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HABITABLE UNDERWATER HYPERBARIC FACILITIES: RESPIRATORY BALANCE IN THE HUMAN ORGANISM DURING ADAPTING TO SATURATION NITROGEN-OXYGEN HYPERBARIA

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ABSTRACT

There were evaluated responses of the respiratory system to changes in the variables of the external environment under increased pressure. To the model of professional underwater human activity underwater served the conditions of full saturation in compressed air or nitrogen-oxygen gas mixtures. Technical devices were presented by a number of underwater laboratories, mounted at the bottom (Ikhtiander-66, 67 and 68), hyperbaric chambers, submersible drilling rigs (Bur-1 and 2), and an autonomous diving Ikhtiander-2 for a long stay in the water.

Studies of respiratory gases mass transport conditions in man showed than within the pressure range of 0.25-1.1 MPa at density of moderate hyperoxic and nitrogen-helio-oxygen environment up to 14 kg/m^3 oxygen and carbon dioxide regimes of the organism come to a new functional level which provides the adaptation to the extremal conditions. It is determined that an increase of physiological dead breathing space, a decrease of the rate of the O_2 diffusion through the alveole-capillary barrier, intensification of unevenness of ventilator-perfusional relations in lungs and an increase of blood shunting in lungs are the main respiratory mechanisms which regulate mass transfer of O_2 and CO_2 in man under hyperbaria. The leading hemodynamic mechanism is the retention of volume blood circulation and cardiac output. It is studied how the compression rate, high partial pressures of oxygen and nitrogen, microclimate parameters in inhabited hypebaric chambers influence changes of functional breathing system. Absence of hypoxic state is proved in man (full saturation of man with nitrogen) under normoxia in nitrogen-oxygen environment with the density 6.34 kg/m^3. These are also the data about accelerated rehabilitation of divers using the method of active adaptation o high altitudes. Basic directions in physiological studies of functional breathing system under increased pressure of gas and water environment are described.

Keywords: underwater laboratory, Ikhtiander, hyperbaria, aquanaut, respiratory gases transport, saturation diving, oxygen and carbon dioxide regimes of the organism, autonomous diving suit, submersible drilling rigs.

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INTRODUCTION

Man's paths under water are significantly different from space routes. While the latter always remain the objects of general attention and limitless financing, the pioneers, as enchanted, often pierced with their bodies the barriers of misunderstanding, lack of money, and multi-stage danger. Little has been written about the problems that had to be overcome by a person who always wants to penetrate deeper and stay longer.

The last 50 years have been characterized by the emergence, rapid progression, and stabilization of a new method of the underwater work - a long saturation stay with a single final decompression (Fig. 1, p. 5-7). Although a man, in this case, is exposed to less extreme impacts and a correspondingly lower risk of direct death compared to unsaturated dives, there came first the unresolved mechanisms of the long-term effects of factors carrying along deeper disorders of many organism systems in the chronic mode. There appear questions of compensating high density of the respiratory medium and hyperbaric hypoxia, toxic effect of the inert gases on the central nervous system, degradation of the psychophysiological state, etc. The difficulty has always been the need to create a unique decompression mode for each depth range, which was not always ideal. But the first place has always been occupied by the question of how much oxygen should be in the respiratory environment in order to avoid hypoxia and prevent oxygen poisoning of the lungs or central nervous system. The situation was aggravated by the fact that each depth was characterized by its own set of density, inert gas partial pressure and exposure, as well as the mode of human activity and its initial physical state. Of all this cocktail of problems, the underwater pioneers had to choose vital and therefore priority ones. They undoubtedly include the task of creating PO_2 of the inhaled environment, its dynamics depending on the specific complex of factors of hyperbaria, activity of aquanauts, exposure, decompression and stay/work in the aquatic environment outside the underwater shelter.

The technical side of man`s penetration under water for a long time consisted in choosing a convenient dwelling that would allow to create gas environment, living conditions and decompression. The first step was presented by construction of facilities at the bottom (underwater houses-laboratories). Then came the adapted pressure chambers, adapted for a long stay of people in them, located on the ship with elevator cameras for delivery to the bottom, as well as combined devices with submarines.

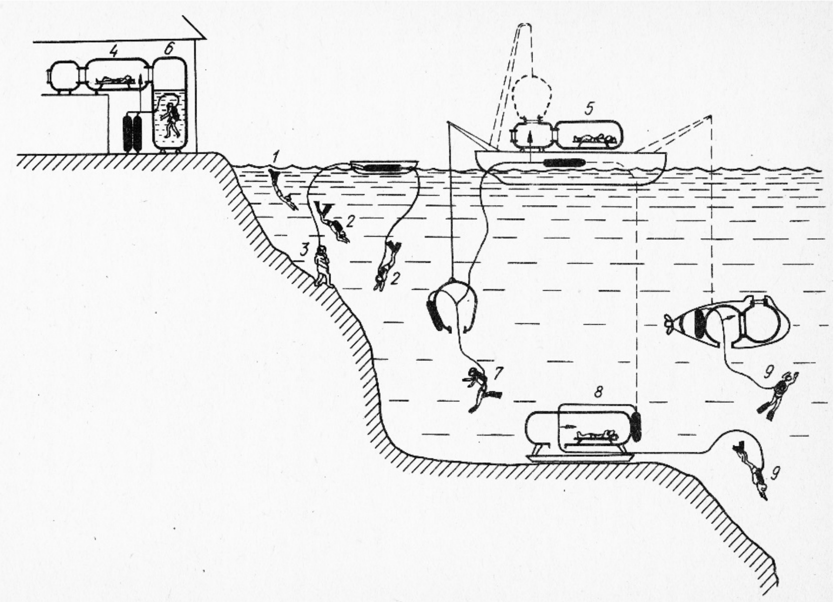


Fig. 1. Types of human activities under water and technologies for protecting him from factors of hyperbaria and the water environment [1]:
1 - free diving, 2 - diving in autonomous and hose equipment, 3 - work in a spacesuit, 4 - imitation dive in a "dry" hyperbaric chamber, 5 - imitation dive in a ship's deep-sea diving complex, 6 – diving in a hydro-pressure-chamber, 7 - work from the diving bell, 8 - diving in the underwater laboratory, 9 - working from the underwater laboratory or from an underwater vehicle with a hyperbaric compartment. 1-3 - diving operations are carried out only by the method of "unsaturated" dives, 4-9 - mainly "saturated" dives are used.

A functional respiratory system with its complex mechanisms, which provides gas exchange in lungs, transport of gases by blood and oxidative processes in tissues, plays a crucial role in the adaptation of man to hyperbaric gas environment. Changes in breathing determine the effectiveness of adaptive mechanisms and stability of the organism during underwater diving and working underwater, the adequacy of the gas environment for metabolic needs, and respiratory shifts with a high density of the atmosphere can become a factor limiting the production activities of divers.

Depending on the degree of saturation of the body's tissues with inert gases under increased pressure, the role of separate hyperbaria factors is different. The most fully studied are the effects of increased PO_2 [2-4], high partial pressure of nitrogen [5-8], high density of the respiratory medium [9-12] and differential pressure [13-15] with partial gas saturation under increased pressure. This made it possible to determine the main functional changes and pathological processes that develop in the body under these conditions. These include: oxygen poisoning or starvation, carbon dioxide poisoning, nitrogen anesthesia, high pressure nervous syndrome, isobaric gas anti-diffusion syndrome, decompression illness [16,2,3,17,5,6,18,10,19-21]. The core of each of these conditions is a violation of the mass transfer of respiratory and inert gases, as well as its regulation. With full saturation of the organism tissues with hyperbaric gas environment, action of the listed factors is supplemented by their chrono concentrating and potentiating effects, the influence of sensory deprivation and altered habitability against the background of frequent stresses caused by work in water and hypothermia (pressure, temperature, physical overload, increased risk, etc.) [22-24]. Qualitative characteristic of the interactions of the main stressors impacts during hyperbaria and the body's response is shown in Fig. 2 [25].

Fig. 2 Factors linking the stressful effect on the human body, which is under increased pressure of gas and water mediums, the main physiological and pathophysiological syndromes and their interrelationships (to [25] with our changes [1]).

