

## DIVING OPERATIONS IN CONNECTION WITH PARACHUTE JUMPS

Ryszard Kłos

Department of Underwater Work Technology, Naval Academy in Gdynia

### ABSTRACT

The article discusses selected issues related to the exposure of special forces operators to hypo- and hyperbaric environments, as well as the expenditure of combat effort during military missions. Combat tasks/missions should be organised within a relevant<sup>1</sup> and comprehensive military system, ensuring their legitimacy, consistency with the objective, efficiency, timeliness, effectiveness, accuracy, cost-effectiveness, etc. [1]. High altitude transfer processes related to diving and other combat processes require compatible, adequate, effective, proportionate and applicable procedures constituting part of the aforementioned system, based on sufficient knowledge of the effects of exposure to reduced and increased pressure, and combat effort [2].

**Keywords:** hypobaric pressure, hyperbaric pressure, hypoxia, hyperoxia, oxygen toxicity, pre-oxygenation, pressure sickness.

---

### ARTICLE INFO

---

PolHypRes 2026 Vol. 94 Issue 1 pp. 19 – 46

**ISSN:** 1734-7009 **eISSN:** 2084-0535

**DOI:** 10.2478/phr-2026-0002

Pages: 16, figures: 3, tables: 3

**page www of the periodical:** [www.phr.net.pl](http://www.phr.net.pl)

**Original article**

**Submission date:** 14.01.2026 r.

**Acceptance for print:** 26.01.2026 r.

**Publisher**

Polish Hyperbaric Medicine and Technology Society

## SELECTED DEFINITIONS AND ABBREVIATIONS

Asystole – cessation of electrical and mechanical heart activity or heart activity with a frequency of less than  $\nu \leq 10 \text{ min}^{-1}$ .

Baroreflex (homeostatic regulation of blood pressure) – baroreceptors cause a decrease in the tension of smooth muscles in arteries (arterial dilation), which lowers blood pressure, and conversely, an increase in the tension of smooth muscles in arteries causes an increase in blood pressure.

HAAMS - High-Altitude Airdrop Missions.

HAHO (High Altitude High Opening) – parachute jumps, which constitute important techniques used in special forces operations, are performed from an altitude of  $H \in [9\,000; 12\,000] \text{ m ASL}$ , and the parachute is opened at an altitude of approximately  $H \in [7\,000; 8\,000] \text{ m ASL}$ , allowing for a long glide to the target; modern parachutes allow for flights even above  $l = 60 \text{ km}$  depending on weather conditions.

HALO (High Altitude Low Opening) – are important techniques used in special forces operations, performed from an altitude of  $H \in [9\,000; 12\,000] \text{ m ASL}$ , with the parachute opening at an altitude of approximately  $H \in [800; 1\,000] \text{ m ASL}$  and the descent speed ranging from  $\dot{v} \in [200; 220] \text{ km} \cdot \text{h}^{-1}$ .

HGRP (High-Altitude Group Readiness Profile) – in the environment of special forces or military high-altitude operations, the abbreviation HGRP is used as an informal abbreviation, e.g. for: assessing the readiness of a team for high-altitude operations (e.g. HAHO/HALO) or a medical and operational protocol specifying tolerance to hypoxia, altitude stress, oxygen capacity and psychophysical abilities. However, this is not a standard medical term or abbreviation used by scientific literature, but functions as an internal abbreviation in military units.

HH (Hypobaric hypoxia) – Hypobaric hypoxia *HH* occurs at high altitudes, where atmospheric pressure and partial oxygen pressure are reduced.

Hypercapnia – a condition of elevated partial pressure of carbon dioxide in the blood above  $p_{\text{CO}_2} \geq 45 \text{ mm Hg}$  ( $p_{\text{CO}_2} \geq 6,0 \text{ kPa}$ ).

Hypocapnia (hypocarbica) – a condition of reduced partial pressure of carbon dioxide in the blood below normal. It is caused by hyperventilation and thus increased excretion of carbon dioxide through the lungs. This condition causes so-called "dark spots" before the eyes, dizziness, tinnitus and muscle weakness. Hypocapnia can lead to periodic apnoea, reflex cerebral ischaemia and alkalosis.

Hypoxaemia – hypoxia.

NH (Normobaric hypoxia) – normobaric hypoxia can occur in a simulated environment in a hypobaric chamber by reducing the oxygen content  $x_{\text{O}_2}$  in the chamber atmosphere under normal pressure conditions –  $p_0$ .

Homeostasis (maintenance) – the ability to maintain a balance of relatively constant internal parameters in a closed or open system. This concept usually refers to the self-regulation of biological processes.

Chronic obstructive pulmonary disease (COPD) – a disease characterised by progressive and incompletely reversible airflow limitation through the airways.

Otoscopy (physical examination of the ear) – visual examination of the external auditory canal and, indirectly, the middle ear by assessing the eardrum. In the case of eardrum perforation, the contents of the tympanic cavity are also examined.

SAAMS (Special Assignment Airlift Missions) – special air transport missions are part of top-secret or classified operations, involving the transfer of elite military units from all branches of the armed forces; paratroopers from all formations jump from heights of up to  $H = 35\,000 \text{ ft}$ . (approximately  $H \approx 10\,668 \text{ m ASL}$ ).

