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TOXICOLOGY OF GASEOUS ENVIRONMENT IN DECOMPRESSION CHAMBER

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The paper presents basic concepts of toxicological problems under human containment in a closed hermetic hyperbaric volume basing on the literature data and our own long-term scientific and practical experience aimed at diving and diving medicine, development and testing of the decompression chambers. The paper describes the following essentials of the problem: gaseous atmospheric composition in closed hermetic volumes, evolution of exogenous gases in human organism under lowering in the chamber, evolving hazardous gaseous substances (HGS) in the closed volume, design average daily rate of HGS evolving, effect of conditions on HGS evolving, their maximum permissible concentrations, methods of CO_2 and HGS removal in the chambers, and regulatory requirements. It is shown that the most of the modern existing chambers do not meet the regulatory requirements that may result in negative effects on human health. The ways to except the cases of human intoxication in the decompression chambers and systems are offered in the paper.

Key words: marine medicine, toxicology, hazardous gaseous substances, maximum permissible concentration [hereinafter lowest-observed adverse effect level, LOAEF], closed hermetic volume, hyperbaric conditions, decompression chambers, decompression systems, ventilation, gaseous environment purification.

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Health preserving is the task of medicine including
decease understanding and its causes eliminating.
Avicenna

1. Gaseous atmospheric composition in closed hermetic volumes. The gaseous composition of the atmosphere in a closed hermetic volume is formed from the gases originally contained in it and/ or the gases, which are fed into the closed volume to correct or replace the gaseous environment. In the conditions of the decompression chamber, the gas mixture is supplied for compression (pressure increase). These gases are exogenous to a human body. In addition, as it stays in an airtight volume, air pollution occurs – accumulation of hazardous gaseous substances (HGS) of biological origin, including those formed in the body and released into the environment in the form of endogenous impurities, which can be supplemented with a man-made pollution.

2. Evolution of exogenous gases in the body during descents in a decompression chamber. O_2, air (20.9% O_2, 78.1% N_2, 0.9% Ar, and 0.03–0.04% CO_2), indifferent gases (inert gases, N_2, H_2) or their combinations can be fed into an enclosed pressurized volume. Compression with these exogenous gases (with the exception of biologically active O_2 and CO_2) leads to saturation of the body with them according to Henry – Dalton's law: as the pressure of the gaseous atmosphere to a liquid increases and the same temperature remains, the amount of dissolved gas increases in direct proportion to the partial pressure of this gas in the gas mixture (gaseous environment). The dissolution of gas in the tissues of a body occurs with a slowdown exponentially (doubling per unit of time), and the distribution of gas through the tissues is carried out in accordance with the Meyer – Overton coefficient of fat and water. Saturation, desaturation and dynamics of respiratory gases (O_2 and CO_2) in a body have their own characteristics. During decompression, the desaturation of the body from exogenous indifferent gases occurs according to the same laws as the saturation, but in the reverse order, and there is also a redistribution of gases between the "slow" and "fast" tissues of the body.

A healthy person in a calm state at a temperature of 20°C and a relative air humidity of 65% per day passes about 7200 l of air (inhaled gas mixture) through the lungs. Of this volume, it absorbs 720 l of O_2 to the needs of the main systems of the body (brain, heart, liver, kidneys and other organs), and the remaining 6480 l of air (mixture) removes moisture, CO_2 and volatile metabolism products from the lungs [1, p. 42–45]. Under conditions of high pressure (the hyperbaric medicine), the volume of pumped air increases in proportion to the pressure, but the requirements of the main exchange are satisfied almost the same as at normal atmospheric pressure.

The limitation of staying in a closed volume without cleaning and regeneration of the gas environment is not a lack of oxygen but the accumulation of carbon dioxide and a number of HGS.

A clean gas environment inside a decompression chamber is one of the most important requirements for a person to stay under high pressure, because unlike other workers, a person who is in a closed decompression chamber system is continuously exposed to a large set of specific environmental factors, including hazardous and dangerous ones, especially when alternating descents into the water and stay in the chamber. A diver must be in good health to perform complex work, and in the event of a disease in him, the possibility of providing qualified assistance in a decompression chamber or quick evacuation is limited. A patient undergoing therapeutic recompression should not be exposed to an additional hazardous impact and a hazard aggravating his or her condition.

3. Release of hazardous gaseous substances in a closed volume. Contamination of closed volumes (spacecraft, submarines, underground bunkers, decompression chambers, etc.) can be regarded as biological (anthropogenic and microbial) and man-made (structural materials and technological processes).