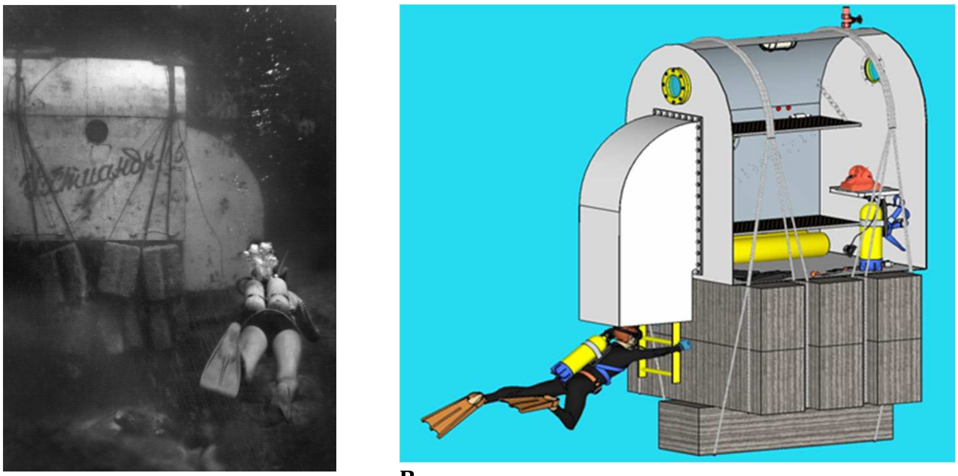
However, despite the concentration of researchers' attention to these problems and achievements of pressures and depths close to the humans` limits (6–7 MPa), until recent years such fundamental questions as the possibility and peculiarities of the organism's adaptation to hyperbaric conditions remained poorly studied; regulation of respiratory gas transport in the body under hyperbaria; physiological grounds for assessment of the adequacy of PO_2 in the inhaled gas medium. Progress in these areas was largely constrained by significant methodological difficulties for studying the parameters of mass transfer of respiratory gases in conditions of real dive.

Conducted at the A.A.Bogomolets Institute of Physiology, National Academy of Sciences of Ukraine, studies of the regularities of functioning of the respiratory system of gas mass transfer in the hyperbaric nitrogen-helium-oxygen medium are based on the application of a progressive methodological approach - the concept of the organism oxygen modes [25-26] and developed methodological techniques for direct registration of the main respiration parameters under hyperbaria in hyperbaric chambers and in an water medium, blood circulation and gas transport function of blood [23,28,29]. This allows us, at the modern level, to assess changes in oxygen and carbon dioxide regimes of the organism, respiratory, hemodynamic and hemic mechanisms, controlling them. And taking into account the state of mental and physical performance, to characterize the degree of compensation of the influence of the extreme hyperbaric conditions, identify the presence and peculiarities of adaptation to them.

In this article, we analyze the results of experimental studies of physiological mechanisms of regulating the mass transfer modes of respiratory gases in the human organism in the nitrogen-oxygen medium under high pressure.

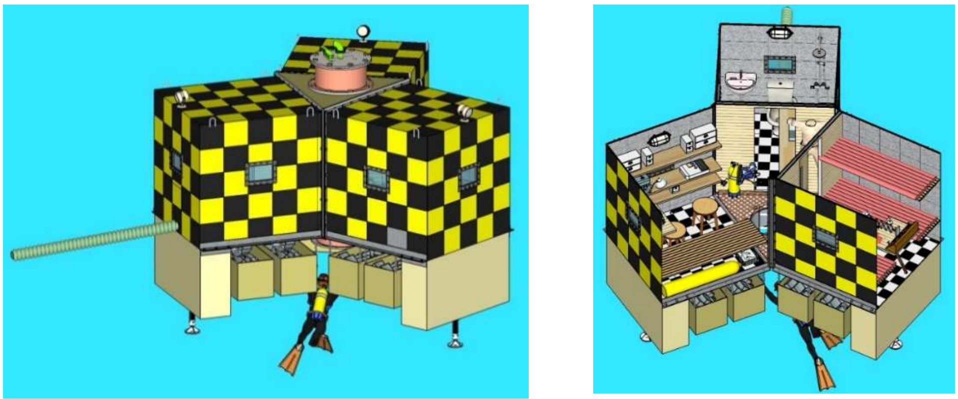
METHODS

We studied the features and dynamics of changes in respiration, blood circulation and gas transport function of human blood during hyperbaria in real (underwater laboratories Ikhtyander and Chernomor) and simulated (pressure chamber for a long stay of a person) conditions, depending on the exposure. Historically, the beginning of work on the program of the public laboratory Ikhtyander (Donetsk, Ukraine) was the first in the USSR (Fig. 3-5) and the 4th (underwater lab Ikhtyander-66) in the world practice for saturation underwater constructions with compressed air after work of J.I. Cousteau (Diogenes and Starfish, France, 1962-63) and Glokes (United Kingdom, 1965) [1,24]. In this series, we do not consider the work performed at depths beyond the use of compressed air using nitrogen and helio-oxygen gas mixtures [6,7,10,12,14,21,27]. Below we give the external and internal view of the underwater laboratory-houses Ikhtiander-66, 67, 68, their main technical characteristics (Fig. 3-5) [28-33] and the general organization of experimental studies that were carried out in Ukraine (Crimea) in August 1967 (Fig. 6), as well as some types of specialized equipment (Fig. 7-9) [34,35].



A **B**

Fig. 3 Underwater laboratory Ikhtiander-66 (Ukraine):
A - under water, *B* - internal view; Dimensions - 2x1.6x2 m, volume - 6.8 m^3, number of compartments - 2, number of seats - 2, number of aquanauts - 3, immersion depth - 11 m, breathing medium - compressed air 2.1 kgf/cm^2, maximum human exposure - 4 days Location is Peninsula Tarkhankut, Crimea, the period of work is August 23-27, 1966. Crew: A. Khayes, Yu. Sovetov, D. Galaktionov. Work completed before the schedule due to storm.



A **B**

C

D

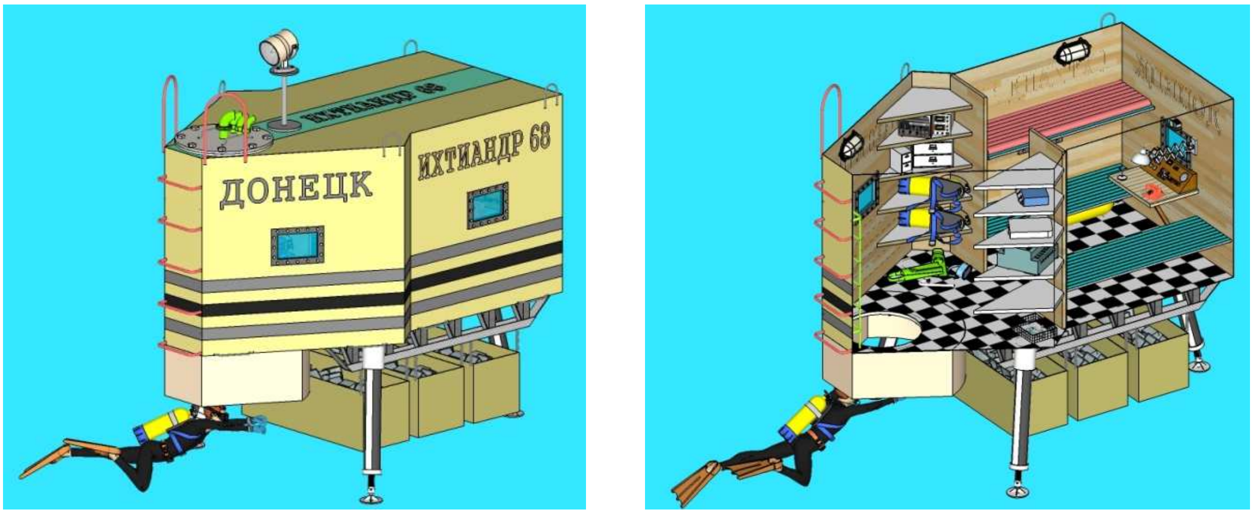
Crew 1: A. Khayes, S. Gulyar, V. Pesok, Yu. Kachuro, Yu. Sovetov.

Crew 2-1: G. Tunin, E. Spinov, A. Garkusha, A. Kardash, B. Pesok;
In the bottom row: heads of directions E. Akhlamov (medical support), Y. Kiklevich (scientific program), Y. Barats (design and technical support, A. Zubchenko (technical and hyperbaric support).

Crew 2-2: M. Barats, G. Guseva.

Examination of the breath of an aquanaut in an underwater laboratory.