$SpO_2$  – (blood oxygen saturation) – refers to the percentage of oxygen-saturated haemoglobin in relation to the total amount of haemoglobin in the blood, i.e. it is the oxygen saturation of arterial blood, most often measured by pulse oximetry (it works by measuring the difference in light absorption by oxygenated and unoxygenated haemoglobin). The normal value is within the range of  $SpO_2 \in [95; 100]\%$ , slightly reduced (hypoxaemia) is within the range of  $SpO_2 \in [90; 94]\%$ , dangerous hypoxaemia, requiring intervention, occurs when  $SpO_2 < 90\%$ . During ascent, there is a decrease in  $SpO_2$  due to a decrease in partial oxygen pressure. During sports training or lung disease, hypoxia and breathing efficiency are often monitored by monitoring  $SpO_2$ .

Tympanometry (a form of non-invasive hearing test) – measuring of the reflection of sound waves from the eardrum during pressure changes in the external auditory canal.

$VO_{2\text{max}}$  – (maximum oxygen consumption, known as the oxygen threshold) is the largest amount of oxygen that the body can take in from the air, transport through the bloodstream and use in tissues (mainly muscles) during intense physical exertion.  $VO_{2\text{max}}$  is measured in millilitres ( $10^{-1} \cdot \text{dm}^3$ ) of oxygen consumed per kilogram of body weight per minute [ $10^{-1} \cdot \text{dm}^3 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ], which is an indicator of aerobic capacity (the higher it is, the more efficiently the body uses oxygen): untrained  $\sigma VO_{2\text{max}} \in [35; 40] \cdot 10^{-1} \cdot \text{dm}^3 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ; untrained  $\varphi VO_{2\text{max}} \in [27; 31] \cdot 10^{-1} \cdot \text{dm}^3 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ; endurance athlete  $\sigma VO_{2\text{max}} \in [60; 85] \cdot 10^{-1} \cdot \text{dm}^3 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ; marathon runner  $\sigma$  (world record)  $VO_{2\text{max}} \in [85; 90] \cdot 10^{-1} \cdot \text{dm}^3 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ .  $VO_{2\text{max}}$  is measured by an exercise test on a treadmill or ergometer, with a mask analysing the volume and composition of respiratory gases, or approximately by a test  $PWC_{170}$  [3].

$VO_{2\text{peak}}$  – this is the highest oxygen consumption value recorded during the test, regardless of whether a plateau was reached. It may be lower than  $VO_{2\text{max}} \geq VO_{2\text{peak}}$  if the subject was unable to

reach full maximum effort, e.g. due to fatigue, pain, illness, etc.

International standard atmosphere [4].

| $p(O_2)$ |        | $p$     |       | $H$    |         | $T$    |        |
|----------|--------|---------|-------|--------|---------|--------|--------|
| [kPa]    | [mmHg] | [kPa]   | [ata] | [ft]   | [m ASL] | [°C]   | [K]    |
| 21       | 760    | 101,325 | 1     | 0.3048 | 0       | 15.00  | 288.00 |
| 19.8     | 716    | 94.2    | 0.94  | 1640   | 500     | 11.73  | 284.73 |
| 18.6     | 673    | 88.6    | 0.89  | 3,281  | 1000    | 8.50   | 281.50 |
| 17.5     | 632    | 83.2    | 0.83  | 4921   | 1500    | 5.25   | 278.25 |
| 16.4     | 593    | 78.0    | 0.78  | 6,562  | 2000    | 2.00   | 275.00 |
| 15.3     | 555    | 73.0    | 0.73  | 8202   | 2500    | -1.25  | 271.75 |
| 14.3     | 519    | 68.3    | 0.68  | 9,843  | 3000    | -4.50  | 268.50 |
| 13.2     | 479    | 63.0    | 0.63  | 11,483 | 3,500   | -14.25 | 258.75 |
| 12.5     | 451    | 59.4    | 0.59  | 13,123 | 4000    | -11.00 | 262.00 |
| 11.6     | 420    | 55.2    | 0.55  | 14,764 | 4,500   | -14.25 | 258.75 |
| 10.8     | 389    | 51.2    | 0.51  | 16,404 | 5000    | -17.50 | 255.50 |
| 10.0     | 361    | 47.5    | 0.47  | 18,045 | 5,500   | -20.75 | 252.25 |
| 9.2      | 334    | 43.9    | 0.44  | 19,685 | 6,000   | -24.00 | 249.00 |
| 8.5      | 308    | 40.5    | 0.41  | 21,325 | 6500    | -27.25 | 245.75 |
| 7.8      | 283    | 37.3    | 0.37  | 22,966 | 7,000   | -30.50 | 242.50 |
| 6.6      | 239    | 31.4    | 0.31  | 26,247 | 8,000   | -37.00 | 236.00 |
| 5.5      | 199    | 26.2    | 0.26  | 29,528 | 9,000   | -43.50 | 229.50 |
| 4.5      | 164    | 21.6    | 0.22  | 32,808 | 10,000  | -50.00 | 223.00 |
| 3.7      | 134    | 17.6    | 0.18  | 36,089 | 11,000  | -56.50 | 216.50 |
| 3.2      | 114    | 15.1    | 0.15  | 39,370 | 12,000  | -56.50 | 216.50 |
| 5.4      | 197    | 25.9    | 0.26  | 42,651 | 13,000  | 56.05  | 329.05 |
| 2.3      | 83     | 11.0    | 0.11  | 45,932 | 14,000  | -56.50 | 216.50 |
| 2.0      | 71     | 9.4     | 0.09  | 49,213 | 15,000  | -56.50 | 216.50 |
| 1.7      | 61     | 8.0     | 0.08  | 52,493 | 16,000  | -56.50 | 216.50 |
| 1.4      | 52     | 6.8     | 0.07  | 55,774 | 17,000  | -56.50 | 216.50 |
| 1.2      | 44     | 5.8     | 0.06  | 59,055 | 18,000  | -56.50 | 216.50 |
| 1.0      | 38     | 5.0     | 0.05  | 62,336 | 19,000  | -56.50 | 216.50 |

