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ARALOVA N.I.[1], DSc (Engineering), Senior Researcher,
Senior Researcher of Optimization of Controlled Processes Department,
https://orcid.org/0000-0002-7246-2736, e-mail: aralova@ukr.net
RADZIEJOWSKI P.A.[2], DSc (Biology), Professor,
Professor of Educational Studies Department
https://orcid.org/0000-0001-8232-2705, e-mail: p.radziejowski@wseit.edu.pl
RADZIEJOWSKA M.P.[3], DSc (Biology), Professor,
Professor of Faculty of Management, Department of Innovations
and Safety Management Systems
https://orcid.org/0000-0002-9845-390X, e-mail: maria.radziejowska@pcz.pl
ARALOVA A.A.[1], PhD (Mathematics)
Researcher of the Department of Methods for Discrete Optimization,
Mathematical Modelling and Analyses of Complex Systems
https://orcid.org/0000-0001-7282-2036, email: aaaralova@gmail.com
[1] Institute of Cybernetics of the National Academy of Sciences of Ukraine,
40, Acad.Glushkov av., 03187, Kyiv, Ukraine
[2] Kazimiera Milanowska College of Education and Therapy,
22,Grabowa str., 61-473, Poznań, Poland
[3] Czestochowa University of Technology
19b, Armii Krajowej str., 42-200, Częstochowa, Poland

APPLICATION OF THE MATHEMATICAL MODEL OF THE FUNCTIONAL BREATHING SYSTEM FOR OPTIMAL CONTROL OF THE TRAINING PROCESS OF HIGHLY QUALIFIED ATHLETES

Introduction. *One of the most important tasks of sports training in modern sports of the highest achievements is the ability to control the state of the athlete's body in the process of training and competitive activities. The use of a systematic approach in the training of highly qualified athletes, the system-forming factor in which is sports performance, presupposes the use of various non-traditional methods of improving the adaptation of athletes to the ever-increasing training loads. The development of methods and means for increasing physical performance and, in particular, in the practice of high-performance sports, is one of the most important principles of modern sports medicine. One of these methods is interval hypoxic training.*

The purpose of the paper *is to reveal the effectiveness of the process of adaptation to hypoxic hypoxia during the training process in the middle mountains and during the course of normobaric interval hypoxic training as a means of controlling the training process for increasing work capacity and improving the state of the functional respiratory system.*

Methods. *A system approach was used to assess the functional state of the respiratory system, combining instrumental examination with the subsequent use of mathematical models of the oxygen regimes of the body, predicting the state of functional respiratory system on the mathematical model of the respiratory system with optimal control, aerobic performance and working capacity.*

Results. *The combination of separate conducting of the intermittent hypoxic training (IHT) course and the traditional planned training process plays a significant role in the management of the training process because increases the effectiveness of the constructive effect of hypoxia*

Separate use of hypoxic hypoxia and load hypoxia significantly increases the functional state of the respiratory system, increases aerobic performance and performance of athletes in comparison with the simultaneous effects of hypoxic hypoxia and load hypoxia during the training process in mid-altitude mountains.

Keywords: *optimal control, functional respiratory system, mathematical models, intermittent hypoxic training, athletes' performance, the effectiveness of the adaptation process of athletes.*

INTRODUCTION

One of the urgent problems of modern physiology and medicine is the problem of optimizing the activity of the functional systems of the organism in order to enhance the ability to work and maintain health. One of the directions in this activity is the optimization of the process of adaptation to various types of hypoxia and an increase in the process of such adaptation of the functional capabilities of the external respiration system, blood circulation, oxygen transport to tissues and its utilization in mitochondria. Tissue hypoxia arising in the process of intense muscular activity serves as one of the stimuli that stimulate adaptive changes in the body during training.

Trainings in a pressure chamber, mid-altitude, breathing in a confined space have been used for decades in the practice of professional sports as a means of increasing the stability of the athlete's body to work in hypoxia. Representatives of cyclic sports pay close attention to the consequences of the use of hypoxic training. The training process in mid-altitude conditions has a number of significant limitations. Overcoming these difficulties became possible thanks to the use of normobaric intermittent hypoxic training (IHT). In Ukraine, this direction is primarily associated with the works of A.Z. Kolchinskaya [1, 2].

The theoretical prerequisites for using the course of intermittent hypoxic training in the training process are based on the presence of positive cross-over effects of adaptation, realized through various mechanisms of compensation and adaptation to two types of hypoxia: hypobaric hypoxia and load hypoxia. The effects of cross-adaptation arising from various combinations of different types of hypoxia, or the potentiating effect of artificially induced hypoxic conditions additionally used after the main training session, have a significant impact on the development of adaptation to a constantly acting hypoxic stimulus, for example, load hypoxia.

