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

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***Abstract***—*The mathematical model and a set of informational support for the investigation of reliability and professional selection of operators for the systems of uninterrupted interaction for the work in extreme conditions of environment is suggested. The results of numerical analysis of model functioning for the average person organism are given.*

**Index Terms**—Operator of continuous interaction; reliability of operator work; adaptation; mathematic model of respiratory system.

## I. INTRODUCTION

State of military air forces have to be maintained at high level for provision of effective defense capability of Ukraine. Construction and production of the new modern technique samples, upgrading of existing ones, consequent complications of combat missions set more stringent requirements for the personnel and their professional efficiency, maintaining of the pilot functional state at optimal level in process of professional activity, extending of professional longevity.

## II. PROBLEM REVIEW

Professional activity requires good health, high efficiency and endurance, fast and precise reactions, good memory, emotional stability, and etc. of pilots [1], [2]. Aviation medicine defines professional health as organism property to maintain compensatory and protective mechanisms for ensuring of professional activity efficacy in different conditions [2]. In medical chapters related to operators' activities in systems of continuous interaction (including pilots), where doctors permit assessment to the work, the human health state estimation with its forecasting is the cornerstone of diagnosis [3]. In order to ensure fly safety in publication [4] were proved that existing medical control system have to be supplemented with pilot functional status estimation. We would like to note that efficacy of professional military activities after the professional selection, training and appropriate equipment is 65% determined by the soldier organism functional state [5]. According to [5] the functional state of human body is integrated set of operator features and qualities that provide professional problems solution directly or indirectly with different quality level. Primary it was demonstrated that functional human status is a complex of characteristics of physiological functions and psycho physiological characteristics that define the level of functional systems activities, peculiarities of the livelihoods and work ability. Classification of organism functional states according to the level of organism adaptability to environmental conditions, reliability and its activity estimation, the degree of homeostasis regulatory mechanisms tension, review of the body reaction adequacy have been done in [4]. In ergonomics for the evaluation of the person activity the term "functional reliability" is suggested; it refers to person's ability for maintaining of a stable high functionality that allow to show the high efficacy and effectiveness of professional activity in stressed (extreme) conditions [6].

The notion "professional military pilot conditions" include the high-altitude flight factors (low barometric pressure and the associated low oxygen partial pressure, sudden changes in barometric pressure, low temperature environment, etc.) and dynamic flight factors. Among them piloting overload possesses specific place with such consequences as displacement and accumulation of blood in the vessels of the abdomen and lower limbs and relative lowering of blood pressure and head blood supply reducing, high vibration, intense noise, factor of stress, and etc. The combination of these hazards conditions of the flight, constant stress and long-term phychophysiological functions tension during the flight leads to a decrease in functional reserves and adaptive capacity of the body as a whole.

In numerical investigations that are reviewed in [4] the concept of organism "adaptation" become closer to the concept of "reliability" that defines such level of regulation and physiological ratio of elements of physiological process, when the optimal activity of physiological systems and the whole organism is provided.

From other side, in publication [7] were demonstrated that some methods of reliability theory (with some limits) may be applied to natural objects, including human organism.

## III. Problem Statement

The ***purpose*** of this article is to prove that the "weak element" (link) of pilots are respiratory system and system of psychophysiologic functions using methods of reliability theory for suggesting the reliability model of operator functional state as continuously interacting system like a chain with "weak element" (link). For reaching of this purpose the software package for studying of reliability and professional selection for pilots were necessary to suggest.

Living system would operate reliably in constantly changing internal and external environment, so making the optimal solutions for providing of highly reliable life. For example, in human organisms the main functions of the respiratory system is 1) ensuring of metabolizing tissues by oxygen adequately and in time; 2) metabolic carbon output. This system is operated by the network of central, local and humoral mechanisms that interact closely with each other. Living system – a focused system, it forms the life purposes, optimality criteria by itself, and may sacrifice life safety for own purposes, or even refuse to work for normal life conditions. For reaching of stated purpose numerical experiments were necessary to carry out; the results of simulation modeling of average person in conditions of increased situational stress we would like to study. Obtained results are given below.