*FL* (flight level) is a conventional altitude at which an aircraft is located in airspace, expressed in hundreds of pressure feet *ft*, i.e. it is based on atmospheric pressure at given altitudes expressed in pressure feet *ft*.

## INTRODUCTION

The risks associated with selected combat diving processes will not be discussed here in detail, as they have been sufficiently described in numerous articles and summarised in monographic publications [3,5,6,7].

The most significant risk during high-altitude airdrop missions (*HAAMS*) is hypoxia, which is also one of the major risks during diving missions.

Hyperbaric hypoxia *HH* occurs at high altitudes *H*, where atmospheric pressure *p* and oxygen partial pressure *pO<sub>2</sub>* are reduced compared to normal reference values<sup>2</sup>:  $p_0 \cong 101,325 \text{ kPa} \wedge pO_2 \cong 21 \text{ kPa}$ .

Normobaric hypoxia *NH* can be simulated by reducing the oxygen content to  $xO_2 < 21\%$  in the

chamber atmosphere under normal pressure conditions –  $p_0$ .

Hyperbaric hypoxia can be simulated in a hyperbaric chamber by reducing the oxygen content  $xO_2$  in the atmosphere under pressure *p* conditions higher than atmospheric pressure  $p > p_0$  relative to sea level pressure  $p_0$ , so that the partial pressure of oxygen  $pO_2$  is significantly lower than atmospheric pressure  $pO_2 \ll 21 \text{ kPa}$ . However, this is only theoretical<sup>3</sup>, as in practice, even during saturation dives, where the oxygen content  $xO_2$  is significantly lower than  $xO_2 < 21\%$ , the partial pressure is at the level of  $pO_2 \cong 39 \text{ kPa}$ .

Probably owing to the lower density of the respiratory medium  $\rho$ , under hyperbaric conditions *HH*, increased lung ventilation  $\dot{V}_E$  and increased peak

expiratory flow  $\dot{v}_{Ex}$  are observed, especially during exercise [8].

*HH* conditions generate higher values of blood saturation  $SpO_2$  and oxygen threshold  $VO_{2max}$  at maximum workload compared to the conditions of *NH* [9]. The baroreflex does not differ significantly between *HH* and *NH* [10].

Hypoxic training in a hypobaric chamber showed that 96.8% of 110 participants felt better prepared for work at high altitudes [11]. Training with exposure to hypoxia and 5 days of hypobaric exercise effectively improved blood oxygen saturation  $SpO_2$ , oxygen threshold  $VO_{2max}$  and cognitive functions that are important in *HAHO* [12]. Respiratory muscle training increased maximum oxygen consumption, i.e.  $VO_{2peak}$ , and reduced subjective effort in hypoxia, which may be important for *HAHO* [13].

Therefore, it follows that hypobaric training<sup>4</sup> improves physiological tolerance and performance at high altitudes.

## HYPOBARIC PRESSURE

The permissible pressure  $p$  in a commercial aircraft cabin is regulated by the Convention on International Civil Aviation, commonly known as the

Chicago Convention. According to this convention<sup>5</sup>, the cabin pressure must not be lower than  $p \in [620; 700]hPa$  under normal operating conditions.

Standards in the US and EU codify pressure values in relation to the pressure prevailing at a given altitude<sup>6</sup>, e.g. the pressure prevailing at an altitude of  $H = 8\,000\,ft$ , (approx.  $H \cong 2\,438\,m\,ALS$ ); this pressure is referred to as *cabin altitude* [14].

Modern aircraft designs, such as the Boeing 787 Dreamliner, maintain a pressure corresponding to an altitude of  $H = 6\,000\,ft$ , (approx.  $H \cong 1\,829\,m\,ASL$ ), which improves passenger comfort.

Hypobaric pressure causes a decrease in  $SpO_2$  compared to normal values of  $SpO_2 \in [95; 100]\%$ , but these values are higher than in cases of pathology – Table 1.

