optimal set of control parameters $\bar{V}$, Q, Q_{C_j}, $j=\overline{1,m}$, from equation (37) is that provide a minimum of the functional on the trajectories of the disturbed dynamic system

$$I = \int_{t_0}^{\tau_0+T} \left[\rho_1 \sum_{i=1}^{m} \lambda_{t_j} (G_{t_j}O_2 - q_{t_j}O_2)^2 + \rho_2 \sum_{i=1}^{m} \lambda_{t_j} (G_{t_j}CO_2 + q_{t_j}CO_2)^2 \right] d\tau.$$

This is actually the above-mentioned optimal control problem (23).

Self-regulation of the respiratory system is carried out not only during short-term adaptation, but also at the stages of medium-term and long-term adaptation, when disturbances act on the system for a long time or are periodically repeated. This leads to the development of additional adaptation mechanisms that allow, in response to disturbances, to carry out a more effective organization of metabolic functions in the tissues. When oxygen is utilized in the tissues, energy is released, which is necessary for the work of muscles, the musculoskeletal system, and the maintenance of the main functions of human organs. Part of the energy is released as heat. Then the rate of oxygen consumption by the tissues can be expressed as:

$$q_{t_j}O_2 = q^f_{t_j}O_2 + q^T_{t_j}O_2, \quad j = \overline{1, m},$$

where $q^f_{t_j}O_2$ is the rate of oxygen utilization necessary for the performance of organ and tissue functions at a given level; $q^T_{t_j}O_2$ is a component of the oxygen consumption rate that ensures the release of thermal and other types of energy.

At the medium-term stage of adaptation for a given level of load, $q^f_{t_j}O_2 = \text{const}$, $j = \overline{1, m}$, and $q^T_{t_j}O_2$, $j = \overline{1, m}$, can be reduced in the adaptation process due to better organization of metabolic processes. It is assumed that

$$q^T_{t_j ad.}O_2(\tau) = (q^T_{t_j nad.}O_2 - q^T_{t_j crit.}O_2)e^{-k\tau} + q^T_{t_j crit.}O_2, \quad j = \overline{1, m},$$

where $q^T_{t_j ad.}O_2$, $q^T_{t_j nad.}O_2$ are thermal components of the rate of oxygen consumption in the adapted and non-adapted organism, respectively; $q^T_{t_j crit.}O_2$ — the rate of oxygen consumption, the minimum amount of energy required to maintain the body's heat balance during adaptation; k — a given coefficient; τ — the rate of the adaptation process. Similarly, the expression for carbon dioxide can be written.

During medium-term adaptation, the coefficients of sensitivity to hypoxia and hypercapnia change:

$$\rho_{1ad.} = (\rho_{1nad.} - \rho_{1crit.})e^{-k\tau} + \rho_{1crit.},$$

$$\rho_{2ad.} = (\rho_{2nad.} - \rho_{2crit.})e^{-k\tau} + \rho_{2crit.},$$

where $\rho_{1crit.}$, $\rho_{2crit.}$ are minimum sensitivity coefficients that provide hypoxic and hypercapnic stimulation during the operation of short-term adaptation mechanisms.

Long-term adaptation of the body to the effects of hypoxia consists of structural changes in the body, for example, redistribution of tissue mass, hypertrophy of the executive organs of self-regulation of the respiratory process, primarily hypertrophy of the left ventricle.

Mathematical model of erythropoiesis

It is also natural to assume that in the initial stage of the disease, passive self-regulation mechanisms are activated — erythropoiesis, the release of hemoglobin and myoglobin into the blood. An increase in the content of erythrocytes in the blood and the content of hemoglobin in them is a powerful regulatory mechanism for maintaining a stable state of the body in conditions that lead to oxygen deficiency under various disturbances. In [13], the obtained linear dependences of erythropoietin (EPO), hemato-

crit (Ht) and hemoglobin (Hb) were introduced into a mathematical model of the functional respiratory and circulatory systems to enhance the regulation of the main function of the respiratory system during hypoxia. A regression relationship was established

$$EPO = \alpha_1 \cdot p_a O_2 + \alpha_2 \cdot p_{\bar{v}} O_2 + \alpha_3 \cdot p_a CO_2 + \alpha_4 \cdot p_{\bar{v}} CO_2,$$

where $\alpha_1 = 0{,}180552928$, $\alpha_2 = -0{,}54563859$, $\alpha_3 = -0{,}052882973$, $\alpha_4 = 0{,}551511209$.

$$Hb = \beta_1 \cdot EPO, \quad Ht = \delta_1 \cdot EPO,$$

where $\beta_1 = 6{,}097190346$, $\delta_1 = 1{,}94699695$.