Fig. 4 Underwater laboratory Ikhtiander-67 (Ukraine):
A - general view; *B* - internal view; *C* - before diving, *D* - under water, *E* - crews of aquanauts, F - Aquanaut breath test in an underwater laboratory; Dimensions - three cubes 2x2x2 m, connected by the transition compartment in the form of a trihedral prism with an edge of 2 m, volume - 28 m^3, number of compartments - 4, number of seats - 5, number of aquanauts - 12, immersion depth - 14 m, breathing medium - compressed air 2.4 kgf/cm^2, maximum human exposure - 7 days. Location - Laspi Bay, Crimea, period of work - 28.08-11.09.1967.



A **B**

Fig. 5 Underwater laboratory Ikhtiander - 68 (Ukraine):
A - general view; *B* - internal view; Dimensions - a 2x2x2 m cube connected to the transition compartment in the form of a trihedral prism with an edge of 2 m, volume - 15.3 m^3, number of compartments - 2, number of seats - 4, number of aquanauts - 4, immersion depth - 10 m, respiratory medium - compressed air 2.0 kgf/cm^2, maximum human exposure - 4 days. The installation site is Laspi Bay, Crimea, the period of work is 17-20.08.1968. Crew: Y. Sovetov, E. Spinov, S. Hazet-Lyalko, V. Skubiy. Work completed ahead of schedule due to a storm.

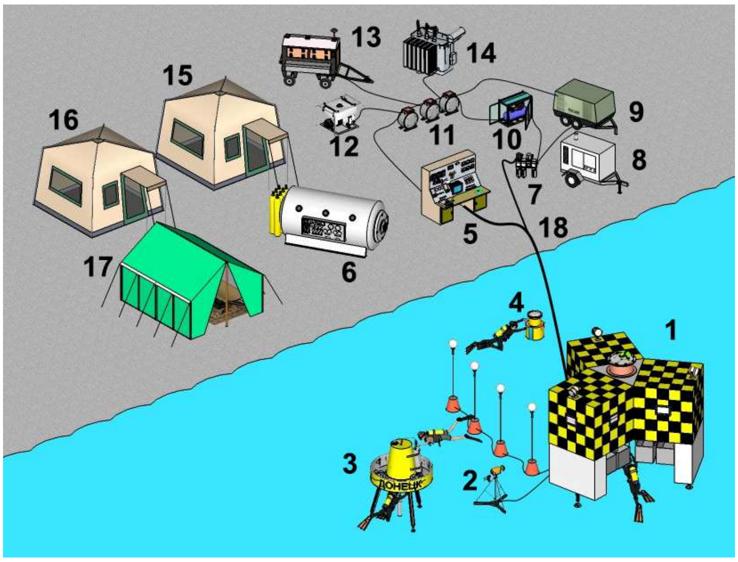
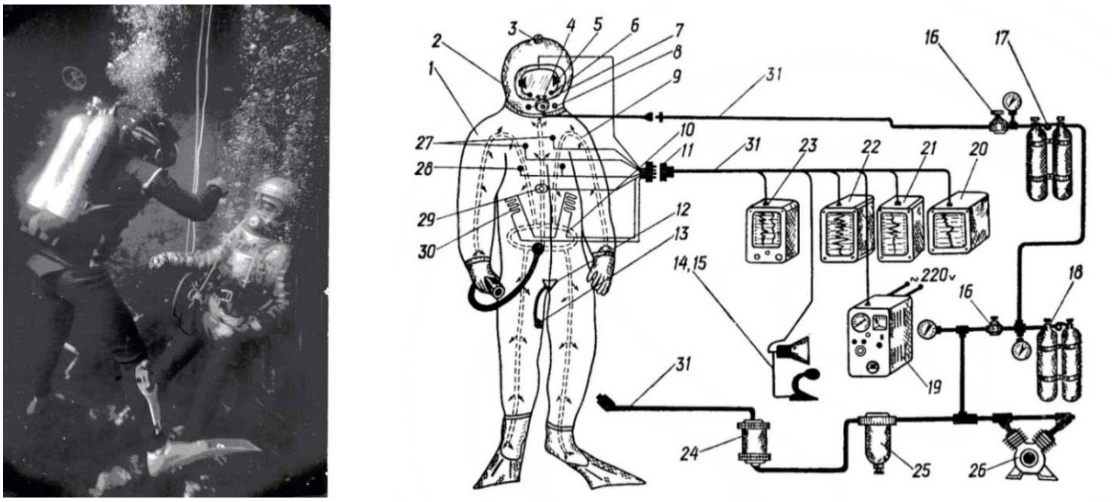


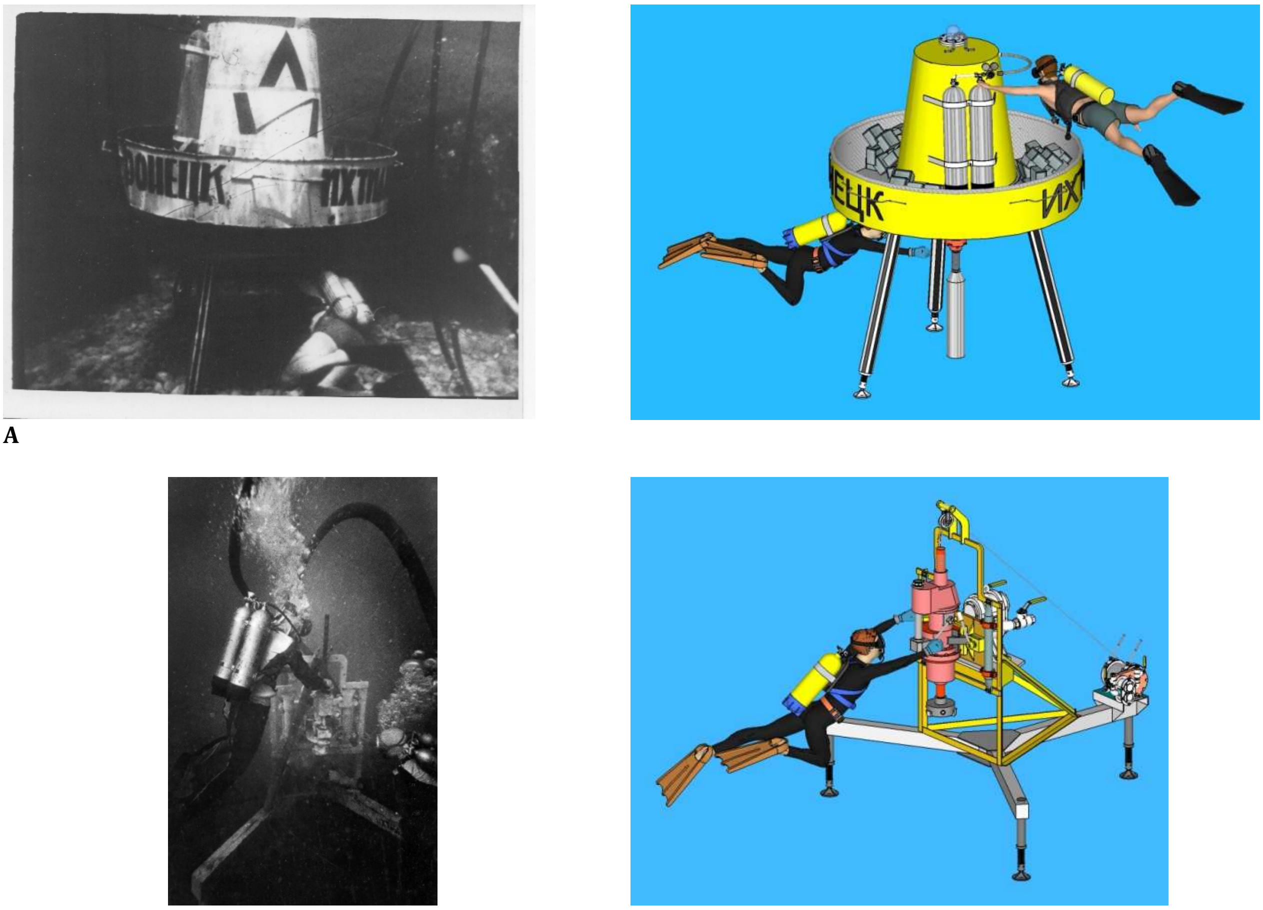
Fig. 6 Infrastructure of experimental work with the underwater laboratory Ikhtiander-67:
1 - Ikhtiander-67 underwater laboratory, 2 - television camera, 3 - Bur-1 subsea drilling rig, 4 - semi-automatic logistics container, 5 – underwater lab and systems control panel, 6 - recompression chamber and air storage, 7 - air filter, 8 - diesel high-pressure compressor, 9 - low-pressure electric compressor, 10 - backup low-pressure electric compressor, 11 - electrical switching unit, 12 - backup power station 220 V, 13 - backup diesel power station 380 V, 14 - high-voltage transformer station 380 V, 15 – medical-physiology laboratories, 16 – mini hospital, 17 - adjustment and repair workshops, 18 - air and water lines, power supply cables, communication and telecontrol.