## BAROTRAUMA

Barotrauma is damage to tissues within body cavities<sup>7</sup> caused by sudden changes in pressure. It accompanies explosive pressure changes both in hyperbaric and hypobaric conditions. Effective countermeasures include:

Tab. 1

Examples of blood oxygen saturation values  $SpO_2\%$ .

| Specification                                | $SpO_2[\%]$ | Interpretation                    |
|----------------------------------------------|-------------|-----------------------------------|
| Rest (sea level)                             | 98–100      | Normal                            |
| Athlete during exercise                      | 94–96       | Normal, physiological decrease    |
| Healthy at 3000 m above sea level            | 90–93       | Low saturation, physiological     |
| Healthy at 5000 m above sea level,           | 80–85%      | Significant hypoxia – adaptation  |
| Asthma attack                                | 88–92       | Hypoxemia – intervention required |
| COPD (chronic obstructive pulmonary disease) | 88–90       | Chronic hypoxemia                 |
| COVID-19 (so-called silent hypoxia)          | <85%        | Severe hypoxia without symptoms   |
| Heart failure                                | 85–90       | Exertional hypoxemia              |

- Identification of individuals at risk of laryngological injury during hypo-/hyperbaric exposure through preliminary examinations, e.g. using otoscopy or tympanometry [15]. Performing sinus X-rays and otoscopy during exposure to a hyperbaric environment, both during qualifying and periodic examinations [16].
- Identification of individuals with a deviated nasal septum and possible correction. Exclusion of individuals with infections from diving [17]. Chronic infections increase the risk of otitis media caused by pressure changes, also known as ear congestion, which occurs when the Eustachian tube becomes blocked and air accumulates in the middle ear [18].
- Acclimatisation and training in a hypobaric chamber for and hyperbaric chamber training for divers [16].
- Use of biomedical sensors to monitor saturation and pulse in both hyperbaric and hypobaric conditions [19].

## EXPLOSIVE DECOMPRESSION

Sudden decompression of an aircraft cabin, in addition to hypoxia, can lead to serious physiological disorders such as pulmonary barotrauma and damage to the middle ear. Moreover, the expansion of gases in body cavities can cause severe pain and thus affect the ability to perform tasks [20].

Explosive decompression of divers occurs when a diver is ejected to a shallower depth<sup>8</sup> or when components of the hyperbaric complex become unsealed. In this case, in addition to the discomfort caused by gas expansion, divers usually experience decompression sickness [16,17].

## RISK FACTORS

Hypoxia<sup>9</sup> causes, inter alia, coordination disorders, euphoria and loss of consciousness. The time of useful consciousness at an altitude of  $H = 35\,000\,ft$ , (approx.  $H \cong 10\,668\,m\,ASL$ ) is within the range of  $t \in [30; 60]s$  [21].

Hypothermia, or extreme cooling<sup>10</sup> leading to frostbite and loss of manual dexterity [22].

Decompression sickness, caused by a sudden drop in pressure, can lead to joint pain and neurological problems. In *HALO* and *HAHO* skydiving operations, a pre-oxygenation procedure is used prior to the jump, which involves breathing oxygen to eliminate nitrogen from the body. This process also applies to other members of the aircraft crew [23]. Pre-oxygenation reduces the risk of decompression sickness, improving the safety of

jumpers and flight personnel. A similar procedure can be implemented for divers. However, normobaric exposure of a diver may complicate the diving process by exceeding the permissible limits of central oxygen toxicity, rarely pulmonary oxygen toxicity, and may affect subsequent treatment procedures for a possible case of pressure sickness.

Decompression sickness also constitutes a major risk when diving [16].

A more detailed description of selected risk factors in diving has been provided in previous publications and will not be presented here [24,25].

#### SAFETY MEASURES

When jumping from altitudes exceeding  $H = 18\,000\text{ ft}$ , ( $H \cong 6\,000\text{ m ASL}$ ), a trained specialist in aviation physiology should be present in the airborne assault vehicle to monitor the health of the jumpers and ensure that pre-oxygenation procedures are carried out correctly.

Strict regulations are in place specifying the required composition of the diving team during the diving process, depending on the depth and type of underwater combat operations, etc. [26].

#### SUMMARY

HALO and *HAHO* jumps are important techniques used in special forces operations. They require strict control of the physiological and technical aspects of the jump, as well as rigorous application of procedures to minimise the risk of hypoxia and decompression sickness.

Hypobaric hypoxia *HH* induces more pronounced respiratory responses, better saturation and performance than normobaric hypoxia *NH*. Hypobaric training increases physical and cognitive tolerance and is recommended, especially for *HAHO* jumpers. Avoiding anatomical risks, training and biomedical sensors are preventive measures applicable both in parachuting and diving.

Combat diving plays an important role in military missions. The topic of oxygen-nitrox diving has not been analysed extensively here, as it has already been summarised in a monograph [7].

#### HAAMS

*HAAMS* missions carried out as part of special air transport missions *SAAMS*, often top-secret or classified operations, involve the transfer of elite military units from all branches of the armed forces. Paratroopers from all formations are prepared to perform jumps from heights of up to  $H \cong 35\,000\text{ ft}$  (approximately  $H \cong 10\,668\text{ m ASL}$ ) – *HGRP*.<sup>11</sup>

The greatest dangers during *HAAMS* jumps are hypoxia and decompression sickness. The most intense moment of the operation is the two minutes preceding the jump. During this time, the jumpers activate their oxygen inhalers – *BIBS*<sup>12</sup> check their equipment and monitor the pressure in their cylinders, and, after the ramp opens, observe themselves and their companions for any symptoms of hypoxia.