Hypoxia accompanying the performance of intense physical exercises is one of the main stimuli that stimulate the development of adaptive rearrangements and form the training effect in the athlete's body. The athlete experiences the combined effects of hypobaric hypoxia and exercise hypoxia. Despite the differences in the generation and conduction of a nerve impulse during hypobaric hypoxia (excitation of chemoreceptors is transmitted to the vasomotor and respiratory centers of the medulla oblongata and to the centers of the sympathetic nervous system) and load hypoxia (excitation of mechanoreceptors is transmitted first to the cerebral cortex and then to the centers of the medulla oblongata), the central nervous system receives a summed signal about a lack of oxygen, and, in accordance with the strength of the impulse, turns on compensatory mechanisms. In this case, the magnitude of the nerve impulse entering the medulla oblongata can be enhanced both due to the proportion of working hypoxia (with an increase in the intensity of the load) and due to the proportion of hypoxic hypoxia.

The physiological effect of the IHT modes used is determined by the strength of the hypoxic stimulus, which corresponds to the oxygen concentration in the inhaled air, the duration of a separate hypoxic exposure, the duration of normoxic pauses separating repeated hypoxic exposures, and the duration of the hypoxic exposure session. In the process of sports training, intermittent hypoxic training sessions can be used simultaneously with physical activity (in this case, they have a potentiating training effect) or separately from them, as a rule, before and after physical activity (in this case, an IHT session has an additional training effect) .

It should be noted that at present there is a significant number of domestic and foreign publications devoted to this issue [1–59]. At the same time, the range of studies is quite wide — from the influence of sessions of intermittent hypoxic training on the performance of athletes in various sports (cyclic, combat sports, games) to the study of this process at the mitochondrial level. We also note that very relevant works have already appeared on the issues of rehabilitation of people who have recovered from COVID-19 using intermittent hypoxic training [60]. There is also a number of works related to the use of information technology to optimize the choice of IHT course for a particular person [61–66]. Nevertheless, there is no definite answer as to which of the variants of hypoxic training — being in the middle altitude or normobaric intermittent hypoxic training is more effective. There are also works, although there are few of them, which cast doubt on the effectiveness of this approach [67–70].

PURPOSE

To reveal the effectiveness of the process of adaptation to hypoxic hypoxia during the training process in the middle mountains and during the course of normobaric intermittent hypoxic training as a means of controlling the training process for increasing work capacity and improving the state of the functional respiratory system.

METHOD

In order to identify the features of the use of normobaric intermittent hypoxic training, the functional respiratory system (FRS) was examined, including the external respiration system, the circulatory system and the tissue respiration system. The survey combined instrumental examination and mathematical modeling of the body's oxygen regimes, predicting the state of the FRS, aerobic performance and working capacity.

The simulation of normobaric IHT was carried out on a mathematical model of the functional breathing system taking into account the conflict situation between the governing and executive bodies of self-regulation in the struggle for oxygen [71–73].

To assess the degree of development of hypoxia in individual groups of tissues and in the whole organism, it is proposed to use a mathematical model of the functional respiratory system . With the help of a mathematical model with optimal control of the dynamics of the process of mass transfer of respiratory gases, local and systemic blood flows, tension of respiratory gases in blood and tissues are calculated. Optimal control involves the automatic resolution of a conflict situation that arises under certain conditions between the metabolic needs of the respiratory and cardiac muscles involved in the process of gas mass transfer.

In general, the mathematical model of the functional respiratory system can be represented as:

$$\frac{dp_iO_2}{d\tau} = \varphi(p_iO_2, p_iCO_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}O_2, q_{t_i}O_2). \quad (1)$$

$$\frac{dp_iCO_2}{d\tau} = \varphi(p_iO_2, p_iCO_2, \eta_i, \dot{V}, Q, Q_{t_i}, G_{t_i}CO_2, q_{t_i}CO_2), \quad (2)$$

where the functions φ and ψ are described in detail in [71–73], $\dot{V}$ — ventilation, η — the degree of saturation of hemoglobin with oxygen, Q — the volumetric rate of systemic and Q_{t_i} — local blood flows, $q_{t_i}O_2$ — the rate of oxygen consumption, q_{t_i} — the rate of release of carbon dioxide in the i - th tissue reservoir. Rates $G_{t_i}O_2$ of flow of oxygen from blood to tissue and $G_{t_i}CO_2$ carbon dioxide from tissue to blood. The active mechanisms of self-regulation in the model are respiratory muscles, cardiac muscles, and vascular smooth muscles, respectively, the control parameters in the dynamic system are V, Q, Q_{t_i}, $i = \overline{1,m}$, which are determined as a result of solving the problem of optimally bringing the perturbed dynamic system to a stable equilibrium state characterized by the following relations:

$$G_{t_i}O_2 - q_{t_i}O_2 = 0, \quad G_{t_i}CO_2 - q_{t_i}CO_2 = 0 \quad i = \overline{1,m}. \quad (3)$$

Those values of control parameters that provide a minimum are considered optimal

$$I = \int_{t_0}^{T} \left(\rho_1 \sum_{t_i} \lambda_{t_i} \left(G_{t_i}O_2 - q_{t_i}O_2 \right)^2 + \rho_2 \sum_{t_i} \lambda_{t_i} \left(G_{t_i}O_2 + q_{t_i}O_2 \right)^2 \right) dt \quad (4)$$

with restrictions

$$\dot{V}^{\min} \le \dot{V} \le \dot{V}^{\max}, \quad Q^{\min} \le Q \le Q^{\max} \quad Q_{t_i}^{\min} \le Q_{t_i} \le Q_{t_i}^{\max}, \ \sum_{t_i} Q_{t_i} = Q. \tag{5}$$

In (4) ρ_1, ρ_2 — are the coefficients of the organism's sensitivity to a lack of oxygen and an excess of carbon dioxide, λ_{t_i} which characterize the functional and morphological features of the tissue region.