Anthropogenic pollution is the most important contamination: about 150 substances are released from the lungs, about 200 through the gastrointestinal tract, about 180 through the urinary system, through the integuments of the body (skin and sweat glands, mucous membranes of the oral cavity, etc., hair) 270 [1. p. 42–45; 2. p. 11–42; 3. p. 89–90; 4. p. 124–137; 5. p. 58–64; 6. p. 74-108]. The exhaled air, in addition to water vapor, contains O_2, CO_2, CO, acetaldehyde, formaldehyde, acetone, methyl ethyl ketone, propionaldehyde, ethanol, methanol, butanol, propanol, isopropanol, formic, acetic, propionic, isovaleric and valeric acid, acetaldehyde, ammonia, dimethylamines, methane, ethane, ethylene, propane, hexane and other substances. The gastrointestinal tract and urinary system are the source of excretion of feces, intestinal gases and urine with the release of indole, skatole, O_2, CO_2, hydrogen, hydrogen sulfide, methane and other hydrocarbons, nitrogen, nitrogen oxides, aliphatic acids, phenols and various mercaptans into the gaseous environment. When urine is decomposed by bacteria, ammonia is the main pollutant entering the atmosphere. The outer integuments of the body also secrete ammonia, phenols, and a number of other trace impurities. Horny solids of the skin, which may be suspended in the external environment, as well as proteins and lipids formed as a result of their desquamation (shedding) carry a multitude of microorganisms. In discharge of many endogenous HGS, the role of intestinal microorganisms prevails over the role of microflora of body surfaces.

The growth of microflora (bacteria, fungi and sometimes algae) can occur on the internal surfaces of the decompression chamber, furniture, equipment and devices, body surfaces, clothing, shoes and personal belongings of people in the chamber, as well as in liquids (condensate, underfloor space, sink, a toilet bowl, a container for storing feces and urine prior to release). The microflora can be in a gaseous environment in the form of aerosols and release HGS into the environment.

Constructive materials (plastics, lubricants and insulating materials, paints, adhesives, residues of solvents after degreasing treatments, toilet articles) emit about 70 organic compounds, among them there are CO, epichlorohydrin, cyanide hydrogen, fluoride hydrogen, acrylonitrile and some others. Technological processes (operation of compressors, filters and electrical equipment, ultraviolet irradiation, tidy, personal hygiene procedures, etc.) can cause such contamination as oil fumes, nitrogen oxides, CO, ozone, etc**.**

4. Estimated average daily release of hazardous substances. The average daily human release of HGS was calculated on the basis of studies conducted at the SSC RF-IMBP under the guidance of V. P. Savina, G. I. Solomin, and L. N. Mukhamedieva [2, p. 11–42; 3, p. 89–90; 4, p. 124–137; 5, p. 58–64]. Based on these studies, GOST R 50804-95 “The cosmonaut’s habitat in a manned spacecraft. General medical and technical requirements” was developed. Estimated average daily rates of human HGS excretion are given in Table 1.

Table 1

Estimated average daily rate of human emission of gaseous hazardous trace impurities (GOST R 50804-95)

Sl. No.	Metabolic substances	The average daily release, mg/day
1	Ammonia and amino compounds	6.0±0.6
2	Carbon monoxide	113.0±16.6
3	Hydrocarbons (CH_4)	15.3±0.8
4	Fatty acids (acetic acid)	6.3±0.7
5	Aldehydes	1.4±0.1
6	Ketones (acetone)	5.7±3.4
7	Acetaldehyde	0.8±0.1
8	Methanol	1.52±0.7
9	Ethanol	8.45±4.0
10	Methyl ethyl ketone	0.96±0.16
11	Dimethylamine	0.8±0.1

Note: norms are given for comfortable microclimatic conditions and oxygen-nitrogen atmosphere with P_{tot} = 760–788 mm Hg.

When one person stays in a closed room with a volume of 6 m^3 for 12 hours, the concentration of acetone increases 10 times, ammonia – 5 times, aldehydes – 30 times, carbon monoxide – 5 times [1, p. 42–45].

The increase in HGS concentration (without purification of the gaseous environment of a decompression chamber) occurs linearly and, consequently, the absorption and dissolution of gases in organs and tissues increases linearly, which ultimately leads to poisoning of the human body.