Aircraft cabin decompression can lead to serious physiological disorders in passengers and crew. Sudden pressure changes cause dynamic changes in the body, such

2 min. This technique allows them to quickly disappear from the enemy's field of vision, which increases the safety of the paratroopers. The disadvantage of this method is that it often requires landing over or near enemy territory, which exposes the aircraft to a more likely attack from the ground or air.

#### HAHO

The High Altitude High Opening technique (*HAHO*) is used in operations requiring minimal aircraft detection or limiting the possibility of entering a given area, e.g. near national borders. Jumpers open their parachutes at high altitude, which allows them to glide over long distances with little chance of detection. However, it makes them exposed to extreme weather conditions, such as hypoxia or extreme cold, for long periods of time.

*HAHO* is a method used to deploy special forces over long distances. The moment of leaving the aircraft and the altitude at which the parachute opens are both significant. Parachutes with a high glide ratio allow the use of *HALO* and *HAHO* techniques during day and night operations, regardless of weather conditions. A specialised parachute allows for movement over long distances, enabling discreet infiltration of the operational area. Thanks to *HAHO*, the transport aircraft can remain at a considerable distance from the target, which reduces the risk of detection and increases the safety of the aircraft and the jumpers. The higher the altitude at which the parachute opens and the flatter the flight trajectory, the greater the achievable flight distance. Most often, parachutists jump and immediately open their parachutes, which is a risky manoeuvre as it exposes them to prolonged exposure to adverse weather conditions and possible detection by the enemy. The opening of the parachute itself causes a strong jolt, which can lead to serious injuries – jumpers often experience severe muscle pain for several days following such a jump.

A heavier jumper falls faster than a lighter one when using parachutes of the same size. This phenomenon is not a problem in low-altitude operations, where soldiers usually carry their equipment regardless of its weight. In *HAHO* missions, however, it is necessary to maintain a uniform rate of descent, as the team can cover up to approx.  $D > 40\text{ miles}$  (i.e.  $D \cong 64\text{ km}$ ) while gliding on a parachute. To ensure that the team glides evenly, the weight of the equipment is carefully distributed – heavier jumpers receive lighter equipment, whereas lighter jumpers receive heavier equipment. After landing, the equipment can be redistributed according to operational requirements.

#### RISK OF HYPOXIA

*HAAMS* operations require the support of oxygen systems (*BIBS*) for jumpers and flight personnel, as high-altitude operations expose flight and security personnel and jumpers to the risk of acute hypoxia in the event of oxygen equipment failure [23,27].

Hypoxia, or oxygen deprivation, leads to dizziness, euphoria, impaired muscle coordination and delayed reactions. Without supplemental oxygen at altitude of  $35\,000\text{ ft}$  (i.e. approx.  $10\,668\text{ m ASL}$ ), a jumper's useful consciousness time ranges from 30 s to 60 s, followed by loss of consciousness and death [4,20].

Research on hypoxia at an altitude  $H \cong 10\,000\text{ m ASL}$  is rarely conducted. One recent study was initiated by the Norwegian Army to assess the potential risks associated with *BIBS* failure and to investigate physiological responses during acute hypobaric hypoxia [27]. Simulated *HAHO*, without oxygen *BIBS*, was conducted in a hypobaric chamber at an altitude of  $H = 30\,000\text{ ft}$  ( $H \cong 9144\text{ m ASL}$ ), followed by recompression to ground level at a descent rate of  $v = 1\,000\text{ ft} \cdot \text{min}^{-1}$  (i.e. approx.  $v \cong 305\text{ m} \cdot \text{min}^{-1}$ ). The study was conducted on nine jumpers. Samples of gases dissolved in arterial blood were collected throughout the period of exposure to hypoxia. Moreover, pulse oximetry, cerebral oximetry and haemodynamic variables were used. Desaturation developed rapidly, and arterial oxygen pressure  $pO_2$  fell from a baseline mean of  $\bar{p}O_2 = 18.4\text{ kPa} \rightarrow pO_2 \in (17.3; 19.1)\text{ kPa}$ , corresponding to  $\bar{p}O_2 = 138.0\text{ mmHg} \rightarrow pO_2 \in (133.5; 143.3)\text{ mmHg}$ , to a minimum value of  $\bar{p}O_2 = 3.3\text{ kPa} \rightarrow pO_2 \in (2.9; 3.7)\text{ kPa}$ , corresponding to  $\bar{p}O_2 = 24.8\text{ mmHg} \rightarrow pO_2 \in (21.6; 27.8)\text{ mmHg}$ , after a mean time of  $\bar{s} = 180\text{ s} \rightarrow s \in (60, 210)\text{ s}$ . Hyperventilation with subsequent hypocapnia was associated with increased arterial oxygen saturation and potentially better tolerance to severe hypoxia.

One jumper experienced a rapid decrease in heart rate and loss of consciousness after a 4 – minute exposure to hypoxia. A simulated high-altitude drop scenario without the use of oxygen *BIBS* may result in extreme hypoxemia and loss of consciousness in some individuals.