When solving the task of forecasting the reaction of the respiratory system to an impact disturbance (hypoxia load), individualization of the control model is carried out [71–73]. For this purpose in functional quality

$$J = \int_{t_0}^{T} \left[\rho_1 \sum_t \lambda_i \left(G_{t_i} O_2 - q_{t_i} O_2 \right)^2 + \rho_2 \sum_t \lambda_i \left(G_{t_i} CO_2 + q_{t_i} CO_2 \right)^2 \right] d\tau. \tag{6}$$

The state of the dynamic system presented in the model is determined by the level of tension of oxygen pO_2 and carbon dioxide pCO_2 in the blood and tissue regions. Thus, in the process of modeling, oxygen and carbon dioxide portraits of the body are formed at different intensities of functional muscle activity.

The survey was carried out in the mountains with a reduced partial pressure of oxygen in the air and under normal toxic conditions. Physiological, biochemical methods were used to study the functional respiratory system, aerobic performance and performance, spirometry, gas analysis of exhaled and alveolar air, respiratory rate and heart rate were recorded, the minute volume of blood circulation, acid-base composition, blood hemoglobin, lactate, urea were determined at rest and during muscular load [29].

Five groups of female athletes specializing in cyclic and team sports were examined — three groups of cyclists, a group of female athletes engaged in rowing and a group of volleyball players, and one group of men specializing in cyclic sports — athletics, sprint.

Sportswomen of groups I and III were examined before, during and after one month of adaptation to hypobaric hypoxia in mid-altitude conditions. The rest of the groups (II, IV and V) received a course of IHT, consisting of 24 sessions.

Table 1. *Summary information about athletes*

Group no	Gen-der	Quantity	Kind of sport	Qualifi-cation	age	Body weight	Body length
I	f	14	cycling	zms, msmk	22,4 ± 1,8	57,7 ± 1,4	168,5 ± 2,1
II	f	12	cycling	zms, msmk	24,7 ± 1,3	59,4 ± 1,1	165,0 ± 2,3
III	f	16	cycling	zms, msmk	20,3 ± 2,8	57,7 ± 1,4	163,3 ± 1,2
IV	f	21	ac. rowing	msmk, ms	22,3 ± 2,1	74,8 ± 1,3	183,4 ± 2,1
V	f	27	volleyball	ms, kms	18,5 ± 2,4	67,3 ± 4,1	174,0 ± 6,0
VI	м	12	light atl	msmk, ms	21,0 ± 0,78	73,9 ± 1,4	179,4 ± 1,5

Table 2. Changes in indicators of external respiration among female cyclists during exercise with maximum oxygen consumption

Indicator	Plain	1st day in the middle mountains	after three weeks in the middle mountains	plain after the middle mountains
Maximum work power, W	380 ± 10	250 ± 20	250 ± 10	350 ± 10
Respiratory rate, r / min	$47,0 \pm 2,0$	$54,0 \pm 2,0$	$52,0 \pm 2,0$	$46,0 \pm 2,0$
Respiratory volume, ml	1874 ± 15	1844 ± 16	1925 ± 20	1973 ± 25
RMV, л/мин	$88,1 \pm 1,02$	$90,60 \pm 2,12$	$100,10 \pm 3,5$	$90,8 \pm 2,20$
Alveolar ventilation, l / min	$74,5 \pm 1,4$	$81,1 \pm 1,9$	$83,1 \pm 1,4$	$77,3 \pm 2,4$
AV/RMV, %	$84,6 \pm 0,08$	$81,5 \pm 0,50$	$83,0 \pm 1,0$	$85,2 \pm 1,3$
Oxygen consumption rate, ml / min	3172 ± 41	2792 ± 38	2803 ± 47	3415 ± 55
Intencity of jxygen consumption rate, ml / min * kg	$53,8 \pm 2,31$	$47,32 \pm 1,18$	$47,99 \pm 1,01$	$58,5 \pm 2,38$

Sessions were held daily, except Sundays and consisted of 5 five-minute series of inhalation of hypobaric mixtures with 11% (from the first to the eighth sessions), 10.5% (from the ninth to the eighteenth sessions) and 10% (from the nineteenth to twenty-fourth sessions) oxygen, alternating at five-minute normoxic intervals.

