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MATHEMATIC MODELS AND INTEGRAL ESTIMATION OF ORGANISM SYSTEMS RELIABILITY IN EXTREME CONDITIONS

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Abstract—*Suggested mathematic models may be useful for organism reliable functioning prognosis for the activities at different conditions. Objective characteristics of organism supply by oxygen are used for these models as well as stress degrees of organism regulatory systems for the compensation of perturbation effects in external and internal organism media.*

Index Terms—Reliability of organism functioning; mathematic model; prognosis.

I. INTRODUCTION

Human organisms during the workload at extreme conditions are seeking to maintain own vital functions as well as to optimize the realization of stated tasks (although the high requests to physical and psychophysical organism status are demanded in such situation). For the successful work at extreme conditions the high requests to physical and physiological organism status are necessary.

II. PROBLEM REVIEW

For the estimation of these state and organism functional status in whole the series of mathematic models were developed [1]. The adequacy level of developed models depends on consideration of the real regularities of the self-control and self-organization of organism functional systems; that provide its normal vital functions under the influence of different inner and outer disturbances as well as under extreme workloads. During the workload an organism tends to optimize the realization of assigned task but not to maintain only its living activity. At such problem statement the reliability of different functions fulfillment may serve for integral estimation of functional organism state. Such demands are placed to sportsmen, polar explorers, pilots and others. Sure, professional activity has be defined by rules and its success would depend primary on organism functional state. This organism state includes integrally the estimation of physical state, psychophysiological functions as well as estimation of its energetic resources and the level of individual professional preparation. Obviously, the high reliability of organism functioning (ROF) as a whole may be maintained only in conditions of reliability of all organism systems functioning – respiratory, circulatory, immune, central and peripheral nervous systems, etc. [4]–[7]. In case of normal functioning of all organism systems, the reliability depends in great degree on the state of psychophysiological functions and the abilities of respiratory and circulatory systems to maintain in tissues the metabolic level appropriate to workload [3]. That is why during the estimation of physical state, for example for alpinists [5], physiological characteristics of functional respiratory system (FRS) state are determinative.

III. PROBLEM STATEMENT

The ***purpose*** of this article is a choosing of data model and development of algorithms for the estimation of physical status of human organism on the base of FRS characteristics.

Functional respiratory system is considered as self-organized dynamic system where the processes of respiratory gases mass transfer and mass exchange are considered as objects under control, and self-regulation is fulfilled by the system of physiological mechanisms that includes central, local and humoral chains [2]. The aim of such self-regulation is maintaining of gas homeostasis under the different disturbances of external and internal media of organism. In contemporary physiology such structural chains for respiratory gases mass transfer and mass exchange are defined: respiratory ways, alveolar space, blood of the lung capillaries, arterial blood, tissues and blood of tissue capillaries, and mixed venous blood (Fig. 1).

IV. PROBLEM SOLUTION

The main parameters for characterization of FRS are partial pressures (tensions) of oxygen pO_2, and carbon dioxide pCO_2 in alveolar space, blood and tissues. Functionally these chains are united into systems – external respiration, cardiovascular and blood systems.

The experience of FRS mathematic model use [2], [10], physiological and clinical data evidences that for the wide classes of disturbances influenced on organism the hypoxic stimulus is determinative during the self-organization of the main function. Increasing of organism sensitivity for hypercapnia and its decreasing for hypoxia is linked usually with medium-term adaptation to vital activity conditions. That is why in present work for the elaboration of data models and algorithms of organism state estimations we used the data that characterizes processes of oxygen delivery to tissues and its mass exchange; these characteristics are measured in clinical practice usually. The estimation of reliability of respiratory system functioning we will do taking into account the simple (primary) data that characterize each chain of structure, and their derivative (integral) indices.

Below the brief descriptions of data models for the each of examined chains is given.