5. The effect of conditions on the release of hazardous gaseous substances. The amount of HGS secreted from a body is mainly determined by the level of catabolism (energy metabolism, dissimilation, metabolic decay) of complex substances to simpler ones, that is by the level of oxidizing substances (food), which usually proceed with the release of energy. When the pressure in the decompression chamber increases, the volume amount (as well as the mass amount) of the emitted gases decreases in proportion to the pressure, and their partial pressure remains at the same level. At the same time, a large number of various external and internal factors (conditions of stay in the decompression chamber) can have a significant impact to the quantitative and qualitative characteristics of the gases emitted from the body.

Daily variations in the number of most exhaled compounds correspond exactly to diurnal metabolic changes. During the day, during the waking period, the highest concentrations of CO_2 correspond to the highest release of volatile metabolites, at night these figures are minimal. The greatest amount of research was carried out on the release of carbon monoxide from the body. It has been established that excretion of CO from the body is maximum at noon and minimum at midnight. The release of CO increases with hyperoxia and an increase in the concentration of CO and CO_2 in the environment, and is also associated with the performance of physical work [7, p. 63]. It is worth noting that hyperoxia and elevated CO_2 content often accompany descents in the decompression chamber and therapeutic recompression. In experiments on long stay (LS) [8, p. 22–33; 9, p. 55–59] under pressure up to 20–30 m of water column in conditions of hyperoxia in the underwater laboratory "Chernomor", the release of CO by the crew members was about 2 times higher than expected compared with the literature data on the elimination of CO under normal pressure in the 1960s, which is approximately 4 times higher than the current calculated standards for its content, Table 1.

A number of authors have noted a significant increase in the release of various HGS (anthropogenic and from polymeric materials) with increasing temperature of the gaseous environment. At an air temperature of + 40°C and a relative humidity of 90%, the content of almost all HGS in exhaled air increases by 2–10 times. It is important to note that the use of helium-containing media in itself requires an increase in temperature in the compartments of the decompression chamber to 28–32°C.

Functional and morphological changes in organs and systems of the body can affect the rate of HGS release and sensitivity to various chemicals, with such changes in the activity of the central nervous system, cardiovascular system, hematological changes, as well as in tissue enzymes and immunological characteristics, which are most important for toxicology [10, p.p. 68–100], so these changes can be attributed to the conditions of not only a space flight, but also in a hyperbaric chamber.

The yield of metabolic products and heat off the human body depends on the digestible part and the composition of the diet, as well as on the individual characteristics of metabolic processes. By changing the amount and ratio of secreted substances, some conclusions can be drawn about qualitative changes in metabolism. For example, with increased pressure in the decompression chamber, the release of hydrocarbons, acetone and keto acids increases compared to normal pressure. In combination with the results of the biochemical study of blood, these data suggest that divers have a greater increase in the metabolism of fats than that in carbohydrates and proteins [1, p. 42–45].

The influence of many factors in the enclosed volume of a decompression chamber under pressure, as well as the factors of orbital space flight, requires additional research, since in those and other conditions there is an increase in concentration of a number of metabolic products in comparison with the normal conditions of existence.

6. Effect of major hazardous gaseous substances on the body. GOST 12.1.007-76 "Classification of hazardous substances and general safety requirements" establishes 4 hazard classes of hazardous substances according to the degree of impact on the human body:

Grade 1 – extremely hazardous substances LOAEL [lowest-observed adverse effect level] less than 0.1 mg/m^3);

Grade 2 – highly hazardous substances (LOAEL 0.1–10 mg/m3);

Grade 3 – moderately hazardous substances (LOAEL 1.1–10.0 mg/m^3);

Grade 4 – low hazardous substances (LOAEL more than 10 mg/m^3).

By the nature of the impact on the organs and systems of the body, HGS are divided into the following groups:

- general toxic substances (carbon monoxide, benzene, hydrocarbons, alcohols, aniline, hydrogen sulfide, hydrocyanic acid and its salts, chlorinated hydrocarbons, etc.), which cause poisoning of the whole body leading to nervous system disorders, muscle cramps, disturbances in the structure of enzymes, affect the hematopoietic organs, and interact with hemoglobin;
- irritants (ammonia, acetone, nitrogen oxides, sulfur dioxide, acid mists, etc.), which cause irritation of the mucous membranes, upper and deep respiratory tract;
- sensitizing substances (formaldehyde, various nitro compounds, nicotinamide, hexachlorane, organic azo dyes, dimethylaminoazobenzene, etc.), which increase the body's sensitivity to chemicals, can lead to allergic diseases;