For group VI, intermittent hypoxic training was carried out according to a different scheme: in the first two days, athletes inhaled a hypobaric gas mixture with 11% oxygen, then, for a week with 10% oxygen, then with 9% oxygen. At the same time, the intervals of the sessions were also different — the duration of the hypoxic and normoxic intervals was 1 minute, in the session there were 30 series, that is, the total duration of the hypobaric effect was 30 minutes. The total duration of the IHT course was 15 days.

The response of the athletes' body was determined using a hypoxic test. Before the IHT session in a normoxic environment (20.9% oxygen), at the third and eighth minutes of breathing with a hypobaric gas mixture, the following indicators were recorded — respiration rate (RR), respiratory minute volume (RV), gas composition of exhaled and alveolar air. Heart rate (HR) and arterial oxygen saturation (S_aO_2) were also recorded throughout the test. Also, before and after the session, blood samples were taken to determine the content of hemoglobin (Hb) and lactate (La) in it.

The initial data obtained (25 indicators in total) were processed using an automated information system [63]. The indicators characterizing the efficiency of the respiratory and circulatory system, indicators of speed, intensity, efficiency of oxygen transport in certain parts of its path in the body, indicators of a hypoxic state were calculated (Tables 2, 3).

Table 3. *Changes in indicators of blood circulation among female cyclists during exercise with maximum oxygen consumption*

Indicator	Plain	1st day in the middle mountains	after three weeks in the middle mountains	plain after the middle mountains
Heart rate, beats / min	192 ± 3	198 ± 5	196 ± 3	186 ± 2
BMV, l / min	24,96 ± 0,12	24,55 ± 0,15	24,89 ± 0,21	24,81 ± 0,45
Stroke volume, ml	130 ± 5	121 ± 4	127 ± 3	132 ± 4
Oxygen capacity of blood, ml / l	192,8 ± 4,5	193,1 ± 3,3	197,2 ± 3,8	201,3 ± 3,0
Arterial blood oxygen saturation,%	88,0 ± 0,5	85,0 ± 0,5	86,0 ± 0,5	89,0 ± 0,5
Oxygen content in arterial blood, ml / l	169,7 ± 1,5	164,1 ± 1,2	169,6 ± 1,4	179,2 ± 1,8
Arterio-venous difference in oxygen, ml / l	127,1 ± 2,4	113,8 ± 1,2	112,6 ± 2,4	137,6 ± 1,9
Oxygen content in mixed venous blood, ml / l	42,6 ± 1,5	59,30 ± 2,20	56,99 ± 1,01	41,6 ± 0,62
Oxygen saturation of mixed venous blood,%	22,1 ± 0,44	26,10 ± 0,90	28,9 ± 1,10	20,7 ± 1,71
Hemoglobin content, g / l	141,8 ± 1,2	142,0 ± 1,0	145,0 ± 2,0	148,0 ± 3,0

The data given in Tables 2, 3 indicate that moving to the middle mountains causes compensated hypoxia in athletes of high qualifications, manifested in the strengthening of the function of the respiratory system and the connection of passive self-regulation mechanisms [63, 65, 66]. As shown by the survey data [63, 74], the female athletes experienced a significant decrease in working capacity and aerobic performance, which requires a decrease in the volume and intensity of training loads.

As a result of adaptation to hypobaric hypoxia, the state of the functional respiratory system of highly qualified athletes improved compared to the first days of adaptation, however, laboratory studies carried out at the beginning and end of the training camp showed that a three-week stay in mid-altitude mountains with a reduced partial pressure of oxygen in the inhaled air does not lead to a significant increase in the power of maximum bicycle ergometric loads and the level of maximum oxygen consumption.

At the same time, a survey conducted at sea level, after four weeks of adaptation to the combined effects of hypobaric hypoxia and exercise hypoxia, demonstrated an increase in FSD capabilities, work capacity and aerobic performance. The training camp in the mountains led to an increase in the power of the FRS, had a positive effect on aerobic performance and working capacity, which significantly increased when returning to sea level.

All of the above indicates that a three-week training camp in mid-altitude conditions with the combined effect of hypobaric hypoxia and load hypoxia significantly improves the parameters of the functional respiratory system and oxygen regimes of the body. The increase in the efficiency of FRS significantly increases the aerobic performance and working capacity of athletes.

The power of critical cycle ergometric loads also increased by 15–17%, the integral indicator of the body's aerobic capabilities also increased — the maximum oxygen consumption by 7.66 ± 1.2%. Note that during one training camp at sea level, when only load hypoxia acts on athletes, no significant changes in the state of the functional respiratory system, as well as an increase in aerobic power and work capacity have been revealed.

At the same time, conducting training camps in the mountains is stuck with a number of organizational and material difficulties. The complexity of organizing training camps in the mountains, where conditions for full-fledged sports training are not always available, the need for a longer stay in the mountains for a more complete adaptation to the mountain climate and recovery performance than the terms of usual training camps, the lack of scientific substantiation of the construction of the training process in mountain conditions to achieve the required level of acclimatization and the levels of performance depending on it led to the search for substitutes for mountain conditions. One of these substitutions was normobaric interval hypoxic training, carried out against the background of an incessant training process.