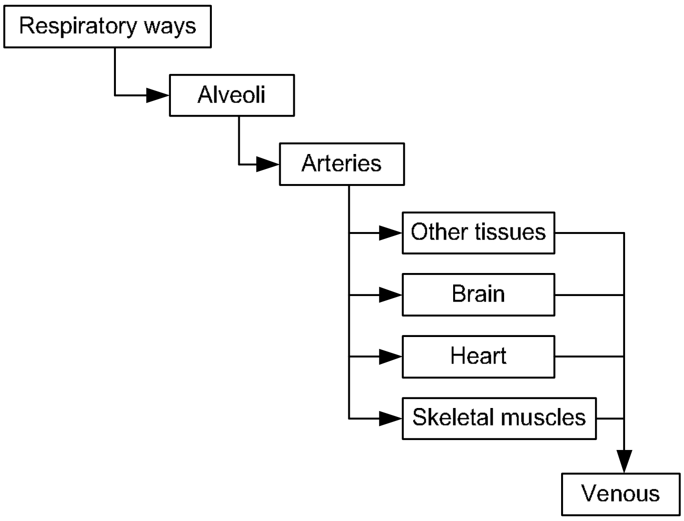

Fig. 1. Structural scheme of respiration functional system

V. RESULTS

A Anthropometric data

It is important that all such experimentally registered data depend substantially on the sex and age of examined individual. That is why these data models have to be supplemented by the system of anthropometric data S_0. In our models the system S_0 is represented by the set of the following data: family name, personal name, father name, age (A), weight (W), and height (H) of sportsman.

$$S_0 = S_0(A, W, H) \tag{1}$$

B System of external respiration (S_1) and system of oxygen delivery in respiratory ways (S_2)

External respiration is provided mainly with the activity of respiratory muscles under the control of central and autonomic nervous system in correlation with oxygen needs of organism. It includes 2 subsystems: one for the organization of mass transfer process for the gas (S_1), other one for autonomic supply of external respiration. The most substantial index for providing of adequacy of main respiratory function in chain (S_1) is index ($\dot{V}$), more simple – respiratory frequency (f) and respiratory volume (V).

So, S_1 may be represented as:

$$S_1 = S_1(\dot{V}, f, V). \tag{2}$$

The system of oxygen delivery at respiratory ways is S_2. Final aim of this chain is formation of $p_A O_2$ (partial oxygen pressure in alveolar space), necessary for defined vital conditions. The most informative index for this chain of process is $q_A O_2$ – the velocity of oxygen arrival to alveoli.

Quantity of the process is estimated by economy index (VE), and effectiveness index (VA). The data that characterize this FRS chain may be represented by following parametric expression:

$$S_2 = S_2(q_A O_2; VE, VA, p_A O_2), \tag{3}$$

where derivative indices (integral) are placed before the “point and comma” symbol, and after it are the simple (primary) indices.

Regulatory mechanisms support index ($\dot{V}$) at the level that is adequate to disturbance influence. The degree of their tension at compensation of disturbances is estimated by the values that may be obtained in result of statistical processing of the data registered in series of planned experiments.

The best way to calculate the tension degree of autonomic supply for external respiration is to calculate it separately for parameters f and V. That is why in the system of external respiration autonomic supply the subsystems S_3 and S_4 are subdivided; data model descriptions for them are the same. As example let demonstrate in details the data, used for S_3.

Derivative (integral) index for S_3 is an index of autonomic system tension according to f (TI_f); it reflects correlation between the main statistic indicators of external respiration, also it characterizes the degree of tension for systems of short-term adaptation to changes of vital conditions as well as degree of centralization of control process [16]. As primary (simple) indices are used:

M_f is the expectation value f; δ_f is the relative number of average deviation of f from normal value (in %); $\Delta\chi_f$ is the length of maximal dispersion of f observation in experiments; D_f is the total variance of f; D_{1f}, D_{2f}, D_{3f} are dispersion of slow waves of the first, the second, and the third order for f; the formation of averaged f under the influence of high frequency subcortical nervous signals using them is analyzed.

So,

$$S_3 = S_3\left(TI_f;\ M_f, \delta_f, \Delta\chi_f, D_f, D_{1f}, D_{2f}, D_{3f}\right). \quad (4)$$

In the same way may be formed the data model that characterized the tension of the system for autonomic supply of external respiration according to (V) definition:

$$S_4 = S_4\left(TI_V;\ M_V, \delta_V, \Delta\chi_V, D_V, D_{1V}, D_{2V}, D_{3V}\right). \quad (5)$$

C System of gases transportation by circulating arterial blood

System of gases transportation by arterial blood consists on subsystems for blood circulation supply (S_5), transportation of gases by blood S_6, and subsystems S_7, S_8 for control and regulation of oxygen transportation to tissues by blood.

Blood circulation is provided by the work of cardiac muscles (executive regulatory organ).