- carcinogenic substances (chromium oxides, 3,4-benzpyrene, nitroazo compounds, aromatic amines, etc.), which cause development of all types of cancer diseases;
- mutagenic substances (ethylene oxide, chlorinated hydrocarbons, etc.), which affect somatic and germ cells (gametes); they cause changes in the human genotype; they are usually diagnosed in the remote period of life, and they manifest themselves in premature aging, in increase in the overall morbidity, and in appearance of malignant neoplasms; they have a mutagenic effect on the next generation, sometimes in a very remote periods;
- substances that affect the reproductive function of the human body (boric acid, ammonia, many chemicals in large quantities), which affect the development of the fetus in the uterus and postnatal development, causing congenital malformations and deviations from the normal structure of the offspring, and impairment of health.

Most of the gaseous air pollutants (volatile metabolites), including anthropogenic, have a toxic effect on the human body and are anthropogenic toxins. The nervous system is the most vulnerable to their action. Many of the substances (acetone, saturated hydrocarbons) have a narcotic effect on the central nervous system. Unlike real drugs that cause hallucinations, the effect of volatile organic substances can be expressed in drowsiness, headaches, and cause fainting. One of the main hypotheses of their mechanisms of action is membrane (anesthesia can cause substances that dissolve in the membranes of nerve cells). Carbon monoxide, which has an affinity for hemoglobin 300 times more than O_2, binds to it and cellular respiratory enzymes, prevents the transfer of O_2 by blood and oxidative processes in tissues, and causes hemolysis of erythrocyte heme and myoglobin during erythropoiesis. Hydrogen sulfide and mercaptans, possessing a strong and unpleasant odor, cause nausea, headache, and in higher concentrations show a depressant effect on the central nervous system. Acetic acid and ammonia have a strong irritant effect on the respiratory tract and mucous membranes of the eyes, causing choking, runny nose and watery eyes.

Intestinal gases in certain conditions create some risk for fire and explosion. Intestinal gases contain about 60% nitrogen, 5% oxygen, 15% carbon dioxide and 20% hydrogen, as well as hydrogen sulfide, methane, carbon monoxide, and mercaptan. All this, when combined with oxygen in certain proportions, create some risk for fire and explosion. V. I. Tyurin [11, p. 42] relates some fires in the oxygen environment of a decompression chamber to the presence of intestinal gases in it

7. Lowest-observed adverse effect levels of hazardous gaseous substances. The lowest-observed adverse effect levels of HGS for an LS decompression chamber (a long stay decompression chamber) were determined in the 1960s by the 40th Scientific Research Institutes based on the cosmic standards developed at the Institute of Biomedical Problems, Russia. Since then there have not been any special studies on the accumulation of HGS in the decompression chambers, with the exception of studies in the Barents Sea in the decompression chamber of “Sprut” Mingazprom’s diving vessel, where the carbon monoxide accumulation was studied in volunteers without using the CO afterburner in CO_2. As a result of these studies, it was confirmed the need for purification from CO in LS decompression chambers.

Afterwards, uniform for all departments, the standards of LOAEL of HGS in a decompression chamber were adopted. Table 2 shows the standards of LOAEL of HGS in the gaseous environment of a decompression chamber in accordance with GOST R 52264-2004 “Diving decompression chambers. General technical conditions, supplemented by LOAEL of a number of other major hazardous substances in accordance with GOST R 50804-95 “The cosmonaut’s habitat in a manned spacecraft. General medical and technical requirements”.

Table 2

Maximum permissible concentrations (that is LOAEL) of hazardous substances in the gaseous environment according to GOSTR 52264-2004 and GOST R 50804-95

Chemical factors	LOAEL of hazardous sub-stances for a decompression chamber, mg/m^3		LOAEL of hazardous substances for a decompression chamber, mg/m^3 (for exposition)		
	LS	ShS	15 days	30 days	360 days
Carbon monoxide	5.0	5.0	–	–	–
Ammonia	0.8	0.8	–	–	–
Acetone	5.0	5.0	–	–	–
Saturated hydrocarbons(in terms of dean)	35.0	35.0	–	–	–
Organic matter (mainly hydrocarbons):					
in terms of carbon	50	50	–	–	–
on oxidability	65	65	–	–	–
Hydrogen sulphide	0.8	0.8	–	–	–
Nitrogen oxides	0.1	0.1	–	–	–
Fatty acids (acetic acid)	–	–	10.0	3.0	0.5
Aldehydes	–	–	1.0	1.0	1.0
Acetaldehyde	–	–	–	–	1.0
Methanol	–	–	–	–	0.2
Ethanol	–	–	–	–	10.0
Hexanoic (caproic) acid	–	–	10.0	6.3	2.9