Using various methodological approaches for performing underwater and hyperbaric operations, we determined the role of such factors as increased density of the respiratory medium with various indifferent components, hyperoxia, isolated or combined with increased density, high compression rate, increased temperature and humidity of the atmosphere of inhabited hyperbaric structures. The set tasks were realized during examination of 173 divers, aged 20-42 years, with diving experience up to 19 years, under pressure of 0.25-1.1 MPa in the atmosphere, with density of 1.29-14.16 g/l. The studies were carried out in conditions of underwater laboratories and hyperbaric complexes, as well as during the work of aquanauts under water for research and production purposes (Fig. 7,8) [34,35].



A **B**

Fig. 7 Autonomous diving suit Ichtiander-2 for a long (saturation) stays (*B*) and work under water (*A*):
1 - shell, 2 - helmet, 3 - valve, 4 - lung automatic machine of the emergency breathing system, 5 - headsets, 6 - laryngophones, 7 - device for eating, 8 - device for taking saliva, 9 - ventilated clothing, 10 - air collector, 11 - electrical connector, 12 - sewage device, 13 - discharge valve, 14-15 - transmitter and receiver for duplex speakerphone, 16 - gearbox, 17 - 5-liter calibrated pulmonary ventilation registration system cylinders, 18 - 40-liter cylinders with emergency stock of compressed air, 19 - power supply for electric warming clothes (12 V), 20,29 - device for monitoring and recording the depth of immersion, 21 - device for monitoring and recording the temperature in the sub diving dress space, 22 - device for circulating control and recording of the body temperature at eight points, 23 - an electrocardiograph, 24 - air filter, 25 - dehumidifier with condensate discharge, 26 - compressor, 27 - temperature sensors, 28 - ECG electrodes, 30 - electric heated clothes , 31 -air ducts, communication and registration lines, power supply for electrically heated clothes, combined into a halyard.

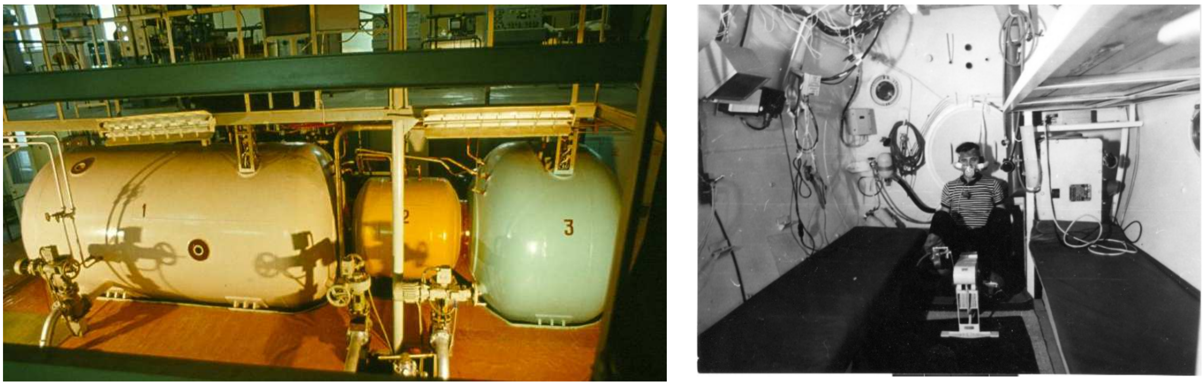


A

B

Fig. 8 Bottom Drilling Rig and work of aquanauts:
A - Bur-1 (1968), *B* - Bur-2 (1969). Technical characteristics and description of the results, see [35].

The scope of the researches was general for all experiments and included obtaining ventilator and gas exchange variables of respiration, indicators of heart performance and the state of peripheral vessels, data on the gas composition of the blood and its acid-base balance (Fig. 14-15) [1]. In addition [25,26,37], we calculated the variables of oxygen and carbon dioxide regimes of the organism, their intensity, profitability, and efficiency. Examinations were carried out under conditions of basic metabolism, relative rest, and dosed physical activity (Fig. 9). A more detailed description of the research conditions and methodological techniques was described by us earlier [5-8,38,36,24].



A **B**

Fig. 9 Hyperbaric complex for saturation ($N_2 + He + O_2$) experiments at “depths” of up to 300 m (P.P. Shirshov Institute of Oceanology, USSR Academy of Sciences, Gelendzhik) (*A*). Examination of the aquanaut Anatoly Yurchyk during exercise in the pressure chamber (*B*).

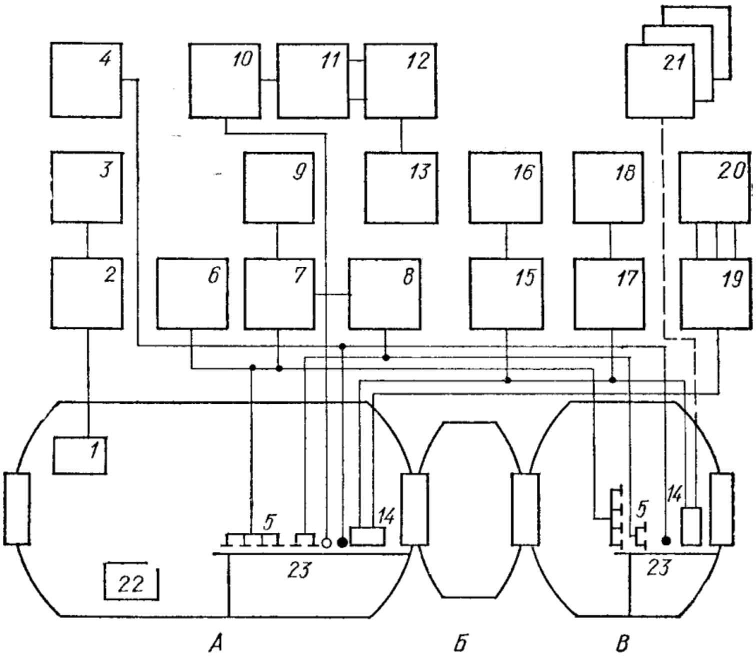


Fig. 10 The block-diagram of the equipment during hyperbaric experiments [22]:
A - living compartment of the pressure chamber, *B* - gateway, *C* - pre-chamber; 1 - chromatograph detector, 2 - gas chromatograph LHM-8md, 3 - graphic recorder KSP-4, 4 - oxyhemograph O-36 m, 5 - set of electrodes and sensors, 6 - electrocardioscope PEKS-01, 7 - electrocardiograph ELKAR-6, 8 - rheograph RG-4-01, 9 - indicator monitor IM, 10 - pulse indicator, 11 - counter F-5007, 12 - transcriptor F-5033, 13 - electrically controlled typewriter ECT-23, 14 - breathing machine, 15 - medium pressure sensor EDD, 16 - graphic recorder KSM-4, 17 - high pressure sensor MDD, 18 - graphic recorder KSP-4, 19 - mass spectrometer MX-6202, 20 - graphic recorder KSPP-4, 21 - gas analyzers, 22 - bicycle ergometer, 23 - research area.

