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COMPROMISE SOLUTION OF CONFLICT SITUATIONS IN THE PROBLEM OF OPTIMAL CONTROL IN DECISION MAKING UNDER THE COMPLEX SITUATIONAL CONDITIONS

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Abstract*—One of the most important directions of the research in medicine of labor is the development of methodology and methods for the estimation and predicting of the functional reserves of organisms of decision-makers, whose professional activity takes place under the extreme conditions, in particular, with the joint action of hypoxic hypoxia and conditions of complex situational stress. In present article it was proposed to apply mathematical model of the functional system of respiration for the simulation conflict-controlled processes that appear during the self-organization of respiratory system under the conditions of complex situational stress in process of decisions' making. The mathematical model of mass transfer and mass exchange of respiratory gases in human organism is represented as a system of ordinary differential equations, which in the dynamics of the respiratory cycle describe the changes in the stresses of oxygen and carbon dioxide at all stages of its path in human organism. The solution of this problem, taking into account both intra- systemic as well as inter systemic mechanisms, allows to predict the optimal values of active control parameters - ventilation, volume velocities of systemic and organ blood circuits. The results of numerical experiments were presented. Their purpose was to study the behavior of quality control functional for hypoxic and hypercapnic regulation stimuli in difficult situational conditions during decision making and to find optimal control parameters when seeking a compromise solution of conflict situation that appear between control elements and executive elements of self-regulation. Numerical simulation has demonstrated that during the load compensation in difficult situational conditions, during decision making the key role belongs to quality control functional of the hypercapnic stimulus and to behavior of quality functional, which is minimized; the change in the parameters of ventilation influences greatly. The optimum control influences were determined at the simulation of load compensation on the brain tissues for averaged person. Further developments can turn this model into a rather simple and reliable research tool and have both theoretical and practical value.*

Index Terms—Decision-makers; difficult situational conditions; hypoxic regulation stimulus; hypercapnic regulation stimulus; cumulative effect of stimuli.

I. INTRODUCTION

The scientific literature contains a limited information only on the study of mechanisms of organism adaptation of the human who works in adverse conditions of professional activity. As it was shown in [1], the professional activity of a person in unusual conditions of the work leads to a sharp change in homeostatic mechanisms, and as a consequence, to the adaptation failure [2] – [4].

In this regard, one of the leading direction of research is the development of methodologies and methods for evaluating and forecasting of functional reserves of organisms of persons whose professional activities are carried out under extreme conditions. The system study of physiological functions and activities, particularly in extreme conditions of flights by modern aircrafts is extremely important with purpose to identify optimal conditions and processes of the work. The use of comprehensive system approach to the estimation and prediction of operator labour efficiency can improve significantly the reliabilities of "man-machine" systems and eliminate uncertainty that appear if to use for this purpose psychophysiological indicators only.

For obtaining of comprehensive information on the state of organisms of the flight crew members, an integrated approach based on modern diagnostic and research methods is required. The part of this approach is the simulation of adverse flight factors. The data obtained using this approach on the physiological characteristics of adaptation and individual stress resistance of organism to extreme activities extends the contemporary imaginations about the ability of organism adaptation to the environment, human reserve capacity, their realization in the restoring of damaged functions, and complement modern ideas about regulatory mechanisms that participate in homeostasis support of the organism.

II. Problem Statement

Development of new methods of mathematical modeling, methods of system analysis, theory of dynamic process control and contemporary information technologies had formed a favorable ground for studying of the processes of self-regulation of the human respiratory system. This is especially true for the problem of optimality criterion choosing at the self-regulation of functional respiratory system during decision making in conditions of complex situational circumstances.

The mathematical model of gas homeostasis control allows to simulate the compensatory reactions of the organism according to the principle of providing of adequate reactions of respiratory and cardiac centers in conditions of decision-making under the difficult situational circumstances, and it could be used for the resolution of conflict situation that arises between the executive elements of self-regulation and other tissues and organs in their struggle for the oxygen.

The ***purpose*** of the work was to identify the role of hypoxic and hypercapnic regulatory stimuli, as well as their cumulative effect in the self-organization of the respiratory system, and to evaluate the contribution of each individual group of tissues in the functionals that formalize these stimuli under the conditions of complex situational circumstances on the mathematical model of respiration functional syste.