## IV. Problem Solution

Living system is a complex dynamic system. So, the general patterns of behavior and reliability of complex systems may be applied for it. Really, in living systems may be defined three stages of failure threat functions change $M(t)$:

– random (non-random) failures linked with the forced organism defects, congenital abnormalities;

– effective work. All physiological systems of the body function normally at this stage, without abnormalities. The level of reliability of the whole organism depends on the specificity of psycho- physiological organism systems and selected purposes. Averaged value of the work without failures may depend greatly on the value of mentioned purpose. It may happen that the purpose reaching on the base of organism internal reserves is impossible, since it would lead to complete exhaustion. Then organism systems responsible for the decision to suspend the work it will take such a decision. Average length of work time without failures uptime also depends on conditions of human activity. That is why it is important to estimate the reliability of the living system in a variety of disturbances;

– risk of work failure (refusal) during organism aging or in case of pathologies development.

Thus it is possible to argue that the models of reliability theory may be applied to assess the reliability of operator work in terms of increased situational stress.

The problem of reliability models is to establish the links between system elements and their impact on the work of the system. The system functional structure defines the rules of element characteristics interaction under which they operate in certain way and sequence.

If the system is constructed in such a way that its successful functioning depends on the work of all elements necessary work, it is called "sequential" system. If in case of failure any element can substitute another one functioning, the system is called parallel one. Living systems as complex systems have to be attributed to "sequential–parallel" systems [8]. Indeed, certain living system functions, if not entirely, but at least partially may be replaced by more intensive work of other systems (blood deposit, erythropoiesis, local and central regulatory mechanisms of the respiratory system, etc.).

The model for living system failures is proposed in [7]. This model is developed for the case $K$ – that the system functions without failures (it supports vitality and performs prescribed (specified) function), and $K$ – a case when subsystems perform their functions without failures in this system. Let's assume for this system, that $K$ – is realized ever in case of $K_j$, $j=\overline{1,n}$, so

$$K = K_1 \cap K_2 \cap K_3 \cap .... \cap K_n. \tag{1}$$

From it

$$P(K) = P\left(K_1 \cap K_2 \cap K_3 \cap .... \cap K_n\right),$$

$$P(K) = \left[\prod_{j=1}^{n} P\left(K_1 \cap K_2 \cap K_3 \cap .... \cap K_n\right)\right] P\left(K_n\right). \tag{2}$$

Assuming that $K_j$ are independent together, then

$$P(K) = \prod_{j=1}^{n} P\left(K_j\right), \tag{3}$$

and reliability function is given by

$$M = \prod_{j=1}^{n} M_j. \tag{4}$$

The model of "weakest chain" also may be used for the dependent "sequential" systems.

Let's examine a system in which the rejection occurs when, and only when one or more subsystems denying:

$$L = L_1 \cup L_2 \cup L_3 \cup .... \cup L_n. \tag{5}$$

Let's consider also that in case of system refusal, also any "marked" subsystem refuses. This suppose may be written as:

$$L \subset L_1. \tag{6}$$

But because $L \supset L_1$, events $L$ and $L_1$ are equivalent and have the same probability

$$P(L) = P(L_1). \tag{7}$$

Because any from $L_j$ leads to $L$ and subsequently leads to $L \subset L_j$, $j = \overline{2,n}$,

hence

$$P(L) = P(L_1) = \max P(L_j), \tag{8}$$

or

$$M = M_j = \max M_j. \tag{9}$$

Let's suppose "marked subsystem" as the "weakest link of consequence chain so, the mechanism of system failures has properties of failures circuit mechanism. The chain consists of links, one or some of them are the weakest one, so this link strength is minimal. The "weakest links" model may be used for the reliability calculation not only for an integrated system, but also for its individual subsystems.

Let's suppose also that for the description of the strength of the individual chain link the probability distribution may be used. Let suppose that number of strengths has the density $\varphi(x)$ and relative function of distribution $\Phi(x)$ such that

$$\Phi(b) - \Phi(a) = \int_a^b \varphi(x) dx, \tag{10}$$

represents the probability of the link strength between $a$ and $b$ ($b > a$).

Similarly, let suppose that the tension on the component is characterized by the density $\psi(y)$ and the distribution function $\psi(y)$ so that

$$\Psi(d) - \Psi(c) = \int_c^d \psi(y) dy. \tag{11}$$

If to add positive random variables $X$ – strength of the component and $Y$ – efforts used, tension, the

$$P(X \le x) = \Phi(x),$$

$$P(Y \le y) = \Psi(y).$$

Reliability level is defined as the probability that a a chain component will be maintained

$$M = P(X > Y), \tag{12}$$

$$M = \int_0^\infty \int_0^\infty \varphi(x) \psi(y) \, dx dy,$$

or

$$M = \int_0^\infty \psi(y) [1 - \Phi(y)] dy. \tag{13}$$

Let's examine the chain consisting of elements (links) $n$ In this case it is possible to assume that it's strength is equal to the strength of it's weaker element. So the strength $Y_n$ of the chain $n$ elements are minimal $X_i$, $i = \overline{1,n}$.