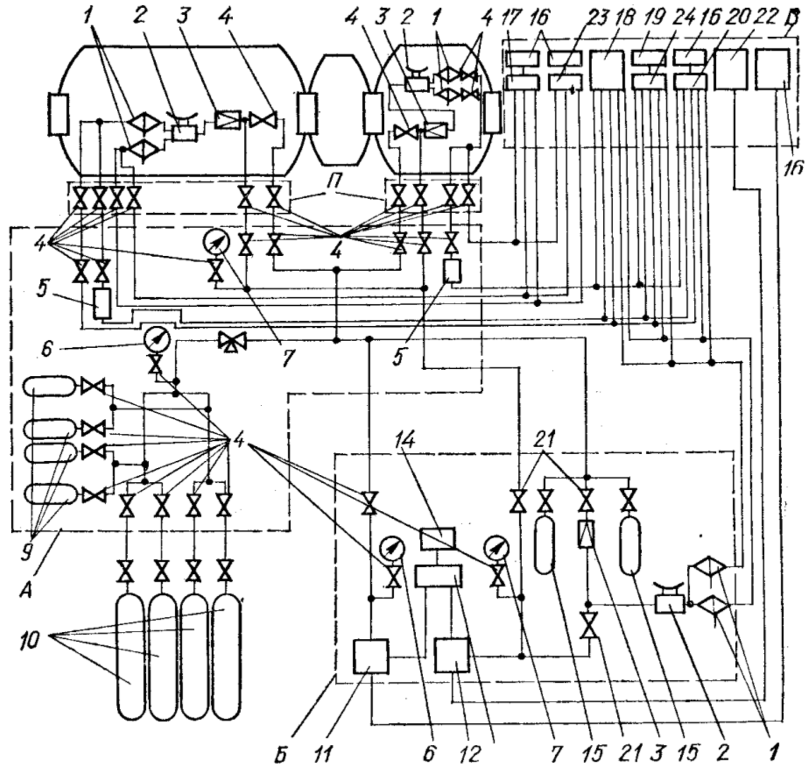


Fig. 11 Principal scheme of the "Bavograph" system to determine respiration variables [22]:
A - remote controller for respiratory mixtures supply, *B* - remote unit, *C* - registration unit, *P* - pneumatic inlet. 1 - mixers of exhaled and alveolar air, 2 - pulmonary automatic controller, 3 - gearbox, 4 - KV-1m valve, 5 - rotameter, 6 - standard pressure gauge 160 kgf / cm2, 7 - standard pressure gauge 40 kgf / cm2, 8 - KV valve -2ms, 9 - 4-liter capacity measured balloon, 10 - breathing gas cylinders, 11 - DMD high-pressure sensor, 12 - EDD medium pressure sensor, 13 - pressure sensor settings unit, 14 - pressure sensor power supply, 15 - 3 liter balloon capacity, 16 - graphic recorder KSP-4, 17 - gas analyzer OA-2209, 18 - mass spectrometer MX-6202, 19 - graphic recorder KSPP- 4, 20 - gas chromatograph LHM-8md, 21 - valve Ru 6/3, 22 - graphic recorder KSM-4, 23 - gas analyzers MN-5130 and GL-5118, 24 - gas analyzer MMG-7.

RESULTS AND DISCUSSION

Summarizing the results of studies of the dynamics of the regimes of mass transfer of respiratory gases in the human body during hyperbaria, we can conclude that under conditions of a moderately hyperoxia nitrogen-oxygen medium, the organism's oxygen balance (OOB) naturally transfers to a new level compared to the initial (normobaria) level. It is characterized by (Fig. 12 A):

- high rate of O_2 intake in the airways and alveoli, PO_2 in the airways, alveoli and arterial blood;
- low speed of O_2 transport by arterial and mixed venous blood, PO_2 of mixed venous blood;
- multidirectional shifts in the rates of O_2 entry into the pulmonary reservoir (increase) and O_2 transport by blood (weakening), similar changes in PO_2 of arterial and mixed venous blood, elevated OOB variables in the pulmonary, and lower - in hemodynamic links.

The mode of mass transfer of carbon dioxide in the human body in the high density hyperbaric medium is characterized by (Fig. 12, B):

- decrease in the rate of CO_2 transport by mixed venous and arterial blood;
- maintaining at a level close to the initial one, or lowering the rate of CO_2 removal from the alveoli and respiratory tract;
- PCO_2 increase in mixed venous and arterial blood, alveolar gas, shift in acid-base equilibrium towards respiratory acidosis - pH decrease, growth of CO_2 total content in plasma, actual and standard bicarbonates while maintaining buffer bases within normal limits.

The described shifts are typical for the range of moderately hyperoxic (increased PO_2 up to 300-400 mm Hg) respiratory medium of increased (up to 6.34 g/l) density, but depending on the compression rate, density of the gas mixture, partial O_2 and N_2 content in it, the level of physical activity and exposure, as well as individual sensitivity to these factors, the characteristics of the oxygen and carbon dioxide modes of the body can deviate, preserving the generally described direction of changes.

Let us consider the main regularities of changes in respiratory, hemodynamic and hemic mechanisms that ensure switching of the mass transfer regime of respiratory gases to a level typical for hyperbaria.

The respiratory rhythm became rarer, which is typical for reactions to an increased density of the respiratory medium. The same reason caused an increase in tidal volume, and with it the minute volume of respiration, most noticeable in the first hours of exposure (Fig. 13). Such changes in the breathing regime explain the observed changes in the mass transfer of O_2 and CO_2, in particular, growth of the minute volume of respiration (VO_2) led to a corresponding increase in the rate of O_2 intake into the respiratory tract. This mechanism was the leading one in changing the rate of O_2 entry into the respiratory tract until PO_2 increased in the inhaled medium, which acquired priority importance.

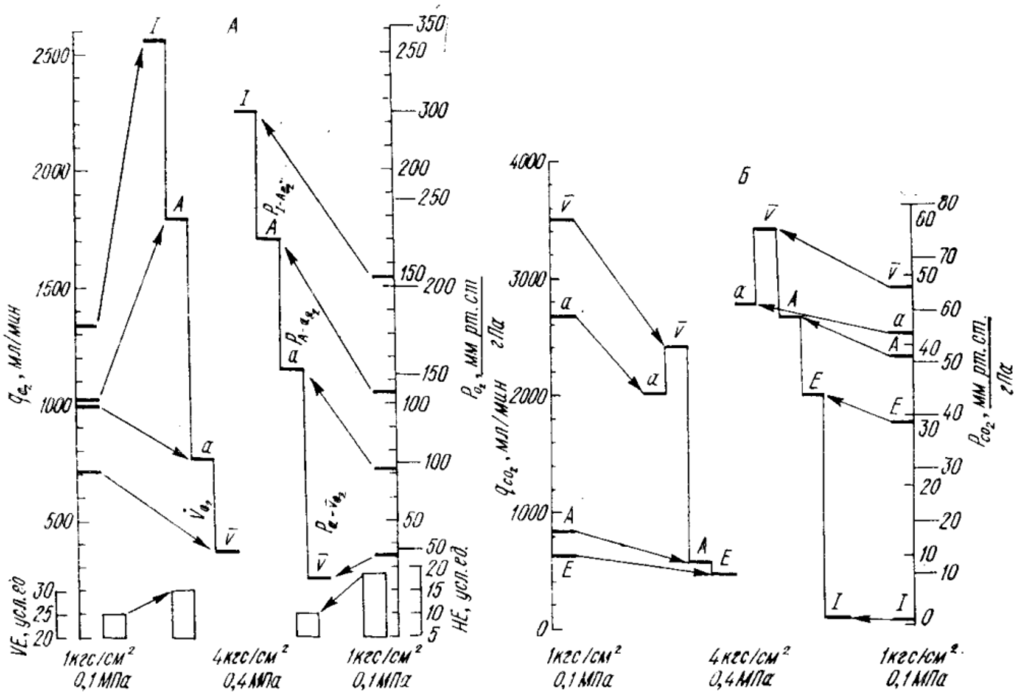


Fig. 12 The speed variables (q) of the phased delivery of oxygen, partial (P) oxygen and its gradients, ventilatory (VE) and hemodynamic (HE) equivalents (*A*); the rate of phased removal of carbon dioxide and its partial pressure in the human body in a nitrogen-oxygen medium (PO_2 up to 340 hPa) under a pressure of 0.4 MPa (4 kgf/cm^2); (B): Average data are given, I - inhaled medium (respiratory tracts), E - mixed exhaled gas, A - alveolar gas, a - arterial, v - mixed venous blood, VO_2 - rate of oxygen consumption by the organism.

The increase in VO_2 in the first hours of exposure in the underwater laboratory was related with physical work when diving in conditions of increased heat loss in the water. This is confirmed by the results of comparison of VO_2 in the underwater laboratory (UWL) and in the hyperbaric chamber (HC) under the same pressure in underwater laboratories at different depths: in UWL at a depth of 15 m, VO_2 increased by 53%* in HC at the same pressure, but without water cooling effect, only by 17.5%*, in UWL at a depth of 4.25 m (without significant hyperbaria, but with diving) - by 27.9%*. In addition, neuro-emotional stress had a certain role: in studies where the weakening of the emotional background was achieved through “hyperbaric” training, VO_2 amplification was not observed. Weakening in the subsequent time of the severity of the factors of transition to hyperbaria led to the fact that after several days in UWL conditions, despite the constant action of hyperbaria, VO_2 normalized. This determined the dependence of the O_2 rate entry into the pulmonary reservoir only on the dynamics of PO_2 in the inhaled medium.