Butane (H-butyric) acid	–	–	20.0	10.8	4.0
Propylene (acrylic) acid	–	–	40.0	18.0	5.6
Ethylene glycol	–	–	100.0	–	1.0
Formaldehyde	–	–	–	–	0.05
Ketones	–	–	–	–	0.5

The standards for standards of LOAEL of HGS in a spacecraft cabin, given in GOST R 50804-95, meet international requirements of 1975 [6, p. 74-108]. In 1994, international requirements were changed [10, p. 68–100], including the duration of stay in the cabin of a spacecraft (1 and 24 hours, 7, 30, and 180 days). The LOAEL s of a number of HGS were also changed. However, they are not given in this paper, since GOST R 50804-95 continues to operate. In addition, these changes are not of fundamental importance, since the content of HGS in a decompression chamber (a decompression system) with complete cleaning is maintained well below the LOAEL, and decompression technology owners will not be able to use either old or new standards without cleaning the gaseous environment.

8. Methods for removing CO_2 and hazardous gaseous substances out off the chamber. In a decompression chamber, there take place a man-made accumulation of carbon dioxide (CO_2), which, despite the danger of certain concentrations acting on the body, is considered a vital biological gas and is not in the list of HGS. According to space research [10, p. 68–100] a person produces 990 g/day of CO_2. Regular monitoring of its content and periodic or permanent removal from the gaseous environment through ventilation or the use of absorbers is required, for example, a chemical lime absorber (CP-I).

For many decades, the only way to correct the gaseous environment (air) in the compartments of a decompression chamber was periodic ventilation, aimed mainly at reducing the concentration of CO_2 and increasing the O_2 content in the gaseous environment. Ventilation is based on the allocation of 25 l/h of CO_2 by a person at rest and a maximum allowable content of CO_2 of 1%. The time to the ventilation is calculated taking into account the volume of the chamber (compartment) and the number of people in it. The amount of air supplied is 50% of the volume, after which the CO_2 content is reduced to 0.5%. The time until the next ventilation is half the time until the first ventilation. A sign with a pre-calculated time for primary and subsequent ventilation is posted on each decompression chamber.

The content in the gaseous environment of all HGS and microflora decreases to a certain extent at each ventilation simultaneously with CO_2, the humidity and temperature of the air (gaseous environment) decrease, deodorization occurs, and the O_2 content also increases. However, the use of ventilation can not remove HGS, so that you can only reduce their number. Almost complete cleaning of the gaseous environment is achieved only by its cleaning.

Since 1960–70s, a method of performing diving works derived from long stay (LS) conditions under increased has been developed and introduced. It is called the saturated diving method abroad Russian Federation (descents with a duration of stay under pressure of more than 1-3 days — full saturation of the body with an indifferent gas). In order to preserve the health of persons under pressure, it was necessary to reduce the permissible content of HGS taken for short-term diving. To replace the ventilation, cleaning gas environment came. All domestic and foreign marine DSDC (deep-sea diving complexes) began to be provided with life support systems for cleaning the gas environment from each HGS. This principle of complete gas cleaning not only from CO_2, but also from all HGSs, has been applied in experimental decompression systems of the 40th Scientific Research Institute of the Moscow Region, the Research Institute of Oceanology named after P. P. Shirshov of the Russian Academy of Sciences and IMBP, as well as in the decompression systems of SKB EO at IMBP RAS.

There are three ways to clean the gas environment from HGS.

1. The dissolution of HGS in the condensate. Polar compounds (hydrogen sulfide, mercaptans, acids, ammonia, amines, aldehydes, and alcohols) dissolve in the moist air of the pressure chamber and in the condensate, after which the condensate is removed from the chamber. However, this method does not provide complete purification even off this group of substances, since water-soluble HGS is not removed.