In reliability theory is shown [6] that for any value of the tension $Y_n$ applied to the chain with density of probability $\psi(y)$, , the probability that the strength $Y_n$ force of strength will dominate $Y$ and

$$M_n = P(Y_n \supset Y) = \int_0^\infty \psi(x) [1 - \Phi(x)] dx,$$

or

$$M_n = \int_0^\infty \psi(x) [1 - \Phi(x)] dx. \tag{14}$$

So reliability of chain is $n$ of elements is equal $M$. Examining the reliability model for the whole organism as a model of the chain, one can assume that the "weakest element"; it has respiratory and blood circulation subsystems as well as subsystems of psychophysiological functions. Since the work capacity of organism depends greatly on how reliably and effectively performed the main function of respiratory and circulation subsystems (weak elements), so, further we examine exactly this system. Output main characteristics of respiratory and blood circulation systems we will define quantitatively, basing on the primary function of the respiratory system - timely and adequate delivery of oxygen to organs for metabolism and output of used carbon.

It is possible to suppose that the system fulfills its function successfully if the oxygen tension ($p_aO_2$) and carbon dioxide gas ($p_aCO_2$) in arterial blood and in tissues ($p_{t_i}O_2$ and $p_{t_i}CO_2$) are in defined limits:

$$
\begin{aligned}
&p_a^{\min}O_2 < p_aO_2 < p_a^{\max}O_2,\\
&p_a^{\min}CO_2 < p_aCO_2 < p_a^{\max}CO_2,\\
&p_{t_i}^{\min}O_2 < p_{t_i}O_2 < p_{t_i}^{\max}O_2,\\
&p_{t_i}^{\min}CO_2 < p_{t_i}CO_2 < p_{t_i}^{\max}CO_2.
\end{aligned}
$$

Minimal value of oxygen and carbon dioxide tension in blood and tissues determined the number of threshold values. If these values are lower than threshold – pathology in blood system and tissue metabolism happen. If these values are higher – they mean characteristics that may be determined in conditions of basal metabolism. So, in the last case it is possible to obtain the values that characterize the state when the refuse of work happen. Functional scheme of process of respiratory system basic function implementation is shown in Fig. 2.

In [7] have been proved that structural and functional diagram of the respiratory system for the determination of reliability of its operation should be presented as a query scheme. Individual elements have to be considered here as subsystems of respiratory, pulmonary circulation, cardiac and vascular functional systems, regulatory and blood systems.