Increase of resistance and a decrease of respiratory gas flow rates in airways, along with the change of gas composition in alveoli, determined the increase of physiological dead respiratory volume (V_DO_2). Therefore, the rate of O_2 influx into alveoli, depended on the alveolar ventilation, was limited by the increase of physiological dead volume, increasing during the first hour of exposure under pressure of 0.25-0.3 by 80-81%* and of 0.4-0.5 by 188-278%*. Correspondingly, the ratio of alveolar ventilation and pulmonary ventilation decreased, which indicated the entry into the alveoli of a smaller volume of gas than at normal pressure. Therefore, the increase in the rate of O_2 entry into alveoli was lower than in the respiratory tract, which is a manifestation of the regulatory effect of V_DO_2 increase, leading to a decrease in the supply of excess O_2 to the alveolo-capillary barrier. However, due to a significant increase in the minute volume of respiration (V_IO_2) and PO_2 in the respirable medium, PO_2 in the alveolar air (P_AO_2) increased, which indicates the insufficient efficiency of this mechanism in regulating the delivery of O_2 to the blood.

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* $P<0.05$

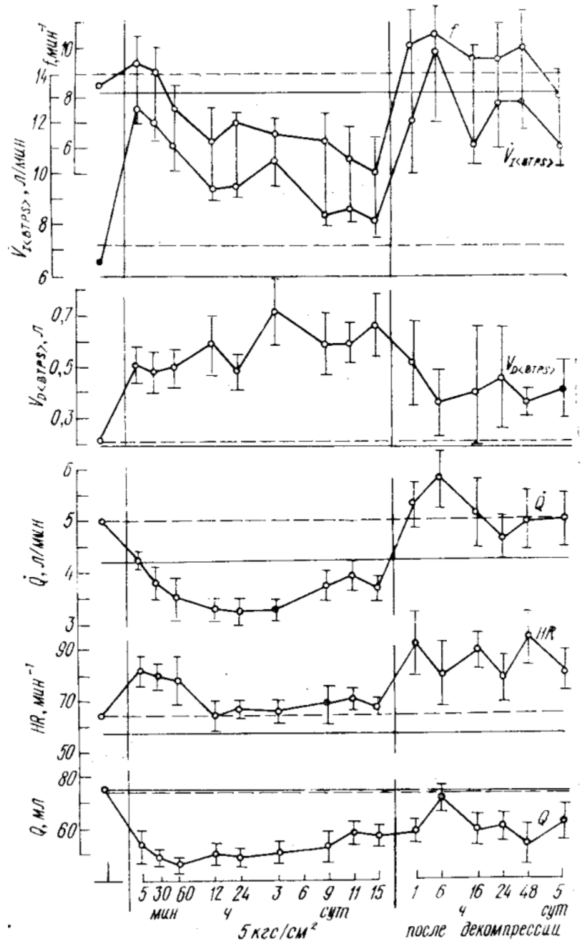

Fig. 13 Dynamics of the frequency (f) and minute volume ($V_{I\ <BTPS>}$) of respiration, volume of physiological dead respiratory volume ($V_{D\ <BTPS>}$), minute (Q) and stroke (Q) blood volumes, heart rate (HR) in person when staying in a nitrogen-oxygen medium (PO_2 up to 340 hPa) under a pressure of 0.5 MPa (5 kgf/cm^2).

The effect of increased density of the gas medium on respiration, consists in its reduction and increase of tidal volume, which is considered an adaptive reaction [3,14,35], manifests itself in hyperbaria regardless of exposure. The observed decrease of the maximum ventilation in lungs and respiratory reserve indicates that at a high density of the respiratory medium, the compensatory capabilities of the respiratory mechanisms of OOB regulation were constantly reduced.

The reason for such shifts is increased resistance in the airways (Fig. 14) - increased resistance in the airways was created when breathing through diaphragms with a diameter of 20, 7, 4 and 3 mm under normal and increased (0.15-0.5 MPa) air pressure, lower speeds of inspiratory and expiratory flows, which limits the ventilatory capacity during spontaneous and, especially, forced breathing (Fig.14, A). With an increase in the degree of training to hyperbaria, the severity of these shifts intensified, and their dispersion narrowed.

Among the respiratory mechanisms that determine the size of P_AO_2 and P_ACO_2, peculiarities of mass transfer of O_2 and CO_2 in the alveoli and blood of the pulmonary capillaries, belongs the unevenness of their perfusion observed under normobaric conditions. An increase in lung ventilation without a corresponding increase of blood flow in the lungs led to an increase in the percentage of ventilated but not perfused alveoli by 2-10%. The increased resistance in the respiratory tract was the reason for the increasing unevenness of ventilation according to phonopulmography in different zones of the lungs, the number of sites in which hyperventilation exceeded the general ventilation level by more than 100%.

The ventilation-perfusion ratio in hyperbaria increased and, depending on P_IO_2 at 0.25-0.3 MPa, it exceeded the initial level by 135-152%*, at 0.5 MPa - by 278%*. These data indicate worsening of the conditions for O_2 transition from the external hyperbaric medium to the alveoli and blood, since the gas flow with which O_2 is delivered to the alveolar-capillary barrier undergoes significant changes compared to the norm, and the number of lung zones, where remain normal conditions for gas exchange, decreases.

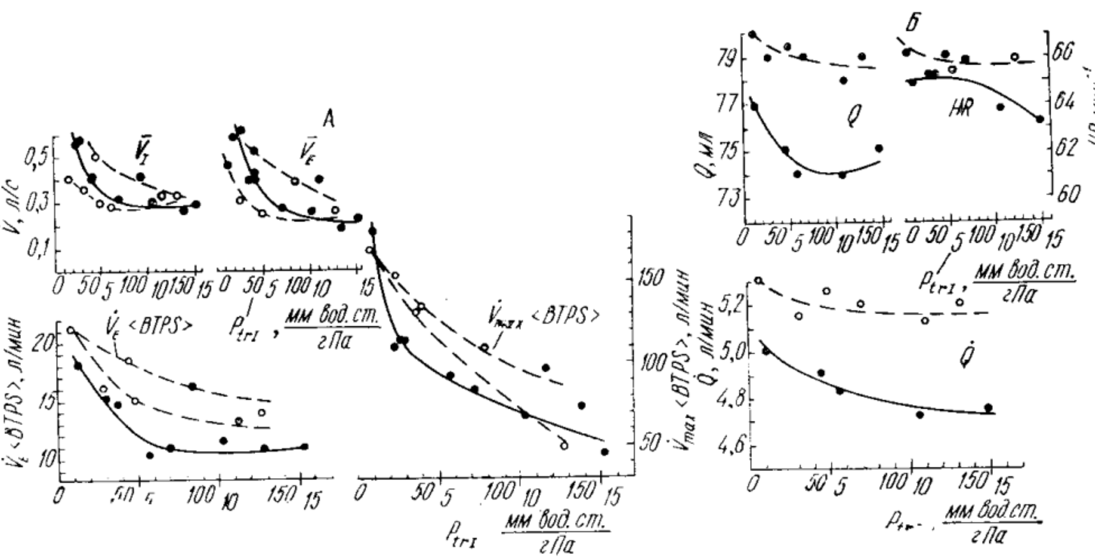

Fig. 14 Change in the speed (V)¯ of respiratory flows at inspiration (I) and expiration (E), pulmonary ventilation ($V_{E <BTPS>}$) at rest and maximum ventilation ($V_{max <BTPS>}$) (*A*); cardiac rhythm (HR), stroke (Q) and minute ($Q^{\cdot}$) blood volumes (*B*) in humans with increased resistance in the respiratory tract: Dotted line - data obtained from untrained to hyperbaria, solid line - from divers.

Calculations of the diffusion rate through the alveolo-capillary barrier showed that with initial D_LO_2 at rest 6.4 ml of O_2/min.mm Hg the diffusion capacity of the lungs at 0.15 MPa decreased to 5.02 (by 21.6%*), at 0.3 MPa to 4.63 (by 27.7%*), at 5 MPa to 3.31 ml O_2/min.mm Hg (48.3%*). D_LO_2 decrease depended on P_IO_2: with its increase, lower D_LO_2 values were observed. In addition, with the exposure increase in a moderately hyperoxic environment, and especially with increasing nitrox pressure, D_LO_2 also showed a tendency to decrease. So, in the underwater laboratory at 0.4 MPa, 10-15 days after compression, D_LO_2 decreased by 30%* compared to the initial one, and by 66.6%* in a hyperbaric chamber at 0.5 MPa. The main reason for O_2 diffusion rate decrease into the blood is hyperoxia, leading first to functional changes in the aero-hematic barrier, and then, with an increase in exposure, it is also possible to morphological changes in the walls of the alveoli [47].