These ratios are entered into the mathematical model of the functional respiratory system (FRS) and participate in the self-regulation of the dynamic system, which occurs at the stage of medium-term adaptation. Thus, to study the ability of flight crew members to perform professional activities under extreme environmental disturbances, the following algorithm can be proposed:

Equipment is installed on the flight simulator for simultaneous study of behavioral reactions of the pilot and study of parameters of the functional respiratory system. The obtained indicators are entered as inputs into the mathematical model of behavioral reactions of the pilot and the model of regulation of oxygen regimes of the body. The calculated parameters characterize the current functional state of the pilot. Further, part of the obtained data is used as input for the operation of a complex of mathematical models of transport and mass exchange of respiratory gases, self-organization of the respiratory and circulatory systems, adaptation, heat exchange and thermoregulation, erythropoiesis. The models interact and influence each other through the circulatory system. The complex allows you to simulate external and internal extreme disturbances, such as changes in the gas composition of inhaled air, changes in environmental temperature regimes, circulatory hypoxia, conditions of increased situational stress. At the output of the proposed intellectual complex, we obtain parameters of the regulatory reactions of the body, which allow us to judge the functional state of the subject. The following algorithm can be proposed (Fig. 7).

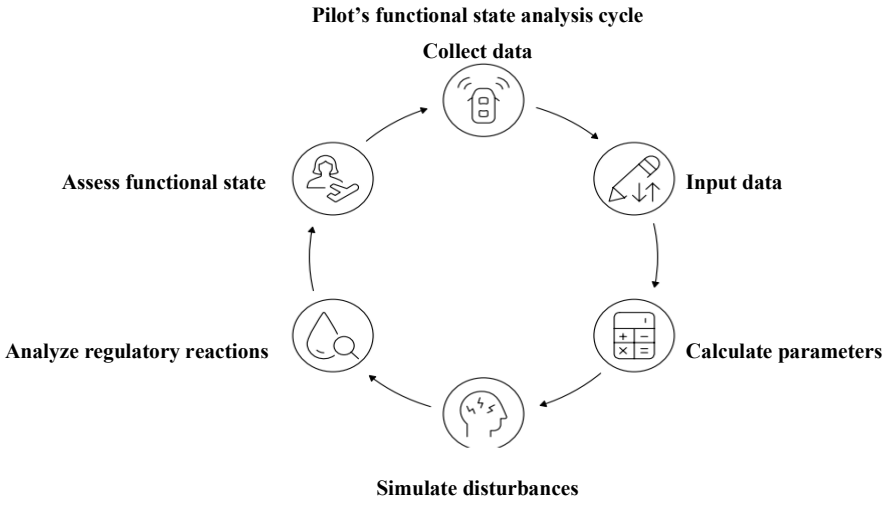

Fig. 7

Conclusion

When determining the functional reliability of flight crew members, it is necessary to take into account, on the one hand, personal characteristics, such as speed, the ability to perceive and process information under various disturbing influences, reliability and accuracy of actions, psychophysiological stability, and on the other hand, the ability of the functional

respiratory and circulatory systems to adapt to extreme internal and external disturbing influences that accompany the professional activities of flight crew members. The proposed complex makes it possible to track the behavioral reactions of the pilot under the complex influence of hypoxic hypoxia conditions and increased situational stress when making decisions. Further research in this area involves more experimental tests with a large group of pilots, obtaining, analyzing and comparing changes in pilot parameters over time and changes depending on the level of training. Further research will also include the use of more advanced models of human behavior or the use of other types of simulators. The proposed engineering installation of the flight simulator can be used to assess the current state of the pilot. Also, the obtained data on the current functional state of the flight crew can be used in the future as input for predicting the regulatory reactions of their functional respiratory system when simulating certain disturbances.

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ІНТЕЛЕКТУАЛЬНА СИСТЕМА ДОСЛІДЖЕННЯ ФУНКЦІОНАЛЬНОЇ НАДІЙНОСТІ ЧЛЕНІВ ЛЬОТНИХ ЕКІПАЖІВ. Частина 2

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Професійна діяльність військового льотчика проходить в умовах екстремальних збурювальних впливів, серед яких зміни якісного складу газового середовища та температурного режиму, підвищена ситуаційна напруга, а також циркуляторна гіпоксія, спричинена перевантаженнями. Тому особливого значення набуває прогнозування функціональної надійності осіб льотного складу у разі сумісного впливу на організм людини екстремальних зовнішніх та внутрішніх збурень. Ефективними для розв'язання цієї проблеми є математичні моделі функціональних систем організму, на яких

можна імітувати ті чи інші збурення. Оскільки функціональна система дихання найбільш чутлива до екстремальних збурень середовища, саме її доцільно застосовувати як базу. Дану систему слід доповнити моделями, що дають змогу імітувати інші екстремальні збурення під час професійної діяльності льотчиків, наприклад зміна температурних режимів середовища, вплив перевантаження тощо. Запропоновано інтелектуальний комплекс, що містить математичні моделі транспортування та масообміну дихальних газів, самоорганізації функціональної системи дихання, теплообміну та терморегуляції, адаптації та еритропоезу, які взаємодіють між собою та впливають одна на одну через системний кровообіг. За допомогою такого комплексу можна прогнозувати регуляторні реакції організму членів льотних екіпажів у разі імітації екстремальних збурень під час професійної військової діяльності.

Ключові слова: функціональна надійність льотчиків, математична модель регулювання кисневих режимів організму, адаптація до екстремальних збурень.

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