The most general index that characterizes an adequate level of heart functioning is (Q). As simple indices are used: stroke volume (SO), heartbeat frequency (HR), total peripheral resistance (TPR), volume of cardiac output (VSO), systolic (SD) and diastolic (DD) arterial pressure. All parameters are linked through the (Q) formation, but the role of each in pathologies development is absolutely specific. Parametric expression of data model for subsystem S_5 may be represented as:

$$S_5 = S_5(Q;\ SV, HR, TPR, VSO, SD, DD). \quad (6)$$

System of gas transportation by arterial blood is described usually by the data model:

$$S_6 = S_6(q_a O_2;\ HE, HA, p_a O_2), \quad (7)$$

where $q_a O_2$ is the velocity of oxygen transport; HE is the haemodynamic equivalent that characterizes efficacy of oxygen delivery to tissues; HA is the coefficient of oxygen delivery efficacy; $p_a O_2$ is the oxygen tension in arterial blood.

The tension of regulatory mechanisms of blood circulation system may be characterized by the data that are formed on the base of statistical methods for processing of the primary haemodynamic indices – (SO) and (HR). With the aim of differentiation of disturbances in the system of regulation the data models for subsystems S_7, S_8 are elaborated; the role of these systems is autonomic supply of cardiac muscle control for the formation of (SO) and (HR). Main derivatives in these models are tension indices TI_{SV} and TI_{HR}. We would like to notice that the synergism in work mechanisms of external respiratory system regulation and haemodynamic system were taken into account by using in S_7, S_8 of dispersion values (SO), (HR) under the influence of external respiratory waves (D_{0SV}, D_{0HR}).

$$\begin{aligned} S_7 = S_7(&TI_{SV}; \\ &M_{SV}, \delta_{SV}, \Delta\chi_{SV}, D_{SV}, D_{0SV}, D_{1SV}, D_{2SV}, D_{3SV}), \end{aligned} \quad (8)$$

$$\begin{aligned} S_8 = S_8(&TI_{HR}; \\ &M_{HR}, \delta_{HR}, \Delta\chi_{HR}, D_{HR}, D_{0HR}, D_{1HR}, D_{2HR}, D_{3HR}). \end{aligned} \quad (9)$$

D System of tissue respiration

The main characteristics of intensity of metabolic processes that are examined and defined in medical examinations is the velocity of oxygen consumption by organism $q_t O_2$. During the estimation of organism health the information about this index may be sufficient. From other side, for characterization of tissue respiration at different organs it is necessary to know the values of pO_2 and peripheral resistance to blood stream in tissue capillaries. Unfortunately, contemporary methods give no possibilities for simultaneous registration of such data at different organs of organism. That is why additionally to this data model it is necessary to use mathematic models of the main respiratory function [2]. In suggested approach $q_t O_2$ is supposed as the simple and integral indicator of tissue respiratory system:

$$S_9 = S_9(q_t O_2). \quad (10)$$

E System of person special workability

All data above may be obtained in rest state of the person (main state of metabolism), and during trainings at bicycle ergometer. But each of human activity type is specific so, has peculiar necessity in oxygen consumption and peculiar demands to some chains of oxygen transportation system. In some cases this specificity may be examined using special bicycle ergometers, in other cases for person examination ordinary bicycle ergometers are used without taking into account the specificity of person professional activity.

For integral estimation of special work ability of examined person we suggest as necessary to use following dependence:

$$S_{10} = S_{10}(P_i), \tag{11}$$

where S_{10} is a system, P_i are parameters of respiratory system, registered in experiments during the tests for studying of person special work ability.

It is known that data models for the systems of regulatory supply of respiratory process are built on the base of statistically processed experimental data obtained usually in rest conditions, during physical loadings of different intensity and after loadings. Further data models will be described in compliance with different experimental conditions, used for the making of estimation spectrum on the base of its analysis the integral estimation of testee physical state may be done.

Each of above described subsystems may be estimated by analysis of its integral indicators with a glance of its main function provision. Besides of such abovementioned estimations, there are also another set of substantial complex estimations of observed subsystems; the last ones are elaborated on the base of all subsystem simple indices analysis. These data will be used for obtaining of estimations of more high level including also estimations of all organism (as will be described below).

It is supposed that for each index x_k the norm intervals are set $\left[x^n_{k\min}, x^n_{k\max}\right]$.