2. Adsorption and absorption. Water-insoluble impurities (hydrocarbons and aromatic non-polar compounds) well eliminate activated carbon filters (about 1 kg of coal is enough for one person). There are types of activated carbon that selectively absorb various HGS. For this reason, it is advisable to use a mixture of coal. This practically does not lead to an increase in the cost of LSS, but requires special studies on the rate of release of various HGSs in a hyperbaric chamber in comparison with their maximum allowable concentrations. Adsorption on zeolites (molecular filters) of gas molecules with a small critical diameter, in particular, ammonia and carbon dioxide, is possible. For deodorization, removal of ammonia and amines, a cupromite unit can also be used, in which activated carbon is impregnated with copper sulfate, followed by drying.

3. It is more difficult to deal with CO. The only way to cope with it is to oxidize on the catalyst to CO_2, which is then removed. The oxidation of CO to CO_2 can be carried out with cupromyte in combination with a gas preheater, as well as using low-temperature hopcalite catalysts (a mixture of manganese oxides, copper and silver). Hopkalitovye consoles are limited due to explosiveness. In high-decompression chambers for oxidation of CO, high-temperature catalysts (platinum or palladium) are usually used — the domestic catalyst AK-62.
Exhausted load is destroyed or, if possible, regenerated.

9. Requirements of normative documents on hazardous gaseous substances. Article 6.1.8.10, paragraph 61 of GOST R 52264-2004 "Diving chambers. General Specifications" provides for the purification of the gaseous environment from carbon dioxide and HGS as one of the functions of the air conditioning system and the purification of the gaseous environment of a decompression chamber. Art. 6.1.5.4, Tab. 5 of this GOST shows the maximum permissible concentrations of HGS - carbon monoxide, ammonia, acetone, saturated hydrocarbons, organic substances (mainly hydrocarbons), hydrogen sulfide and nitrogen oxides.
GOST R 57217-2016 ""Multi-purpose medical decompression chambers with a working pressure of the gas environment of 1.0 MPa. General technical requirements" also contains the requirement for cleaning the gaseous environment of decompression chambers from HGS, and the need for CO removal is noted. At the same time, the lowest-observed adverse effect levels of HGS must comply with GOST R 52264-2004.

10. Compliance of existing decompression chambers with the requirements of regulatory documents. In our previous publication [12, p. 51–62] an analysis of modern domestic samples of diving decompression chambers and diving complexes of modular, mobile and mobile versions was carried out. The analysis showed that all of them, with the exception of the "Spasatel" decompression system manufactured by SKB EO, cannot ensure the safe use of therapeutic regimes (except oxygen) for ventilation of the compartments in a closed cycle due to accumulation of HGS secreted by humans. In addition, in these decompression chambers, the sanitary-fan system replaces a dry closet or a bucket with a lid, which aggravates unfavorable living conditions and contributes to the accumulation of HGS.
During the treatment of a British diver in 2012 in Sochi at the HAUX-Starcom 1800/11 decompression system [13, p. 330–347], a number of technical flaws were noted: the lack of a system for cleaning CO and other HGSs, difficulties in reducing humidity and deodorization. This forced treatment managers, in violation of the therapeutic recompression regime, using the oxygen-nitrogen-helium environment from the "depth" of 8 meters, to carry out frequent ventilation of the decompression chamber with air.
In the majority of domestic and foreign decompression chambers, only a chemical lime sink (HP-I, foreign analogues: sodalaym, sodasorb, etc.) is used to remove CO_2, there are no cartridges for the oxidation of CO to CO_2. HGS in violation of GOST R 52264-2004 and other regulatory documents are not removed, and therefore there is also no deodorization of the gaseous environment. Already not only on the first day, but also in the first hours, the content of some HGS in the atmosphere of such decompression chambers reaches the MAC, and the body begins to undergo the toxic effect of these substances. Due to the fact that in these decompression chambers, not a closed flow system is used, but a block system, problems arise with a decrease in the humidity of the gaseous environment and the removal of condensate. In addition to a significant increase in humidity in the compartments (up to 100% over several days), another unfavorable quality of condensate should be taken into account - it contains dissolved polar compounds, which, being in equilibrium with the gaseous environment, can be eliminated into the gaseous environment of the compartment (such compounds include, for example, ammonia, which dissociates from its form dissolved in water - liquid ammonia). The use of silica gel or active alumina to absorb moisture is often not envisaged, and if silica gel was used, there would be problems with its purchase and regeneration. In addition, the domestic silica gel is significantly inferior in quality to foreign ones.
It follows from the above that the content of volatile impurities in the air must be strictly controlled and a thorough cleaning of the gaseous environment is to be carried out.
Comparing the data of the Tables 1 and 2, it is possible to calculate the time for **LOAEL** to reach some HGSs if there are decompression chambers in the compartments without cleaning them 1 victim or 2 people (the victim and the doctor) depending on the approximate volume of the compartments of the chamber (2 m^3 - RKUM compartment and RKUMu compartment, 3 m^3 - RCM and RKMU compartments, 7 m^3 - PDK-2, BRK and RBC-1600 co,partments, 13.5 m^3 – the volume of HAUX-Starcom 1800/11 decompression chamber in Sochi). These calculations are given in Table. 3.