Some regulations concerning Special Forces specify as a safety requirement that all crew members must breathe from oxygen *BIBS* if the planned landing is carried out during the day above an altitude of  $H > 10\,000\text{ ft MSL}$ <sup>13</sup>, and at night from  $H = 5\,000\text{ ft MSL}$  if exposure to these altitudes will exceed 30 minutes. At night, the requirement to use oxygen *BIBS* begins at  $H = 5\,000\text{ ft MSL}$ , or as per *FT* recommendation. The altitude is given in feet *MSL*, e.g.: “the aircraft is flying at an altitude of 25 000 ft *MSL*,” which means that the flight is taking place at  $H = 25\,000\text{ ft}$ , above mean sea level<sup>14</sup> In *FL*<sup>15</sup>, the reference to standard atmospheric pressure at sea level, which is  $p_0 = 1013.25\text{ hPa}$ , is measured.

In *HALO/HAHO* missions, jump heights and parachute opening heights are determined relative to *MSL/FL*, which ensures precision in planning parachute operations. Regulations are usually formulated in relation to these reference values.

During a drop from an altitude above  $H > 18\,000\text{ ft}$ , an aviation physiology specialist *PT*<sup>16</sup> should be present in the aircraft to monitor the health of the crew and jumpers, recognise symptoms of altitude sickness and, if necessary, provide first aid. *PT* supervises the pre-oxygenation process, which involves breathing oxygen in the time preceding landing.

It is most commonly stated that the pre-oxygenation process should last no less than 60 minutes [28]. The duration of pre-oxygenation should be sufficient to eliminate nitrogen from the body to such an extent that the risk of decompression sickness is significantly reduced. However, it appears that the commonly accepted parameters for the pre-oxygenation process are underestimated, hence attempts have been made to estimate these parameters using the theories used at the Naval Academy [25,29].

## RISK OF HYPOTHERMIA

When jumping from significant heights, jumpers are exposed to extremely low temperatures. For every 1 000 ft increase in altitude, the temperature drops by approximately  $\Delta t(1\,000\text{ ft}) \cong 2^\circ\text{C}$ . Jumpers must maintain mental and manual dexterity before leaving the aircraft<sup>17</sup> as well as immediately after leaving it in order to correctly control the parachute during the descent.

## EXPLOSIVE DECOMPRESSION

Simulations of sudden decompression in laboratory conditions allow for the analysis of physiological reactions of the body exposed to rapid pressure changes and the evaluation of the effectiveness of protective systems. These studies are crucial for the development of safety procedures in civil and military aviation.

Chambers for simulating explosive decompression are used to study the physiological effects of decompression and to test protective measures. For example, such a device allows for the simulation of rapid decompression under controlled conditions at a pressure of 1 s to 3 s in two scenarios [20].

1. From a pressure level of  $p = 364\text{ mmHg}$  (equivalent to a pressure of  $p = 48.5\text{ kPa}$  corresponding to the height  $H = 5\,791\text{ m ASL}$ ) to  $p = 111\text{ mmHg}$  (equivalent to pressure  $p = 14.8\text{ kPa}$  corresponding to height  $H = 13\,716\text{ m ASL}$ ), with a pressure difference of  $\Delta p = 253\text{ mmHg}$  ( $\Delta p = 33.7\text{ kPa}$ ).
2. From a pressure level of  $p = 751\text{ mmHg}$  (equivalent to a pressure of  $p = 100.1\text{ kPa}$  corresponding to an altitude of  $H = 115\text{ m ASL}$ ), to  $p = 498\text{ mmHg}$  (equivalent to a pressure of  $p = 66.4\text{ kPa}$  corresponding to an altitude of  $H = 3\,400\text{ m ASL}$ ), with a pressure difference of  $\Delta p = 253\text{ mmHg}$  ( $\Delta p = 33.7\text{ kPa}$ ).

Experiments conducted in the chamber allow for the analysis of the body's physiological responses to sudden pressure changes and the evaluation of the effectiveness of protective systems.

The threat of explosive decompression from hyperbaric conditions is the subject of many medical monographs, e.g. [16,17,30]. The effects of explosive decompression are mitigated in the same way, through the rapid implementation of hyperbaric treatment [30,31].

As already mentioned, research on hypobaric conditions is crucial for the development of safety procedures in civil and military aviation, as well as for the optimisation of emergency systems and the prevention of the effects of sudden decompression on flight crews and passengers.

## DIVING OPERATIONS AND HAAMS

Based on the available materials,<sup>18</sup> it was not possible to identify publicly available, reliable sources that would discuss in detail the requirements for rest before diving after a *HALO/HAHO* jump.

In scientific literature and in the public domain, information on this subject appears mainly in the form of fictionalised operational descriptions, training materials or military documents, which are not always evaluated by competent reviewers.

In practice, recommendations regarding the rest interval before diving after a *HALO/HAHO* jump depend on the specifications of a given mission, environmental conditions and the physiological conditions of mission participants. Detailed guidelines on rest, as the time needed to stabilise the body's gas metabolism following rapid pressure changes, are probably developed and applied internally by the responsible institutions, but are not published in generally available sources. At present, it is difficult to identify reliable, publicly available sources that discuss this issue in a comprehensive and credible manner.