It is known that main problems of complex systems reliability is the development of methods for setting modes and for selecting of characteristics that provide optimal reliability, for development of optimal methods violations detecting, for revealing of their causes, and etc. For these problems solutions the reliability theory uses the results of physical and chemical processes that lies in base of phenomena associated with quality loss. The same problems are the main in such spheres as physiology of work, sport and recreation. For research of functional respiratory system on mathematical models contemporary physiology has sufficient knowledge about respiratory and blood circulation processes [9]. Due to this today we can investigate successfully the nature of organism mechanisms that provide enough high level of reliability of all his functional systems. Analysis of these models allows you to set the basic rules of respiratory and blood circulation processes, the role of regulatory mechanisms in providing and maintaining of basic respiratory function under various conditions of human life, to set main properties of studied process. For example, during long years the fact of human organism stability, including stability of respiratory system to perturbations of external and internal environment is known. Mathematic modeling of main respiratory functions not only confirmed this property, but also revealed the mechanisms of its manifestation. Properties of sustainability of respiratory and blood circulation processes are very important in ensuring of this functional system reliability. The process of providing of tissues with oxygen and output of waste carbon dioxide is characterizes by following property: for short-term or permanent disturbances of internal environment this is a region of relative equilibrium in which the speed of oxygen delivery (carbon dioxide output) is equal to the rate of its consumption (production). In other words, the urgent (stress-reaction) happen. During it the connection of active self-regulatory mechanisms happen, it is characterized by the increasing of heart rate, blood pressure, respiratory rate or steady adaptation with structural changes in organism. Reliability of functional systems is maintained at high level. But this happen in a case when the disturbing influence does not decrease oxygen tension in tissues lower than critical values (at "chain model" – disturbing forces exceeds the strength of chain element). The model demonstrates that the process is stable for wide range of perturbations and can be supported by passive self-regulation mechanisms by oxyhemoglobin, myoglobin, and etc. However, the stability of process is only a necessary but not sufficient condition for system properties to maintain reliability of its function. It was found that for reliable functioning of individual organs and tissues it is necessary to have high level of average oxygen tension in organism. For example, for brain tissue this value is 33 mmHg. Mechanisms for the maintaining of respiratory processes stability based on biochemical regulators only can maintain this level not for all disturbances. The high level of oxygen homeostasis in tissues is provided by active regulatory mechanisms: by choice of ventilation that adequate to disturbance, blood circulation, distribution of tissue circulation among tissue regions according to their need in oxygen. These mechanisms not only maintain the stability of respiratory and blood circulation processes but they also make conditions for the normal functions realization for respiratory system with changing of life conditions, so they maintain system reliability at high level. Thus the active mechanisms of respiratory and blood circulation regulation are the short-term and medium-term mechanisms of adaptation to changes of internal and external environment [7]. Short-term as well as mid-term adaptation and their impact together in all life conditions cannot guarantee the high reliability of organism functioning in various activities. Explanation of this effect may lie in the physiological, morphological, and structural features of an individual. We would like to note, that human organism ability to long-term adaptation is important also. At this stage the changes in structures of subsystems happens, as well as changes in individual organs and tissues, changes of sensitivity coefficients to hypoxia and hypercapnia. Thus, characterizing organism mechanisms for maintaining of reliability level of respiratory system function, and reliability of whole organism in performance of its purposeful actions, one should provide mechanisms that support the resistance processes of short-term, medium term and long term adaptation mechanisms, as well as mechanisms of central, local and humoral regulation of phychophysiological function resistance. Obviously, the high reliability of the operator's organism as whole can be maintained only on condition of all organism systems reliability – respiratory, blood circulation, thermoregulation, immune, central and peripheral nervous system [8]. Assuming that all organism systems function normally, the reliability depends greatly on physiological functions and possibilities of respiratory and blood circulation system to provide appropriate metabolic level in tissues.

Usually for the evaluation of psychopsychophysical state of operators various functional tests, physical loadings were used [10]. Individually-typological features of higher nervous activity (HNA), functional mobility of the nervous system, brain work ability, and functional state of autonomic nervous system as well as cardiorespiratory, hematopoietic, immune and hormonal systems were examined. Concerning the tension degree of regulatory mechanisms of respiratory and circulatory objective difficulty of experimental data obtaining on the functional mechanisms of respiratory system regulation – it is possible to conduct numerical experiments with mathematical models that describe the behavior of respiratory system at disturbances of internal and external environment (Fig. 1).

Our investigations were conducted on a model with four tissues - brain, heart, skeletal muscle and others (Fig. 2). Simulations were conducted for the mode of average person with 75 kg weight, for which such parameters of functional state in rest are known: tension of oxygen in arterial blood is 95 mmHg, in brain tissues – 38, in heart muscle – 30. Intensity (velocity) of oxygen consumption in brain tissue was 0.62 ml / s, heart muscle – 0.33 ml / s, organism as whole consumed 4.3 ml / s oxygen. The content of hemoglobin in the blood was 140 mg / l, the concentration of buffer bases – 0.479 g / l. The purpose of computing experiments was determination of regulatory parameters that provide oxygen tension in brain tissues at 33 mm Hg level. In computational experiment an increase of operator activity intensity was imitated using the growth rate of oxygen consumption of brain tissue on 10; 20; 30 percents or more. Accordingly, the respiratory rate at rest was taken equal to 0.8, while with loading – 1.2.