Table 3

Estimated time of achievement of maximum permissible concentration (that is LOAEL) in the gaseous environment of a chamber without trace contaminant removal system depending on the number of people and overall volume of the chamber

Sl. No.	Name of hazardous substances	Design average daily rate of HGS evolving, mg/day	LOAEL mg/m³	The time to reach the LOAEL (hours) depending on the volume of compartments of a decompression chamber and the number of people									
				1.7 m^3 in RKUMu		2.15 m^3 in BDK-120T		2.98 m^3 in RBK К-1400		13.5 m^3 in HAUX-Starcom 1800/11		3.38+3.62 m^3 in BKBV-1600	
	Number of people			1	2	1	2	1	2	1	2	1	2
1	Carbon monoxide	113 ± 16.6	5	1.8	0.9	2.3	1.1	3.2	1.6	14.3	7.2	no	no
2	Acetone	5.7 ± 3.4	0.5	3.6	1.8	4.5	2.3	6.3	3.1	28.4	14.2	no	no
3	Methanol *	1.52 ± 0.7	0.2	5.4	2.7	6.8	3.4	9.4	4.7	42.6	21.3	no	no
4	Ammonia and Amino Compounds	6 ± 0.6	0.8	5.4	2.7	6.9	3.4	9.5	4.8	43.2	21.6	no	no
5	Aldehydes *	1.4 ± 0.1	1	29.1	14.6	36.9	18.4	51.1	25.5	231.4	115.7	no	no
6	Ethanol *	8.45 ± 4.0	10	48.3	24.1	61.1	30.5	84.6	42.3	383.4	191.7	no	no
7	Acetic acid	6.3 ± 0.7	10	64.8	32.4	81.9	41.0	113.5	56.8	514.3	257.1	no	no
8	Hydrocarbons	15.3 ± 0.8	35	93.3	46.7	118.0	59.0	163.6	81.8	741.2	370.6	no	no
9	Acetaldehyde	0.8 ± 0.1	5	255.0	127.5	322.5	161.3	447.0	223.5	2025.0	1012.5	no	no

Note: LOAEL of HGS marked with an asterisk (*), were taken hire from GOST R 50804-95 for 360-day flights

After reaching the **LOAEL** (in the absence of HGS removal), the increase in their concentration continues even more, the more people in the compartments of the decompression chamber, and the smaller their volume. It is believed that this increase does not depend on the magnitude of the decompression, although there is evidence that under hyperbaric conditions, an increase in HGS concentration occurs faster than at normal atmospheric decompression. The consequence of such processes may be appearance in the gaseous environment of unpleasant odors, as well as adverse functional and morphological changes in various organs and body systems, up to the clinical manifestations of poisoning.

It should also be taken into account that in the presence of several HGS unidirectional effects on the same body systems in a gaseous environment, the cumulative effect should be taken into account with the calculation of the total toxicity of the gaseous environment (the sum of the ratio of the actual concentrations of substances to their **LOAEL**) according to the formula: C_1 / **LOAEL** $_1$ + C_2 / **LOAEL** $_2$ + ... + C_n / **LOAEL** $_n \leq 1$. The amount of these fractions should not exceed one (Order of the Ministry of Labor of Russia dated January 24, 2014 No. 33n "On Approval of the Methodology for Special Assessment of Working Conditions. Classifier of Hazardous and (or) Dangerous Production Factors, the report form for a special assessment of working conditions and for its completion instruction).