Under the same conditions, it was revealed that the mechanism of blood shunting in lungs turns on as a protective reaction against O_2 excess - according to our calculations, the amount of shunted blood increased 3-4 times. This is important for OOB regulation, since an increase in venous discharge into the pulmonary veins helps to reduce oxygenation in arterial blood.

The listed respiratory mechanisms cause an inhibitory effect on the mass transfer of O_2 from the alveoli, where O_2 is in excess, into capillary and arterial blood. This was evidenced by an increase in $P_{A-a}O_2$. However, the compensatory possibilities of pulmonary changes were insufficient to limit the excessive mass transfer of O_2 to the blood, so hyperoxemia developed. An increase in the physical dissolution of O_2 in blood plasma, an increase in the oxygenation of hemoglobin and O_2 content in arterial blood, as described in the literature [3,7,4,37,48], should lead to an increase in P_aO_2 and the rate of O_2 transport by arterial blood, proportional to the growth of PIO_2 taking into account the weakening effect of the afore mentioned respiratory mechanisms.

However, under real conditions, the mass transfer rate of O_2 by blood turned out to be much lower than its rate of entry into the alveoli and even lower than its normobaric level. This can be explained by a decrease in the volume blood flow rate, which in this case acts as the main factor limiting the delivery of an excess amount of O2 to tissues (the role of reducing hemoglobin and the number of red blood cells, as we have established, is small). In all cases, regardless of the degree of saturation of the body with inert gases, at moderate hyperoxia, it was observed a decrease of minute cardiac output (Q) by 20-28%* in the first hours of exposure and by 7-20%* later. According to our data, the decrease of $Q^{\cdot}$ was based on both a decrease in systolic volume by 17-37%* (the predominant contribution) and a decrease in heart rate by 2-4%*.

There are known bradycardic effect of hyperoxia, which causes activation of the vagus nerve [3,39], a decrease in the contractility of the myocardium, a decrease in its metabolism, confirmed by ECG analysis [40,41,45], which leads to a decrease in stroke volume. Other reasons for the reduction in stroke volume include peripheral vasoconstriction due to hyperoxia, which leads to an increase in total peripheral resistance, insufficient venous blood flow to the heart, caused by an increase of intrathoracic pressure due to an increase of airway resistance (Fig. 14, B). As it is shown by studies of cardiac output by thermodilution in animals that inhaled high-density normoxic mixtures at normal pressure (SF_6+O_2 mixture) or breathed with increased resistance in the airways, the effect of the "density" component is significant, because cardiac output decreased by 15-30% *.

The limitation of the O_2 mass transfer rate by arterial blood resulting from the inclusion of the above hemodynamic mechanisms has a protective value, because it helps to weaken tissue hypoxia, and also reduces the load on the heart.

However, a decrease of OOB can also be regarded as a negative consequence of hyperbaria, since CO_2 transport was simultaneously impaired. In connection with the slowdown of blood flow through tissues, mixed venous blood accumulated CO_2. In conditions of weakening of the role of hemoglobin as a carrier of CO_2 (more complete saturation with oxygen), increased blood shunting in lungs and alveolar hypoventilation, prerequisites are created for retention of CO_2 in arterial blood, a shift in acid-base balance. Such endogenous hypercapnia was not accompanied by a pronounced ventilatory reaction, which can be explained by the low individual sensitivity of the respiratory center to CO_2 in the divers examined by us, which is often observed [40,12,42]. In addition, in the genesis of the weakening of the role of respiratory mechanisms in CO_2 elimination, the inhibitory effect of narcotic nitrogen concentrations on the structures involved in the regulation of respiration is not excluded [43]: our studies of the effect of increased density of nitrogen and neon-oxygen mixtures (11.3 g/l) revealed a decrease in pulmonary ventilation and a greater increase of hypercapnia in a nitrogen-oxygen medium.

The low volumetric blood flow velocity causes a decrease in the rate of O_2 transport by mixed venous blood, which, in conditions of increased utilization of O_2 (the first hours of exposure, increased muscle activity), leads to a decrease in the content and voltage of O_2 in the mixed venous blood, and a decrease in hemoglobin oxygenation in it. These changes are symptoms of venous hypoxemia, which is based on circulatory changes that limit the rate of O_2 transport.

The relationship between the manifestations of the influence of the main factors of hyperbaria on the OOB and the mechanisms of its regulation (respiratory, hemodynamic and hemic) are shown schematically in Fig.15. Analysis of these connections indicates that along the entire pathway of O_2 to tissues, the influence of factors of a hyperbaric environment, which is different in direction, manifests itself, which determines the mismatch of individual varieties and peculiarities of OOB regulation under these conditions. This diagram shows only the main ones and did not specifically depict individual reactions, the deviations of which sometimes had a wider spectrum. In addition, mechanisms for compensating the effects of hyperbaric conditions and for regulating the optimal OBO are often subject to mutual influence.

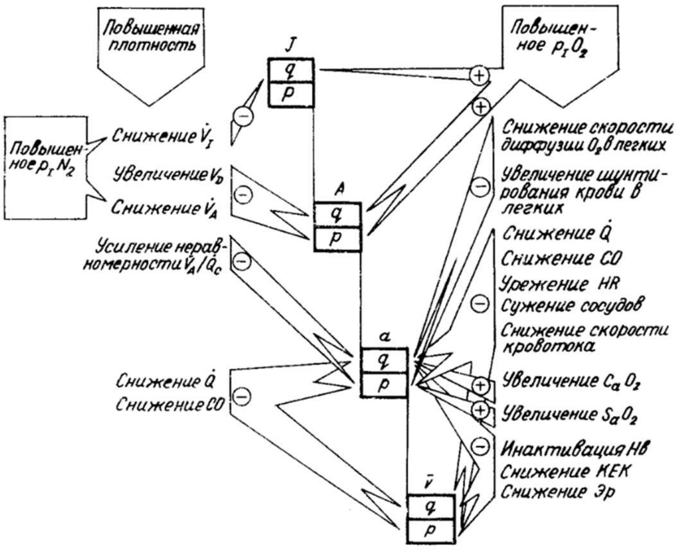

Fig. 15 The relationship between respiratory, hemodynamic and hemic mechanisms of regulation of the oxygen regimes of the human body under the action of the main factors of the hyperbaric nitrogen-oxygen respiratory environment:
Signs +, - indicate reinforcing and inhibitory effects; V_A / Q_C - ventilation-perfusion ratio; S_aO_2 - saturation of hemoglobin of arterial blood with oxygen; Hb - hemoglobin; OCB - oxygen capacity of the blood; Er - red blood cells. Other designations see in fig. 12 and 13.

Evaluation of the dynamics of the functional state of respiration and blood circulation depending on the duration of a person's stay in hyperbaria revealed that with incomplete and then full saturation of tissues with a gas medium, it was noted the phase change of the OOB, CO_2OB and the mentioned systems variables. We have singled out [22,36,24] the phases of initial and relatively stable adaptation, initial decompensation (maladaptation) and re-adaptation (during and after decompression) (Fig. 16).

The influence of one or another factor of hyperbaria or their complex causes a forced deviation of physiological variables from the ground norm, which in essence, reflects tension of this physiological function regulation, which seeks to restore disturbed equilibrium, but due to the constant exposure to extreme conditions, it occurs in intermediate position.

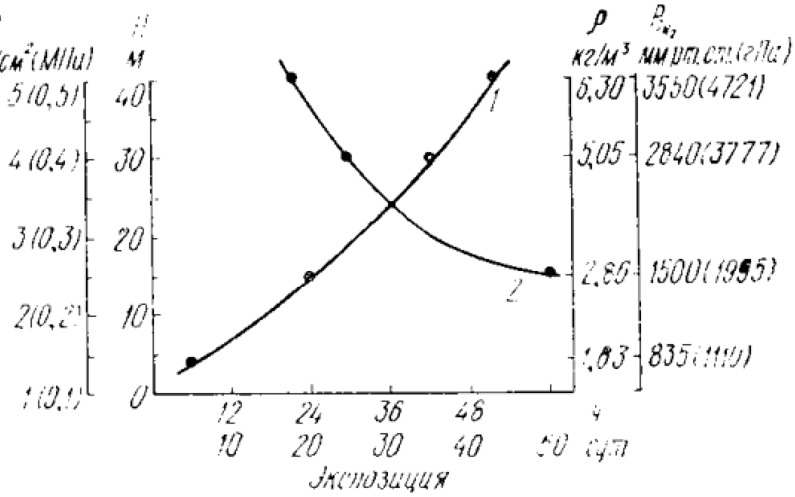

Fig. 16. Dependence of the duration of the phases of adaptation of the respiratory and circulatory systems of a person on the manifestation of hyperbaric factors: 1 - duration of the initial adaptation phase in hours; 2 - duration of the phase of relatively stable adaptation in days; ρ - pressure of the environment; H - depth; - density of the respiratory environment; PIO2 - partial pressure of oxygen in the inhaled environment.