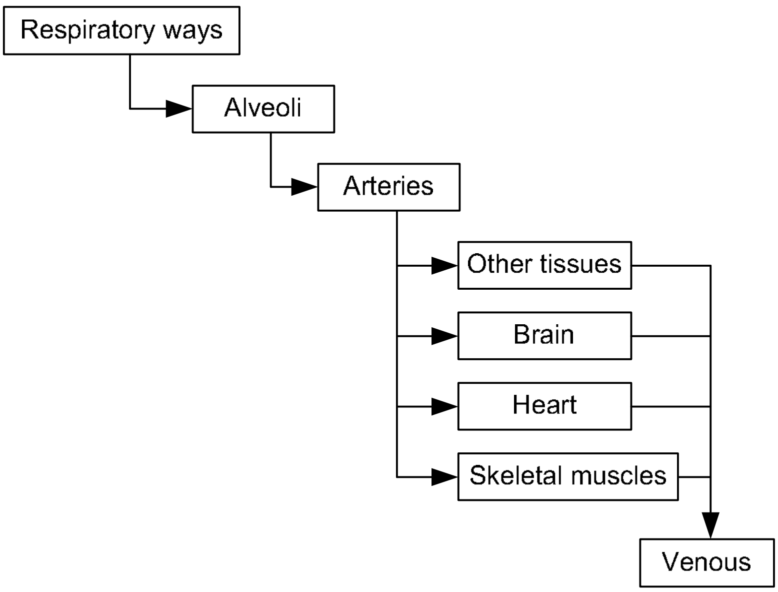


Fig. 1. Structural scheme of a four models of respiratory system

Our calculations demonstrated that maintaining of set level $pO_2$ in brain tissues with increasing of the rate of oxygen consumption by the brain up to 20% of the rest is possible without using of compensatory reactions of respiratory system and blood circulation systems. Let's note that in the rest system volume velocity of blood flow was 95 ml / s, and volumetric velocity of blood flow in brain was 14.88 ml / s.V.