III. Problem Solution

A. The task of optimal control

The mathematical model of mass transfer and mass exchange of respiratory gases in human organism in the dynamics of respiratory cycle [5], [6], which is based on the assumption that the main function of respiratory system is the timely and adequate oxygen supply of tissues of working organs and the output of carbon dioxide and metabolic products; this model is represented by the system of ordinary differential equations that describe the dynamics of stresses of oxygen and carbon dioxide at all stages of its path in the human organism. In parametric form it looks like as:

$$\frac{dp_i\mathrm{O}_2}{d\tau} = \varphi\big(p_i\mathrm{O}_2, p_i\mathrm{CO}_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}\mathrm{O}_2, q_{t_i}\mathrm{O}_2\big), \tag{1.1}$$

$$\frac{dp_i\mathrm{CO}_2}{d\tau} = \phi\big(p_i\mathrm{O}_2, p_i\mathrm{CO}_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}\mathrm{CO}_2, q_{t_i}\mathrm{CO}_2\big), \tag{1.2}$$

where the functions φ and ϕ are described in details in [5] and [6]; $\dot{V}$ is the ventilation; η is the degree of hemoglobin saturation with oxygen; Q is the volume velocity of systemic and Q_{t_i} local blood circulations; $q_{t_i}\mathrm{O}_2$ is the speed of oxygen consumption by ith tissue reservoir; $q_{t_i}\mathrm{CO}_2$ is the rate of carbon dioxide release in ith tissue reservoir. The velocity of $G_{t_i}\mathrm{O}_2$ is the oxygen flow from blood to tissue and $G_{t_i}\mathrm{CO}_2$ is the carbon dioxide from tissue to blood is determined by the ratio

$$G_{t_i} = D_{t_i} S_{t_i} (p_{ct_i} - p_{t_i}), \tag{2}$$

where D_{t_i} are the coefficients of gas permeability through the aerohaematic barrier; S_{t_i} is the surface area of gas exchange.

The problem of optimal control is formulated as following one.

The purpose of control [7] is the transformation of perturbed system to a stationary mode, in which the following ratio is executed:

$$\begin{aligned} &|G_{t_i}\mathrm{O}_2 - q_{t_i}\mathrm{O}_2| \le \varepsilon_1, \\ &|G_{t_i}\mathrm{CO}_2 + q_{t_i}\mathrm{CO}_2| \le \varepsilon_2, \\ &|G_{t_i}N_2| \le \varepsilon_3, \end{aligned} \tag{3}$$

where ε_1, ε_2 ε_3 are are sufficiently small positive numbers given in advance.

In this case, the control parameters are limited by restrictions:

$$\begin{aligned} &0 \le \dot{V} \le \dot{V}_{\max}, \qquad 0 \le Q \le Q_{\max}, \\ &0 \le Q_{t_i} \le Q, \qquad \sum_{i=1}^{m} Q_{t_i} = Q, \end{aligned} \tag{4}$$

where m is the number of tissue reservoirs in the organism. Besides of this, to resolve the conflict situation between the executive organs of regulation (respiratory muscles, cardiac muscle and smooth muscles of the vessels), which at the same time are also consumers of oxygen, and other tissues and organs, lets introduce the ratio:

$$\begin{aligned} &q_{\text{resp.m}}\mathrm{O}_2 = f(V), \quad q_{\text{heart}}\mathrm{O}_2 = \zeta(Q), \\ &q_{\text{smooth.m}}\mathrm{O}_2 = \xi(Q), \end{aligned} \tag{5}$$

The quality criterion will be presented as functional:

$$I = \int_{\tau_0}^{T} \left[\rho_1 \sum_{t_i} \sigma_{t_i} (G_{t_i}O_2 - q_{t_i}O_2)^2 + \rho_2 \sum_{t_i} \sigma_{t_i} (G_{t_i}CO_2 + q_{t_i}CO_2)^2 \right] d\tau, \qquad i = \overline{1,m}, \qquad (6)$$

where V is the alveolar ventilation; Q and Q_{t_i}, $i = \overline{1,m}$ are volume velocities of the systemic and tissue blood circulations; $G_{t_i}O_2$ and $G_{t_i}CO_2$ are values of the flows of oxygen and carbon dioxide through the walls of tissue capillaries; $q_{t_i}O_2$ is the velocity of oxygen consumption; $q_{t_i}CO_2$ is the velocity of formation of carbon dioxide; τ_0 is the moment of the beginning of the influence of perturbation on the system; T is the length of this perturbation; ρ_1 and ρ_2 are coefficients that characterize the sensitivity of a particular organism to hypoxia and hypercapnia; σ_{t_i} are coefficients that reflect the morphological features of a separate tissue reservoir i.