Estimation V_{x_k} that points on the degree of x_k deviation from its norm interval is calculated according to rule (%):

$$V_{X_k} = \begin{cases} V^0_{X_k} - 50, & V^0_{X_k} > 50; \\ V^0_{X_k} + 50, & V^0_{X_k} < -50; \\ 0, & \left|V^0_{X_k}\right| \le 50, \end{cases} \tag{12}$$

$$V^0_{x_k} = \frac{2x_k - \left(x^n_{k\min} + x^n_{k\max}\right)}{2\left(x^n_{k\max} - x^n_{k\min}\right)} 100, \tag{13}$$

where $V^0_{x_k}$ is an order of deviation of x_k from its optimal one (in %).

From (12) and (13) is follows that "zero" estimation of index x_k will be formed in a case when x_k is in of its norm. Indication of "not zero" estimation points on direction of x_k deviation from the norm interval, and its meaning – on degree of deviation.

Complex estimation of S_0 subsystems (anthropometric data) is elaborated using following regression model:

$$V_{S_0} = \gamma_w \left|V_w\right| + \gamma_H \left|V_H\right| + \gamma_{TCh} \left|V_{TCh}\right|, \tag{14}$$

where $\gamma_W, \gamma_W, \gamma_{TCh}$ is the group of normalized weight coefficients that characterize the importance of elaborated according to (12) and (13), estimations V_W, V_Y, V_{TCh} (for indices W, H, TCh) in elaboration of estimation V_{S_0}.

By analogy other complex estimations are elaborated $V^j_{S_i}$, $i = \overline{1,10}$, $j = \overline{1,r}$, where j is the number of experiment in which the data of tested person were measured (r is the total number of experiments, data from which are used for the obtaining of integral estimations):

$$V^j_{S_i} = \sum_{k=1}^{n_i} \gamma_{x^j_k} \left|V_{x^j_k}\right|, \tag{15}$$

where n_i is a number of simple indices x^j_k of subsystem S_i; $\gamma_{x^j_k}$ is the weight coefficients for the fixed j, they form the separate group of normalized coefficients; $V_{x^j_k}$ is the estimation of index x^j_k of system S_i, it is measured in j th experiment.

Based on (14), the formula for the complex estimation of the system S_1 is:

$$V^j_{S_i} = \gamma_{VE^j} \left|V_{VE^j}\right| + \gamma_{VA^j} \left|V_{VA^j}\right| + \gamma_{p^j_A O_2} \left|V_{p^j_A O_2}\right|. \tag{16}$$

For subsystems S_9, S_{10} that characterized by one index only in present work, the estimation is following:

$$V_{S_9}{}^j = \left|V_{q^j_t O_2}\right|, \tag{17}$$

$$V_{S_{10}}{}^j = \left|V_{P_i}\right|. \tag{18}$$

According to obtained estimations $V_{S_i}^j, j=\overline{1,r}$ for each subsystem S_i, $i=\overline{1,10}$ the estimation of more high degree is formed:

$$V_{S_i}=\sum_{j=1}^{r} v_{S_i}^j V_{S_i}^j, \tag{19}$$

where $v_{S_i}^j$ is the weight coefficients, in case of fixed i they compile the group of normalized coefficients.

Estimation of system of oxygen delivery V_{SO_2} and total estimation of physical organism state V_S are elaborated according to formulas:

$$V_{SO_2}=\sum_{j=1}^{9}\theta_i V_{S_i}^j, \tag{20}$$

$$V_S=\gamma_0 V_{S_0}+\gamma_1 V_{SO_2}. \tag{21}$$

Equations (15) – (21) represent one of two branches of described algorithms. Estimations elaborated according to these formulas were obtained on the base of analysis of estimations for the simple indices for systems S_i $i=\overline{1,10}$, and anthropometric data of person.

The second branch of algorithm is intended for the elaboration of estimations that are formed on the base of analysis of estimations of integral indices for systems S_i $i=\overline{1,10}$, where the compensatory functions of self-regulatory mechanisms are taken into account.