In *HAAMS* operations, where diving elements may be part of a complex operational scenario,<sup>19</sup> it is advisable to observe surface intervals before boarding an aircraft [32]:

- ✓ Direct decompression diving<sup>20</sup>: After such a dive, it is necessary to wait at least  $t \geq 2\text{ h}$  before boarding an aircraft. This is the time required for the excess inert gases to be expelled from the body, which minimises the risk of decompression sickness during the pressure change associated with landing.
- ✓ Dives requiring decompression or repetitive dives: In such cases, the waiting time before boarding the aircraft is extended to at least  $t = 12\text{ h}$ . As before, this is due to the need to eliminate gases dissolved in the tissues in order to avoid the effects of sudden decompression during the *HAAMS* operation.
- ✓ Saturation diving: Procedures after saturation diving may require a waiting period even longer than  $t > 72\text{ h}$ . This is related to the maximum absorption of inert gas by the tissues, which is critical to ensure safety during subsequent *HAAMS* operations.
- ✓ Diving using oxygen as a breathing gas: For dives using oxygen as a breathing gas, no mandatory surface decompression period is established, as this procedure does not cause the accumulation of dissolved inert gases in the body.

The procedures described should enable the achievement of an approved level of inert gases in the body tissues. When implementing these guidelines, it is important to closely monitor the physiological condition of the personnel deployed in order to minimise the risk of decompression sickness, which is one of the main hazards in the context of the dynamic change in atmospheric pressure that occurs during the transition between diving and *HAAMS* procedures [28,32].

However, the data cited resemble a compilation of procedures taken from various regulations concerning diving and related air transport, hence they may not be adequate in all conditions. For this reason, these procedures will be compared here with the models used at the Naval Academy [3].

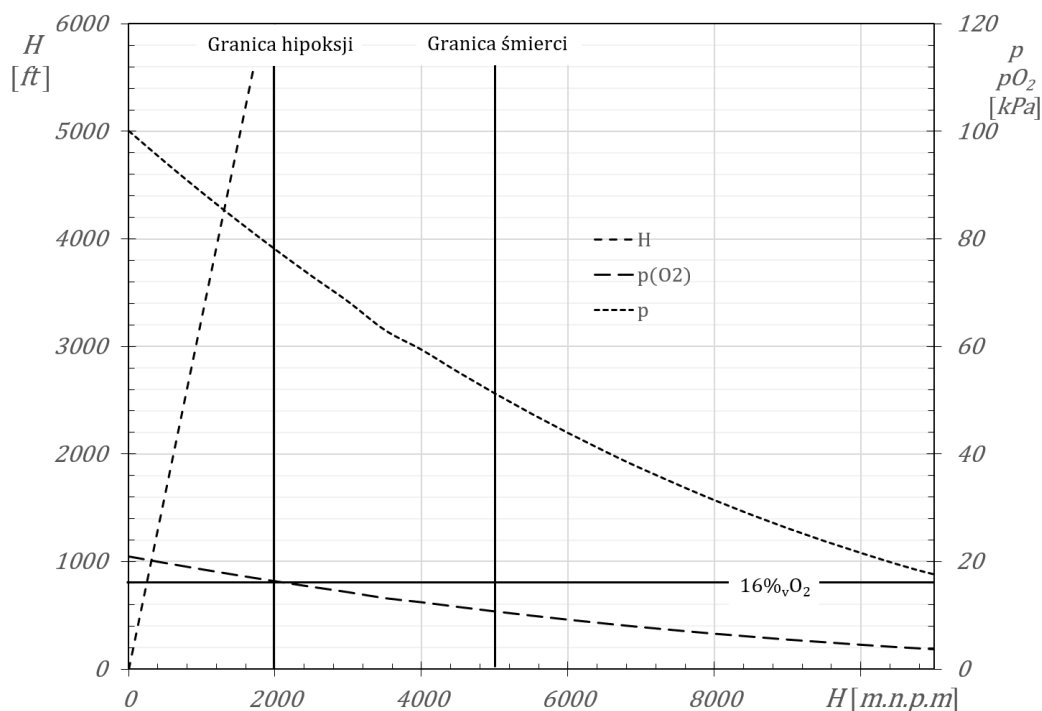
For dives using oxygen as a breathing gas, the procedure<sup>21</sup> described seems adequate. Diving procedures are mentioned, but only in the context of preparation for *MFF*<sup>22</sup> operations – table “Surface Interval Chart for Conducting Military Free-Fall Operations After Diving”<sup>23</sup> describing the minimum waiting periods after diving, but there are no similar recommendations for diving following a *HAHO/HALO* jump [32].

## NITROGEN ELIMINATION

At altitudes around and above  $H \gtrsim FL350$  ( $H \cong 10\,668\text{ m ASL}$ ), decompression processes begin to pose a serious threat. Up to this altitude, the “oxygen window,” i.e. the difference between the total pressure of gases in the venous capillaries and the breathing atmosphere, provides protection against decompression sickness [29,33]. In the past, this problem affected the entire crew, e.g. during bombing missions by *Liberator*-type aircraft during World War II [34]. After the widespread introduction of oxygen inhalers *BIBS*, it mainly affects parachute jumpers landing from a level above  $H \gtrsim FL350$ .

### Example

Based on the International Standard Atmosphere [4] the hypoxia threshold ( $H = 2000\text{ m ASL}$ ) and the “death threshold” ( $H = 4500\text{ m ASL}$ ) were established.



\*Granica hipoksji – Hypoxia threshold; granica śmierci – death threshold.