The solution of this problem leads to the prediction of optimal values of active control parameters – ventilation, volume velocities of systemic and organ blood circulations. The minimum of functional (6), taking into account the restrictions (4) can be written as:

$$I_3 = \min_{0 \le V \le V_{\max}} I,$$

where

$$I = \int_{\tau_0}^{T} [\rho_1 \sum_{t_i} \sigma_{t_i} (G_{t_i}O_2 - q_{t_i}O_2)^2 + \rho_2 \sum_{t_i} \sigma_{t_i} (G_{t_i}CO_2 + q_{t_i}CO_2)^2 \Big] d\tau, \quad i = \overline{1,m}. \qquad (7)$$

Taking into account that integral function is additive, I can be represented as:

$$I = I_1 + I_2, \qquad (8)$$

where

$$I_1 = \rho_1 \int_{\tau_0}^{T} \left[\sum_{t_i} \left(G_{t_i} O_2 - q_{t_i} O_2 \right)^2 \frac{V_{ct_i}}{V_{t_i}} \right] d\tau, \qquad (9)$$

$$I_2 = \rho_2 \int_{\tau_0}^{T} \left[\sum_{t_i} \left(G_{t_i} CO_2 + q_{t_i} CO_2 \right)^2 \frac{V_{ct_i}}{V_{t_i}} \right] d\tau, \qquad (10)$$

The meaning of the functionals I_1 and I_2 is quite clear. Since $G_{t_i} O_2$ in (9) characterizes the velocity of delivery, and $q_{t_i} O_2$ is velocity of oxygen utilization in ith tissue region, the functional I_1 is essentially a hypoxic stimulus of regulation known in physiology. Similarly, the functional I_2 is the functional that reflects the hypercapial stimulus of regulation.

B. Investigation of the behavior of functional of quality

In difficult situational conditions x , when taking decisions, the consumption of oxygen by muscle tissue increases not so much [8], oxygen consumption is carried out mainly by brain tissues. A series of experiments [9] – [12] was carried out to study the processes that happened as a result of oxygen consumption. The aim was the studying of the behavior of functional of the quality control for hypoxic and hypercapnic regulatory stimuli (7) under the difficult situational conditions when making decisions and finding optimal control parameters.

During the simulating difficult situational circumstances, oxygen consumption by brain tissue was increased by 100%. Then $q_{\text{brain}} O_2$ will be increased from 0.6 ml/s (under the condition of main metabolism) to 1.16 ml/s. In addition, lets increase the velocity of oxygen consumption by muscle tissue by 10% (up to 1.64 ml/s). Then the total consumption of oxygen by organism will be 5.4 ml/s. The body weight of the average person is 75 kg. The time of simulation is 300 s. By changing the controlling parameters V, Q, Q_{brain} lets choose and find the optimal values of functional of the quality control for the hypoxic and hypercapnic regulatory stimuli, as well as its constituents.

In articles [9] – [12] it was shown that in case of uncompensated loading under the difficult situational circumstances, during the decision-making, the part of the functional I_1 increased from 4% within the norm to 16%, and the proportion of functional I_2 decreased accordingly from 96% to 84%. However, as in the conditions the main metabolism, the leading role belongs to the functional of quality of the hypercapnic stimulus. It is possible to estimate the contribution of hypoxia and hypercapnia in certain tissue groups in functionals I_1 and I_2 under the simulated conditions. In the functional of the hypoxic stimulus, the proportion of brain hypoxia is 34%, heart muscle

4%, skeletal muscle 62%. In the functional of the hypercapnic stimulus, the proportion of hypercapnia in tissues is 3%, 22%, 75%, respectively.

The value of the functional I with constant ventilation and increased blood circulation in the brain tends to decrease. If to fix the cerebral circulation with an increase in the volume of alveolar ventilation, it is possible to register a sharp increase in values I. The minimal value of the functional of the joint effect of the hypoxic and hypercapnic stimuli of regulation obtains at the following values of the control parameters: $V = 9.75 l/\min$, $Q = 112.3$ ml/s, $Q_{\text{brain}} = 29.8$ ml/s. With these optimal values of control influences, the contribution of I_1 to the general functional is 7%, and the contribution of the functional of the hypercapnic stimulus I_2, respectively, is 93%. With such control parameters, the values of oxygen and carbon dioxide in brain tissues are stabilized.

IV. Conclusion

The functional of quality control of the hypercapnic stimulus plays the main role in case of compensating of the load in difficult situational conditions, during the decision-making. On the behavior of the functional which minimizes, the changes in the parameters of ventilation influence greatly. The optimal control effects when simulating the compensation of the load on the brain tissues in the average person have the following values $V = 9.75$ l/min, $Q = 112.3$ ml/s, $Q_{\text{brain}} = 29.8$ ml/s (increase by 100%). Determining the optimum of human-operator and its corresponding changes in the most informative indicators opens the possibility of forecasting its efficiency, and in the prospect – to move to the management of the functional states of operators.