Taking into account phasing adaptation to hyperbaria allowed to reveal that dynamic equilibrium between the adverse effects of the hyperbaric microclimate and compensatory reactions of the body (relatively stable adaptation) was observed at each exposure at 0.25-0.5 MPa. The proximity in the direction and manifestation of the responses allows to admit a possibility of formation of a new functional level ("hyperbaric" norm) of respiration, blood circulation, oxygen and carbon dioxide regimes of the body in aquanauts.

When analyzing the characteristics of the dynamics and nature of responses to nitric hyperbaria, the question arises of the possibility of adapting the human body to these conditions and its physiological essence. General mechanism of such adaptation is the formation of a new organization of the functional respiratory system that meets the needs of the moment, provides an adaptive

Probably adaptation to hyperbaria should be considered indirect, since it is represented by a number of complexes of adaptive reactions to individual factors, which as a whole constitutes a hyperbaric effect. Adaptation to each of these factors has a different physiological meaning: to factors that the body did not meet during evolution (hyperoxia, increased partial nitrogen pressure), the adaptation is non-specific, most likely it is adaptation to the physiological reactions that arose as a result of the action of the mentioned factors; to other factors familiar to the body (increased resistance in the airways, increased PCO_2, temperature changes), development of specific compensatory mechanisms is possible.

Among the adaptive reactions of the organism to hyperbaria, it can be distinguished as physiologically appropriate (limiting the delivery to tissues of the excess O_2 coming to the lungs, compensating the effect of the increased density of the respiratory medium), and inappropriate ones, the cause of which was appropriate (retention of CO_2 in the body). In general, until the dose of unusual factors (increased partial pressures of O_2 and N_2), determined by their concentration and exposure time, exceeds the permissible limits, and the response will be within physiological fluctuations, we can assume the presence of adaptation to a specific combination of hyperbaric factors. Taking into account the effects caused by the chronic effects of sub-narcotic nitrogen concentrations (decreased mental performance), it was found that adaptation to hyperbaria in the pressure range up to 0.5 MPa provides vital activity in a narrowed range of the body's functional reserves.

Special attention should be paid to changes in the functional state of the organism that are observed during and after decompression (phase of re-adaptation). These shifts are a reflection of the total adverse effect of hyperbaric conditions and are characterized by asthenization, the severity of which depends on the magnitude of the previous pressure. During this period, in response to decompression effects, the stress of which is manifested in pressure drops, the composition of the respiratory mixture, and supersaturation of the body tissues with indifferent gases, the regulation of function occurs at many levels, including systems that regulate respiratory gas mass transfer. Return of the OOB and CO_2BO variables to the pre-compression values is accompanied by lability of the respiration ventilatory indicators, heart rate, signs of myocardial contractility worsening, changes in pumping function of the heart, which was especially noticeable during physical load. The overall decrease of physical performance is probably also associated with microcirculatory disorders caused by asymptomatic intravascular gas bubbles [13].

These data served as the basis for further studies of the functional reserves of the body, the time of their full recovery and the possibility of accelerating rehabilitation after hyperbaria. One of the ways to adequately influence the process of re-adaptation is the use of hypobarium. Moreover, in addition to enhancing nonspecific resistance to extreme factors achieved by the method of stepwise mountain adaptation [20], conditions arise for improving the elimination of inert gases ("stagnant" areas with reduced perfusion), additional opening and growth of tissue capillaries, and removal of the influence of the hyperoxia chronic effects. Studies of the functional state of the organism of divers who went through a training cycle at an increasing exponential exposure at altitudes up to 4000 m (based on the Elbrus Medical and Biological Station of the A.A.Bogomolets Institute of Physiology, NAS of Ukraine), revealed a decrease in the physiological cost of physical work and improvement in special working capacity, which indicates the advisability of using adaptation to hypobaria to accelerate re-adaptation after hyperbaria.

Our [24] studies of human labor activity under the cooling effect of water revealed stressful effect of diving into water, which leads to significant changes in the regulation of visceral systems and shifts in their functional state, which subsequently was confirmed [39,10,19]. The significance of this syndrome for a human body under conditions of complete saturation with a hyperbaric gas environment, in particular, for a mass transfer system of respiratory gases, the speed and completeness of the restoration of the initial state after diving, as well as the influence of the frequency of dives on accelerating the development of maladaptation, are still to be studied.

Despite the solution of a number of fundamental problems in the field of underwater physiology described in this paper, there are much more issues that deserve close attention. In particular, among the first can be called studies of the mechanisms of regulation of gas homeostasis in conditions of compression and decompression pressure drops, hyperbaric hypoxia and hypercapnia. This determines the need for experimental determination of the effect of a multicomponent gas medium on respiration, blood circulation, blood gas transport function, the exchange of water and electrolytes with their complex neuroendocrine regulation. Considerable attention is required to study ways to increase adaptive reserves and the body's resistance to hyperbaria, prevention of adverse disorders in divers: specific (training for hyperbaric effects, a specific set of living conditions and components of the respiratory environment) and non-specific (training in high altitude conditions).

Studying the peculiarities of individual reactions of the human body to isolated factors of a hyperbaric environment (increased partial pressures of O_2, CO_2 and N_2, lowered PO_2, pressure or resistance differences in the airways, and ambient temperature) will allow us to estimate their specific contribution to the complex of changes caused by increased gas and water pressure environment, and optimize selection of divers.

CONCLUSIONS

Under conditions of a moderately hyperoxic hyperbaric medium with a density up to 6.4 g/l, the organism's oxygen regime is characterized by an increased rate and intensity of O_2 intake into the alveoli, a reduced rate and intensity of its transport by arterial and mixed venous blood; increased PO_2 in the alveoli and arterial blood, as well as reduced PO_2 of mixed venous blood.

The regime of CO_2 transport in the body at hyperbaria is characterized by a reduced rate of CO_2 removal by arterial and mixed venous blood, close to the normal rate of CO_2 elimination from the lungs, increased PCO_2 in arterial and mixed venous blood, alveolar gas, and changes in acid-base equilibrium towards respiratory acidosis.

The main respiratory mechanisms of regulating the body's oxygen regimes at hyperbaria are an increase in physiological dead airspace, a decrease in the proportion of alveolar ventilation in lungs, a decrease in the rate of O_2 diffusion through the alveolar-capillary barrier, an increase in the unevenness of ventilation-perfusion relationships in the lungs, a decrease in pulmonary capillary blood flow, and an increase of the blood shunting in lungs.

The leading hemodynamic mechanisms of the oxygen regimes regulation in hyperbaric conditions include a decrease in the volumetric rate of the blood flow, stroke volume and, to a lesser extent, a decrease of the heart rate.

The increased partial pressure of O_2 in the hyperbaric respiratory environment is the cause of reactions aimed at reducing the penetration of O_2 to tissues, however, they also lead to a decrease of CO_2 elimination from the body. An additional effect of increased density of the nitrogen-oxygen respiratory medium leads to alveolar hyperventilation, decrease of the heart pumping function and hypercapnia.

For a pressure range of 0.25-0.5 MPa of the nitrogen-oxygen medium, the factors of hyperbaria in terms of their effect on the functional respiratory system and modes of the respiratory gases transport in the body locate in the following sequence: compression and temperature stress, hyperoxia, increased density, nitrogen partial pressure and temperature of the respiratory environment, hypodynamia.

Adaptation to hyperbaria has a non-specific character and phase structure: there are differentiated phases of initial and relatively stable adaptation, initial decompensation and re-adaptation to normobaric conditions. Duration of the first phase increases with increasing nitrox pressure. The severity of asthenic syndrome in the phase of re-adaptation and its duration depends on the intensity of exposure to each of the factors of hyperbaria.

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It is dedicated to the 50th anniversary of the first in the USSR technical and medical-physiological experiments which study the possibility of a long saturation stay of aquanauts under high pressure in the underwater laboratories Ikhtiander.

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