Intermittent hypoxic training, like other types of hypoxic effects, is based on the body's response to a decrease in the partial pressure of oxygen (pO_2) in the inhaled air. This reaction depends on gender, age, the degree of adaptation of the organism to a low pO_2 , its genetically predetermined individual characteristics, on the strength and duration of the action of the hypoxic stimulus - the gradient of decrease pO_2 and the duration pCO_2 of inhalation of the mixture with a low one.

The concept of secondary tissue hypoxia put forward by A.Z. Kolchinskaya [75], according to which tissue hypoxia occurs only with subcompensated, decompensated and terminal degrees and is an optional sign of tissue hypoxic state, makes it possible to distinguish between the damaging and constructive training effects of hypoxic exposure . And this, in turn, makes it possible, using mathematical models of the functional respiratory system (FRS), to formalize the criteria for the rationality of IHT modes and build algorithms for their selection, taking into account the individual characteristics of the human body. Based on the rich factual material and analysis of mathematical models of FRS, now it has been established that compensation for hypoxia in the body is carried out by mechanisms aimed at [1]:

• reduction of arterial hypoxemia and maintenance of the rate of oxygen supply to the lungs by increasing the respiratory minute volume (RMV). This is due to increased respiration, an increase in the respiratory surface of the alveoli with deeper breathing, an increase in the diffusion capacity of the lungs, and a decrease in blood shunting in the lungs;

• ensuring the rate of mass transfer of oxygen by arterial blood from the lungs to the tissues by increasing the oxygen capacity of the blood by increasing the hemoglobin content in it and its ability to attach oxygen, give it to tissues and increase the volumetric rate of systemic blood flow;

• providing cells with the necessary amount of oxygen by increasing microcirculation of blood in tissues, shortening the distance of oxygen diffusion from blood into cells and increasing oxygen reserves as a result of an increase in myoglobin in muscles;

• increasing the ability of the cell to utilize oxygen at its low voltage in the blood by increasing the number of mitochondria, their respiratory assemblies, the activity of respiratory enzymes and the antioxidant system.

All these mechanisms of compensation for hypoxia are aimed at short-term adaptation to changed environmental conditions.

We also note the following. During intermittent hypoxic training, hypobaric hypoxia and hypoxia of the load act on the body separately, IHT is carried out at rest, before the planned sports load and does not interfere with sports training. At the same time, the physiological mechanisms that compensate for these two types of hypoxia do not overlap, but complement each other. This allows the athlete not to reduce the volume and intensity of the training load, which is inevitable in the initial period of stay in mountain conditions. Thus, favorable conditions are created for improving the state of the functional respiratory system, increasing aerobic performance, developing general and special working capacity, i.e. to achieve a combination of factors leading to the achievement of high sports results.

SELECTING AN ALGORITHM FOR INTERMITTENT HYPOXIC TRAINING

As noted above, the mechanisms of compensation for hypoxia during IHT are aimed at short-term adaptation to changed environmental conditions. In the mathematical model of the FRS, they are represented by the executive organs of self-organization of the respiratory system. This and, as a consequence, adaptation is carried out due to the work of the respiratory muscles (change in ventilation of the lungs V), cardiac muscle (change in the volumetric velocity of systemic blood flow Q), smooth muscles of tissue vessels (redistribution of blood flow among tissue regions Q_{t_i}, $\sum_{t_i} Q_{t_i} = Q$) and the organization of tissue respiration (change in the rate of consumption oxygen $q_{t_i}O_2$ by tissues depending on the oxygen tension $p_{ct_i}O_2$ in the flowing blood).

The degree of adaptation of the organism to hypoxia is in very good agreement with the dynamics of changes in the coefficients of sensitivity ρ_i to oxygen and carbon dioxide in the FSD control model [71–73]. So, if we assume that $\rho_1 = 1$ for individuals who are acutely responsive to hypoxia, and $\rho_1 = 0$ for those who practically do not react (which is very dangerous for life), then in the process of adaptation of a person to hypoxia ρ_1 it decreases, and if in this process there is no decrease $p_{t_i}O_2$ to values below critical, it is possible consider the adaptation successful. Similar reasoning leads to the identification of a role ρ_2 in the process of short-term adaptation.

In reality, the values of the coefficients ρ_1 and ρ_2 can be find only as a result of a series of computational experiments with FRS models with known parameters of the external respiration and blood circulation system. However, indirectly, the dynamics V and Q in the process of IHT can be judged by the change from the IHT session to the next session, from the course of treatment to the next course. Indeed, as established both experimentally and theoretically, the body's response to a decrease pO_2 in the respiratory mixture is expressed in an increased value of ventilation V and the volumetric velocity of systemic blood flow Q (the frequency and depth of respiration increases, and bradycardia is observed).

However, if the hypoxic effect lasts for several days (in the mountains), the values of these most important parameters of the cardiorespiratory system practically return to those that they took under conditions of normoxia and normobaria (on the plain). This fact is usually associated with the adaptation of the body to hypoxia, since the modes of the external respiration and blood circulation system are economized under conditions of hypoxic hypoxia.