Continuation of the works, further developments can turn this model into a rather simple and reliable research tool; they have both theoretical and practical importance.

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Н. І. Аралова, О. М. Ключко, В. Й. Машкин, І. В. Машкина. Компромісний розв'язок конфліктних ситуацій в задачі оптимального керування під час прийняття рішень у складних ситуаційних обставинах

Одним із актуальних напрямків дослідження в медицині праці є розробка методології та способів оцінки та прогнозування функціональних резервів організму осіб, що приймають рішення, професійна діяльність яких відбувається в екстремальних умовах, зокрема при сумісній дії гіпоксичної гіпоксії та умов складної ситуаційної напруги. Пропонується застосувати математичну модель функціональної системи дихання для імітації конфліктно-керованих процесів, які виникають при самоорганізації системи дихання в умовах складної ситуаційної напруги при прийнятті рішень. Математична модель масопереносу та масообміну респіраторних газів в організмі людини представлена системою звичайних диференційних рівнянь, які в динаміці дихального циклу описують зміну напружень кисню та вуглекислого газу на всіх етапах його шляху в організмі людини. Розв'язок цієї задачі з урахуванням як внутрішньо системних, так і між системних механізмів дозволяє прогнозувати оптимальні величини активних параметрів керування – вентиляції, об'ємних швидкостей системного та органних кровообігів. Представлено результати чисельних експериментів. Їх метою було дослідження поведінки функціоналу якості керування за гіпоксичним та гіперкапнічним стимулами регуляції у складних ситуаційних умовах при прийнятті рішень та пошук оптимальних параметрів керування при пошуку компромісного розв'язку конфліктної ситуації, яка виникає між керівними та виконавчими органами саморегуляції. Чисельне моделювання показало, що при компенсації навантаження в складних ситуаційних умовах при прийнятті рішень визначальна роль належить функціоналу якості керування за гіперкапнічним стимулом і на поведінку функціоналу якості, який мінімізується, великий вплив здійснює зміна параметрів вентиляції. Визначено оптимальні керуючі впливи при імітації компенсації навантаження на тканини мозку у середньостатистичної людини. Подальші розробки можуть перетворити модель в досить простий та надійний інструмент дослідження та мати як теоретичне, так і практичне значення.

Ключові слова: особи, що приймають рішення; складні ситуаційні обставини; гіпоксичний стимул регуляції; гіперкапнічний стимул регуляції; сумісна дія стимулів.

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Н. И. Аралова, Е. М. Ключко, В. И. Машкин, И. В. Машкина.Компромиссное разрешение конфликтных ситуаций в задачах оптимального управления при принятии решений в сложных ситуационных обстоятельствах

Одним из актуальных направлений исследования в медицине труда является разработка методологии и способов оценки и прогнозирования функциональных резервов организма лиц, принимающих решения, профессиональная деятельность которых происходит в экстремальных условиях, в частности при совместном действии гипоксической гипоксии и условий сложного ситуационного напряжения. Предлагается применить математическую модель функциональной системы дыхания для имитации конфликтно-управляемых процессов, возникающих при самоорганизации системы дыхания в условиях сложного ситуационного напряжения при принятии решений. Математическая модель массопереноса и массообмена респираторных газов в организме человека представлена системой обыкновенных дифференциальных уравнений, которые в динамике дыхательного цикла описывают изменения напряжений кислорода и углекислого газа на всех этапах его пути в организме человека. Решение этой задачи с учетом как внутрисистемных, так и меж системных механизмов позволяет прогнозировать оптимальные величины активных параметров управления - вентиляции, объемных скоростей системного и органного кровообращений. Представлены результаты численных экспериментов. Их целью было исследование поведения функционала качества управления по гипоксическим и гиперкапническим стимулами регуляции в сложных ситуационных условиях при принятии решений и поиск оптимальных параметров управления при поиске компромиссного решения конфликтной ситуации, которая возникает между руководящими и исполнительными органами саморегуляции. Численное моделирование показало, что при компенсации нагрузки в сложных ситуационных условиях при принятии решений определяющая роль принадлежит функционалу качества управления по гиперкапническому стимулу и на поведение функционала качества, который минимизируется, большое влияние оказывает изменение параметров вентиляции. Определены оптимальные управляющие воздействия при имитации компенсации нагрузки на ткани мозга у среднестатистического человека. Дальнейшие разработки могут превратить модель в достаточно простой и надежный инструмент исследования и иметь как теоретическое, так и практическое значение.

Ключевые слова: лица принимающие решения; сложные ситуационные обстоятельства; гипоксический стимул регуляции; гиперкапнический стимул регуляции; совместное действие стимулов.

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