Unidirectional effects on the body of workers, as a rule, have:

a) a combination of substances with the same specificity of clinical manifestations:
- substances of irritating type of action (acids and alkalis, etc.);
- allergens (epichlorohydrin and formaldehyde, etc.);
- substances of narcotic type of action (combination of alcohols, etc.);
- fibrogenic dust;
- substances that are carcinogenic to humans;

b) combinations of substances similar in chemical structure:
- chlorinated hydrocarbons (limit and unsaturated);
- brominated hydrocarbons (limit and unsaturated);
- various alcohols;
- various alkalis;
- aromatic hydrocarbons (toluene and benzene; toluene and xylene);
- amino compounds;

- nitro compounds, etc .;
c) combinations studied in the experiment:
- nitrogen oxides and carbon monoxide;
- amino compounds and carbon monoxide;
- nitro compounds and carbon monoxide.

Guideline P 2.2.2006-05 “Guideline for the hygienic assessment of factors of the working environment and labor process”, approved by Roskomnador on July 29, 2005, provides examples of combinations of unidirectional substances: nitrogen oxides and carbon monoxide, carbon monoxide and amino compounds, carbon monoxide and nitro compounds, amino and nitro compounds, various alcohols, various acids, various alkalis, various chlorinated hydrocarbons, various brominated hydrocarbons, etc.

In studies performed in the IBMP [4, p. 124–137], it was shown that when the concentration of a chemical in a gaseous environment is 10 times lower than the **LOAEL** (i.e. with full purification), there is no additive effect (summation) of the combined effects of substances, and this constant “chemical background” can be ignored in toxicological assessment of environmental quality.

The high risk of HGS poisoning in modern decompression chambers is evidenced by the recent case of treatment in April 2018 of a diver who received lung barotrauma in the decompression chamber of JSC Divevtohnoservis RBC-1400 at 1477th Vladivostok Marine Clinical Hospital of MD of RF (Vladivostok) [14, p.p. 57–72]. Therapeutic recompression with a maximum decompression of 100 m water column was conducted for 2 days in the air with ventilation every 30–90 minutes. Active and competent actions of therapeutic recompression leaders had given a positive result in the treatment of the lung barotrauma. However, at the end of treatment, an increase in the level of bilirubin and AST was noted, which, as noted in the article by treatment managers, “is most likely due to exposure to gaseous hazardous substances of anthropogenic origin in concentrations above permissible, which may be due, among other things, to lack of sanitary “a domestic decompression chamber system, an elevated temperature in the gas environment of the compartment, and re-evaporation of condensate with hazardous impurities by the electrical heating system of the decompression chamber.” It would have been hard to imagine the consequences of treatment in this decompression chamber if therapeutic recompression were used with the use of an oxygen-nitrogen-helium environment, longer and without the use of frequent and volumetric ventilation.

In the course of planned tests of the “Spasitel” decompression system with the KDV-1600 decompression chamber in 2017, an experiment was conducted on the basis of SKB EO at the IMBP RAS [15, p. 47–53] with the participation of three volunteer testers during a training descent with a maximum air decompression of 100 m water line with a total duration of 3 h and 10 min. At the same time, from the beginning of the experiment, CO_2 was removed, after 1 hour the HGS filter was turned on, and then the decompression chamber was ventilated. It is shown that in the absence of technical means for the removal of HGS (as is the case in most modern decompression chambers), it is necessary to strictly comply with the requirements of the Diving Service Rules of the Navy-2002 in terms of conducting ventilation of the compartments. Comparison of these data with the calculated increase in the HGS content showed that the use of a “closed” ventilation cycle of the compartments using only CO_2 removal means is unacceptable.

Conclusion. We believe that the use of a decompression system (a decompression chamber) that do not have a system for cleaning the gas environment from hazardous substances can only be resolved using air in strict observance of the ventilation mode in accordance with the Diving Service Rules of the Navy-2002 or the “Interindustry rules ...” air reserves must be increased/

The use of oxygen-nitrogen-helium environment in such decompression chambers (decompression systems) for carrying out descents or treatment should be prohibited.

To improve the **LOAEL** standards of hazardous substances in a hyperbaric gaseous environment, work should be performed on the analysis of available literature data, mathematical modeling of the processes of formation of the chemical composition of the gaseous environment. In particular, the combined effect on the multicomponent chemical composition of the air environment of the international space station on CO_2 at a concentration of 0.79 kPa (GOST R 50804-95) required a decrease in the CO_2 content to 2–3 mm Hg and the need for experimental justification of standards for long-term orbital and interplanetary flights. Similar studies can be carried out in satellite studies in decompression chambers in parallel with long-term ground-based and orbital space research, since the effects of mutual enhancement of carbon-acid action when combined with other factors (including hyperbaric) are known.

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