Calculations based on mathematical models of FRS show that such economization can be achieved only with a decrease in the coefficient of the body's sensitivity to hypoxia (lack of oxygen). It was also found that adaptation to hypoxia may not occur when pO_2 in the respiratory mixture is less than 4 %. The reasons are also known — the oxygen content in the arterial blood drops sharply, the regulatory capabilities of the body in such conditions are limited and the oxygen tension in the tissue regions becomes below critical levels. These features of the body's response to hypoxia were used as the basis for the algorithms for choosing the optimal IHT modes.

The work on the choice of IHT modes is preceded by the stage of the athlete's examination described above. Objective data on the functional state are determined — the minute volume of respiration and its components — the respiratory rate and tidal volume of the lungs, heart rate and volumetric blood flow at rest and during physical exertion of varying intensity, the gas composition of exhaled and alveolar air. These data are the initial for solving the problem of individualization of the mathematical model of FRS, the essence of which is in determining the sensitivity coefficients ρ and coefficients λ_i that reflect the functional and structural-morphological characteristics of an individual. The IHT procedure consists of a certain number of training (treatment) courses, each of which consists of alternating periods of hypoxic exposure, a certain duration of this exposure, as well as the subsequent normoxic one.

Due to the fact that the IHT procedure should not lead at any of the hypoxic exposure sessions to a decrease $p_{t_i}O_2$ to levels below critical (in the brain tissues $pO_2 \approx 30$ mm Hg), the duration of the hypoxic exposure τ_h depends on the oxygen content in the respiratory mixture:, $\tau_h = \phi(\mu, \beta)$ where β is the integral assessment of the individual characteristics of the organism; μ — the percentage of oxygen in the tidal volume, $4 \le \mu \le 20,9$. It is clear that the less oxygen in the mixture, the shorter the period of hypoxic exposure should be. This is due to the fact that the consequence of prolonged sharply hypoxic exposure will be a decrease $p_{t_i}O_2$ below the critical level. Therefore, the task of choosing IHT modes in a hypoxic session can be simplified by accepting a proportional dependence of the session duration on the force of exposure. If we proceed from the advisability of conducting a normoxic session after a hypoxic one, to restore the functional state of the body, then it should be borne in mind that the recovery period is longer. This is due to the fact that during hypoxic exposure, the control parameters V, Q, Q_{t_i}, react almost instantly, when the hypoxic load is removed, they are still maintained for a long time at a sufficiently high level (the effect of post-work hyperemia). Thus, when solving the problem of choosing IHT modes, the duration of a normoxic session can be predicted by using the model to determine the period of reaching $p_{t_i}O_2$ the level that they take before the experiment.

In essence, the task of choosing IHT modes is reduced to the task of determining the best hypoxic mixture for the adaptation of a particular individual. As mentioned above, the solution to this problem comes down to an enumeration μ from the interval $4 \le \mu \le 20,9$ and the choice of one that will help to reduce the sensitivity coefficient ρ_1 during the course of training sessions or improve the integral indicator β of the state of the cardio respiratory system.

The application of the above-described algorithm for selecting IHT modes becomes definite and effective if the subject's body is examined at each normoxic session. If, at the same time, the survey data V, Q, Q_{t_i}, from session to session, decrease and tend to the norm, and the integral assessments of the functioning of the cardio respiratory system improve, then the positive effect of IHT is obvious. The optimal choice of the number of sessions in the course of treatment, as well as the number of the courses themselves, is possible only in the case of constructing mathematical models of adaptation to hypoxia.

In today's practice of using IHT for the treatment and improvement of functional indicators, the number of sessions and courses is determined by the doctor on the basis of objective clinical data and the results of computational experiments with a mathematical model of FRS. If it turns out that from course to course of IHT, the coefficient of the body's sensitivity to hypoxia can still be reduced without danger that $p_{t_i}O_2$ will enter the area of critical values, and an integral sign of health indicates a constructive effect of hypoxia, then the doctor, as a rule, recommends repeating the IHT procedure. The algorithm of the software package for choosing the optimal IHT modes is shown in Fig. 1.

DISCUSSION

Comparison of the results of the bicycle ergometric test carried out before and after the IHT course showed that the power of the maximum performed load after a three-week IHT course against the background of the planned training process increased by 16.6 ± 2.4%, while the maximum oxygen consumption increased by 9.5 ± 1,5 %.