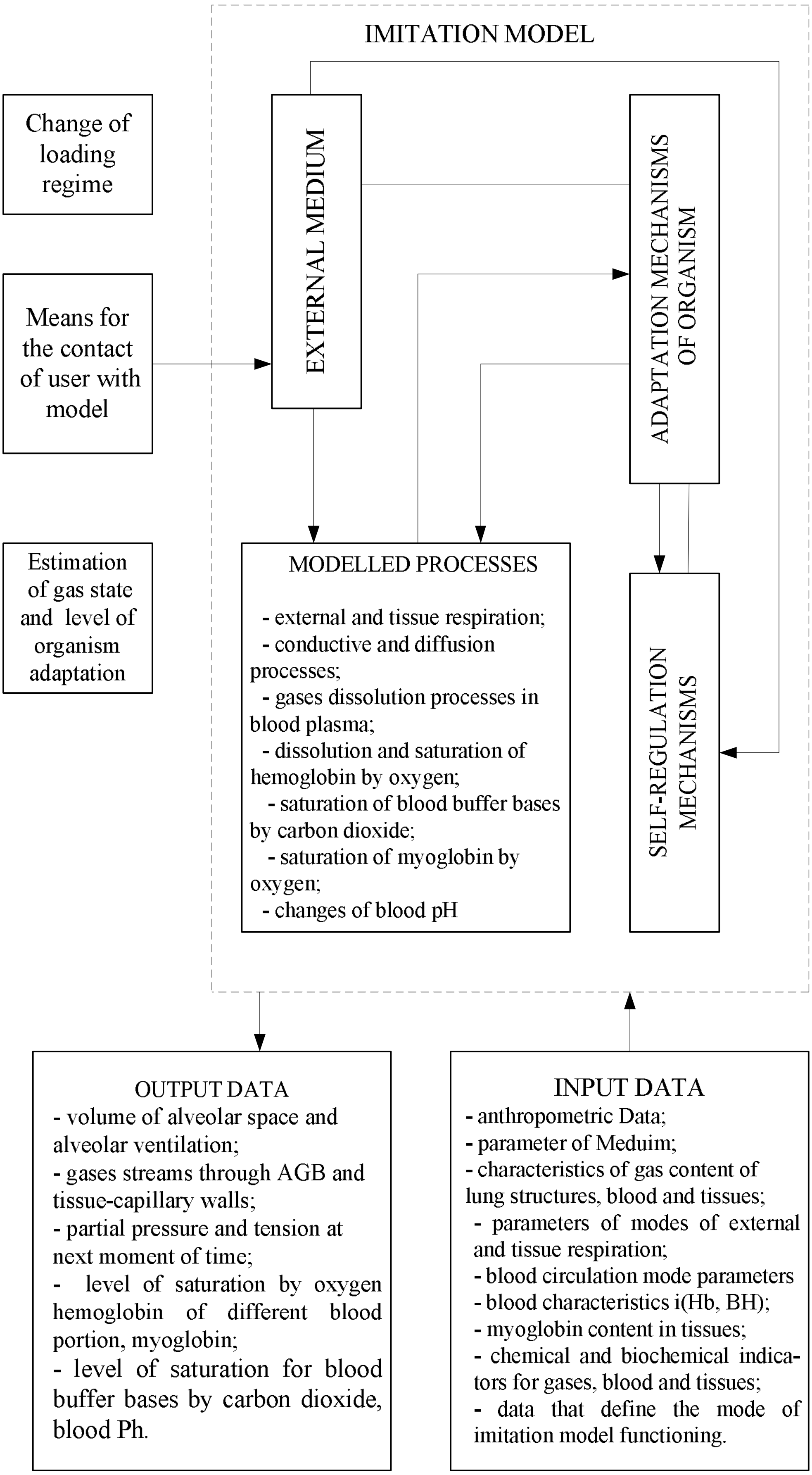


Fig. 2. Scheme of mathematic model of respiratory system

Increase of the brain load by 30% requires the inclusion of regulatory mechanisms. If the response had no regulatory mechanisms $pO_2$, the brain would decrease to 31.77 mm Hg. Calculations demonstrated that the increase in brain tissue of blood flow by 10% would result in oxygen tension in the brain tissues to 33 mm Hg. In this case, we would like to note that the increase in blood flow in brain tissues is possible or due to increasing of the volume of system blood flow velocity that will lead to increasing of the load on the heart muscle, or by systemic blood flow redistribution to other tissues and organs that will lead to hypoxia occurrence in other tissues [8].

Our calculations demonstrated that maintaining of the average level $pO_2$ in brain tissues (33 mm Hg) with increasing of intensity of load on the brain at the level of 30–70% in comparison with rest state is possible by increasing of the volumetric velocity of cerebral blood flow by 10–50% respectively, and this growth is linear. Further tension of operator activity (by 80–150%) needs no more of nonlinear increase of blood flow for providing of brain structures oxygen homeostasis. Thus, the growth rate of oxygen consumption in brain structures by 90% requires an increase of local blood flow by 90%; increase of operator work intensity by 130% can be compensated by increasing of brain blood circulation volume by 150%, and 2,5-fold increase in brain (by 150%) requires a threefold increase $Q_t$ in brain tissues.

Further we would like to show that compensation of hypoxic conditions that occur in brain structures should be carried out not only by cardiovascular, but also by respiratory system. Numerical results demonstrate that if to increase only the volumetric rate of blood flow in brain tissues to maintain $pO_2$ at 33 mm Hg, it will lead to the development of arterial hypoxemia. Thus, increasing of blood flow for hypoxia compensation in brain tissues during the brain growth in 2.5 times lead to a reduction $pO_2$ in arterial blood from 95 to 75.05 mm Hg. Removal of arterial hypoxemia during intensive operator activity carried out by connecting with of external respiratory regulating mechanisms.

Therefore, for maintaining $pO_2$ of brain tissues at 33 mm Hg level while operator work intensity increases by 30% , it is enough simultaneously to increase the minute respiratory volume by 10% in comparison with rest state, and the volume of cerebral blood flow velocity by 5%. This ensures the maintenance $pO_2$ of arterial blood at 95 mm Hg. This example demonstrates that inclusion of combined regulation mechanisms reduces the load of executive regulatory organs and does not violate conditions of oxygen supply in other tissues and organs.

## V. CONCLUSION

In present article new approach for investigation of reliability of professional pilot activity is presented. Applying the methods of reliability theory, we suggest the reliability model of operator functional state as continuously interacting system like a chain with "weak element" (link). It was proved that the "weak element" (link) of pilots are respiratory system and system of psychophysiologic functions. Software package for studying of reliability and professional selection for pilots is suggested. Numerical experiments were carried out and the results of simulation modeling of average person in conditions of increased situational stress were described in article.

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**Н. І. Аралова, О. М. Ключко, В. Й. Машкін, І. В. Машкіна. Математичні моделі та інтегральна оцінка надійності систем организму в екстремальних умовах**

Запропоновано математичну модель та комплекс інформаційної підтримки для дослідження надійності та професійного відбору операторів систем неперервної взаємодії при роботі в екстремальних умовах зовнішнього середовища. Наведено результати чисельного аналізу роботи моделі для організму середньостатистичної людини.

**Ключові слова**: оператор системи неперервної взаємодії, надійність роботи оператора, адаптація, математична модель системи дихання

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**Н. И. Аралова, Е. М. Ключко, В. И. Машкин, И. В. Машкина. Математические модели и интегральная оценка надежности систем организма в экстремальных условиях**

Предложена математическая модель и комплекс информационной поддержки для исследования надежности и профессионального отбора операторов систем непрерывного взаимодействия при работе в экстремальных условиях внешней среды. Приведены результаты численного анализа работы модели для организма среднестатистического человека.

**Ключевые слова**: оператор системы непрерывного взаимодействия; надежность работы оператора; адаптация; математическая модель системы дыхания.

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