According to calculated by (12) and (13) estimations $V_{q_A^i O_2}, V_{\dot{V}^j}, V_{TI_f^j}, V_{Q^j}, V_{q_a^j O_2}, V_{TI_{SV}^o}$ the general integral regulatory systems are elaborated. They characterize the functional state of chains of regulatory system that is responsible for the provision of proper values of integral indices. Calculation of such estimations is done using formula:

$$V_x=\sum_{j=1}^{r}\gamma_{x^j}\left|V_{x^j}\right|, \tag{22}$$

where V_x is the general integral estimation of integral index x; V_{x^j} is the estimation of integral index by data of j th experiment; γ_{x^j} is the normalized weight experiment.

Than were elaborated the general estimations for $V_{\mathrm{SO}_2}{}^j$ – system of oxygen delivery in organism for each $j=\overline{1,r}$, in which the compensatory reactions for mechanisms of integral regulation were provided

$$V_{\mathrm{SO}_2}^j=\theta_{S_1\text{-}S_6}^j\left|K_{S_1}^j V_{q_A^j\mathrm{O}_2}+K_{S_6}^j V_{q_f^j\mathrm{O}_2}\right|+\theta^j{}_{S_2\text{-}S_6}\left|K_{S_2}^j V_{\dot{V}^j}+K_{S_5}^j V_{Q^o}\right|+\theta_{S_3}^j\left|Kj_{S_3}+K_{S_4}^j V_{TI_V^j}\right|$$
$$+\theta_{S_7\text{-}S_8}^j\left|K_{S_7^j}^j V_{TI_{SV}^j}+K_{S_8}^j V_{TI_{HR}^j}\right|+\theta_{S_9}^j\left|V_{q_t^j\mathrm{O}_2}\right|,$$

where $\theta_l^{j,}, l=S_1-S_{6,}, S_2-S_5, S_3-S_4, S_7-S_8, S_9, S_{10}$ is a group of normalized weight coefficients for each one; $j=\overline{1,r}$; $K_{S_1}^j, i=\overline{1,8}$ are numeral coefficients that signify an order of compensatory reactions for the maintaining of necessary values of integral indices.

Calculations of general estimations for the system of oxygen delivery $V_{\mathrm{SO}_2}^R$ and organism physical state V_S^R, where the compensatory reactions for regulatory mechanisms are foreseen, were provided on the base of following decisive rules:

$$V_{SO_2}^R=\sum_{j=1}^{r}\gamma^j V_{\mathrm{SO}_2}^j, \tag{23}$$

$$V_S^R=\gamma_0 V_{S_0}+\gamma_1 V_{\mathrm{SO}_2}^R, \tag{24}$$

where $\gamma^j, j=\overline{1,r}, \gamma_0, \gamma_1$ are the groups of normalized weight coefficients.

VI. CONCLUSIONS

Appears from the above, the suggested algorithm permits to obtain the spectrum of integral estimations that have different levels and degrees of their informative values. Models of linear regression are used in present work. As input data for algorithm were used: medical examination and functional probes data that characterize oxygen regime of organism; norm intervals for each index and for each model for experimental data; weight and other coefficients equipped in algorithm.

Integral estimations elaborated by suggested method may be useful for the forecasting of ROF – organism reliable functioning – in different spheres of human activity. Prerequisites for this are the use of objective indicators of person (f. e. sportsman) oxygen supply as well as degrees of regulatory systems tension that are able to compensate disturbance effects in external and internal organism media.

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Ю. М. Онопчук, Н. І. Аралова, П. В. Білошицький, О. М. Ключко. Математичні моделі та інтегральна оцінка систем надійності організму в екстремальних умовах

Запропоновані математичні моделі можуть бути корисні для прогнозування надійності функціонування організму за різних умов. Для створення цих моделей застосовано як об’єктивні показники кисневого забезпечення організму, так і ступені напруженості регуляторних систем, що компенсують впливи збурень зовнішнього й внутрішнього середовища організму.

Ключові слова: надійність функціонування організму; математична модель; прогноз.

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Ю. Н. Онопчук, Н. И. Аралова, П. В. Белошицкий, Е. М. Ключко. Математические модели и интегральная оценка систем надежности организма в экстремальных условиях

Предложенные математические модели могут быть полезны для прогнозирования надежности функционирования организма в различных условиях. Для создания этих моделей использованы как объективные показатели кислородного обеспечения организма, так и степень напряженности регуляторных систем, которые компенсируют воздействия возмущений внешней и внутренней сред организма.

Ключевые слова: надежность функционирования организма; математическая модель; прогноз.

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