Comparative analysis of the level of special working capacity, determined during natural competitive activity after a training mesocycle in the mountains did not differ significantly from that at its beginning [29, 43]. After the IHT course, the level of special working capacity among female cyclists increased significantly more than after a training camp in the mountains. Determination of special working capacity was carried out during natural competitive activity of female cyclists (individual race 20 km). The average speed of passing the distance has increased from 35.89 ± 0.45 km / h to 37.65 ± 0.55 km / h. (Note

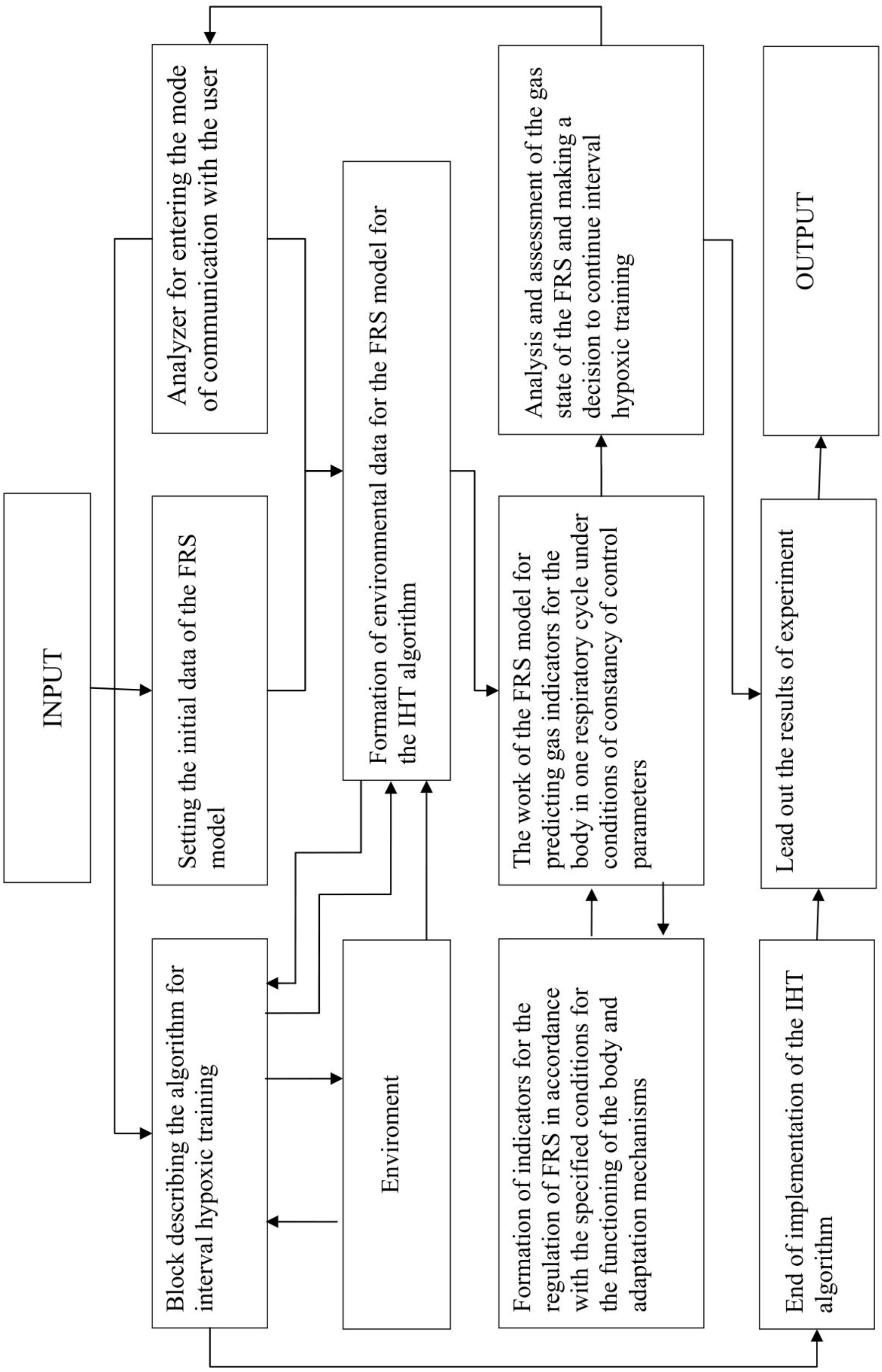

Fig. 1. Algorithm of the software package for selecting the modes of intermittent hypoxic training.

that the analysis of sports training mesocycles was carried out at the beginning of the preparatory period of the annual training cycle, when the athletes were just approaching sports form).

On the mathematical model [76], an imitation of the effect of hypoxia load on skeletal muscle in normobaric and hypobaric conditions was carried out. Priority signs of compensation were identified: a high oxygen demand, requiring a high rate of oxygen consumption, high gradients of the partial pressure of oxygen and its consumption in tissues, which are typical signs of a zone of hypoxia in muscle tissue, increased oxygen exchange between blood and tissues, a decrease in the average level of oxygen tension in tissues and the presence of potential anoxic zones in the most unfavorable areas in terms of oxygen delivery, the formation of a significant oxygen debt.

With combined exposure, the decisive role is played by diffusion restrictions on oxygen delivery to the mitochondria of muscles, this factor is the main limitation of oxygen transport in muscle tissue, as well as the development of venous hypoxemia due to an increase in the rate of oxygen utilization from the blood.

CONCLUSION

The work offers an algorithm for choosing modes of interval hypoxic training based on a mathematical model of the functional respiratory system, which allows more effective management of the training process by selecting individual coefficients of the body's sensitivity to hypoxia and hypercapnia.

The method of intermittent hypoxic training has shown its high efficiency in training athletes. During the course of IHT, hypobaric hypoxia and hypoxia of the load act on the athlete's body at the same time, the hypobaric effect on the athlete's body is carried out at rest, before the planned sports training, without interfering with its implementation. This favorably distinguishes this method from hypobaric training in mountain conditions, where hypobaric hypoxia and load hypoxia act simultaneously on the athlete's body during training, and this cumulative effect can lead to a destructive effect of both types of hypoxia.

The use of the studied forms of intermittent hypoxic training can significantly increase the effectiveness of the means and methods of special physical training of athletes. The use of one intermittent hypoxic training is especially effective as a means of additional training. This form of combination of traditional sports training and the studied modes of interval hypoxic training can be recommended when training highly qualified athletes in the pre-competition period.

From the point of view of the general theory of adaptation to physical loads, the course use of intermittent hypoxic training in combination with traditional sports training leads to a surge in adaptive changes in the athlete's body and this leads to the development of a new methodology of the training process, taking into account the athlete's specialization.

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Аралова Н.І. [1], д-р. техн. наук, старш. наук. співроб.,
старш. наук. співроб. відділу оптимізації керованих процесів
https://orcid.org/0000-0002-7246-2736, e-mail: aralova@ukr.ne
Радзійовський П.О. [2], д-р біол.наук, проф.,
проф. фак-ту освітніх напрямів навчання
https://orcid.org/0000-0001-8232-2705, e-mail: p.radziejowski@wseit.edu.pl
Радзійовська М.П. [3], д-р біол.наук, проф.,
проф. фак-ту менеджменту, відд. інновацій та систем безпеки керування
https://orcid.org/0000-0002-9845-390X, e-mail: maria.radziejowska@pcz.pl
Аралова А.А. [1], канд. фіз.-мат.наук,
наук. співроб. відд. методів дискретної оптимізації,
математичного моделювання та аналізу складних систем
https://orcid.org/0000-0001-7282-2036, email: aaaralova@gmail.com
[1] Інститут кібернетики імені В.М. Глушкова НАН України,
40, пр. Глушкова, 03187, Київ, Україна
[2] Вища Школа Едюкації та Терапії ім. проф. Казімери Мілановської,
22, вул. Грабова, 61-473,Познань, Польща
[3] Честоховський Технічний Університет,
19б, вул. Армії Крайової, 42-200, Честохова, Польща

ЗАСТОСУВАННЯ МАТЕМАТИЧНОЇ МОДЕЛІ ФУНКЦІОНАЛЬНОЇ СИСТЕМИ ДИХАННЯ ДЛЯ ОПТИМАЛЬНОГО КЕРУВАННЯ ТРЕНУВАЛЬНИМ ПРОЦЕСОМ ВИСОКОКВАЛІФІКОВАНИХ СПОРТСМЕНОК

Актуальність. *Одним з найважливіших завдань спортивної підготовки у сучасному спорті вищих досягнень є можливість керування станом організму спортсмена у процесі тренувальної та змагальної діяльності. Застосування системного підходу у підготовці висококваліфікованих спортсменів, системо утворювальним чинником у якому є спортивний результат, передбачає застосування різних нетрадиційних* *методів підвищення адаптації спортсменів до зростання тренувальних навантажень. Розроблення методів та засобів підвищення фізичної працездатності зокрема, у практиці спорту вищих досягнень, є одним з найважливіших принципів сучасної спортивної медицини. Одним з таких методів і є інтервальне гіпоксичне тренування.*

Мета роботи. *Виявити ефективність процесу адаптації до гіпоксичної гіпоксії під час тренувального процесу в середньогір'ї та у курсі нормобаричного інтервального гіпоксичного тренування як засобів керування тренувальним процесом для зростання працездатності та покращення стану функціональної системи дихання.*

Методи. *Застосовувався системний підхід для оцінювання функціонального стану системи дихання, який поєднує інструментальне обстеження з подальшим застосуванням математичних моделей кисневих режимів організму, прогнозування стану ФСД на математичній моделі системи дихання з оптимальним керуванням, аеробної продуктивності та працездатності.*

Результати. *Поєднання роздільного проведення курсу інтервального гіпоксичного тренування та традиційного планового тренувального процесу відіграє істотну роль в керуванні тренувальним процесом, оскільки підвищує ефективність конструктивної дії гіпоксії. Окреме застосування гіпоксичної гіпоксії та гіпоксії навантаження суттєво підвищує функціональний стан системи дихання, підвищує аеробну продуктивність та працездатність спортсменів порівняно з одночасним впливом гіпоксичної гіпоксії та гіпоксії навантаження під час тренувального процесу в середньогір'ї.*

Ключові слова*: керування тренувальним процесом, функціональна система дихання, математичні моделі, інтервальне гіпоксичне тренування, працездатність спортсменів, гіпоксія навантаження, ефективність процесу адаптації спортсменів.*