The graph shows that the hypoxia threshold at  $H = 2000\text{ m}$  ASL is closely related to a decrease in oxygen content to  $C_{O_2} = 16\% \text{ O}_2$ , while for the death threshold, this content amounts to  $C_{O_2} = 11.6\% \text{ O}_2$ .

When discussing the issue of normobaric nitrogen removal from the human body, one thinks of problems related to establishing adequate surface decompression models for divers, but they also serve to protect flight personnel from decompression sickness. Von Schrötter is considered to be the father of the pre-oxygenation concept from 1906 [35]. Currently, it is important not only for skydivers but also for divers when planning repetitive dives [3].

The basic effect of research in this area is cited as the results of nitrogen elimination from the human body obtained by Behnke [36].

$$V(N_2, t) = 0,364 \text{ dm}^3 \cdot [1 - \exp(-0,098 \cdot t)] + 0,364 \text{ dm}^3 \cdot [1 - \exp(-0,085 \cdot t)] \quad (1)$$

where:  $V(N_2, t)$  – is the volume of nitrogen eliminated,  $t$  – is the time of oxygen respiration.

Behnke suggested that the sum factors in the model come from the water and fat phases, respectively. However, Jones showed that when conducting longer observations, it is not possible to approximate the results without introducing a third term [36].

$$V(N_2, t) = 0,10 \text{ dm}^3 \cdot [1 - \exp(-0,46 \cdot t)] + 0,5 \text{ dm}^3 \cdot [1 - \exp(-0,04 \cdot t)] + 0,5 \text{ dm}^3 \cdot [1 - \exp(-0,005 \cdot t)] \quad (2)$$

where the individual terms originate from: the internal organs and vascular segments of the body, other tissues except adipose tissue, and from adipose tissue itself.

## ACCELERATION

As in hyperbaric therapy, the phenomenon of decompression acceleration is also used in hypobaric therapy, however in a slightly different manner.

In hypobaric decompression, it is crucial to take into account the elimination of atmospheric nitrogen. Human body tissues are saturated with nitrogen during gas exchange, and the degree of saturation is maintained in equilibrium with the breathing atmosphere<sup>24</sup> (see Fig. 1 – values for time  $t = 0$ ). The same applies to saturation with noble gases contained in the breathing air. Therefore, reducing the content of nitrogen and noble gases in human body tissues prior to hypobaric exposure should provide additional protection for the jumper during the SAAMS (HAAMS) operation.

The situation becomes more complicated when the jumper has previously spent a significant amount of time at high altitude<sup>25</sup> or at depth<sup>26</sup>. Usually, the body's response changes after diving, when tissue saturation with gases other than oxygen is significantly different from the equilibrium state with the Earth's atmosphere. After diving, the jumper's body tissues are often significantly saturated with gases other than nitrogen.

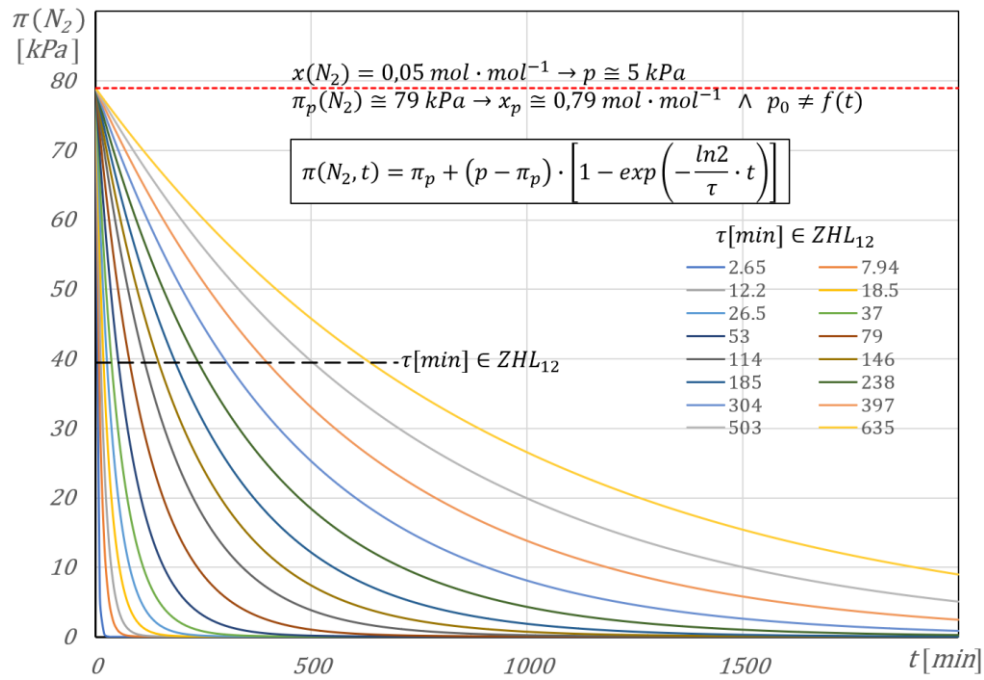


Fig. 1 Model of the process of flushing a diver's body with oxygen  $O_2$  with residual nitrogen content  $x(N_2) = 0.05 \text{ mol} \cdot \text{mol}^{-1}$ , under normobaric conditions:  $\pi_p(N_2) \cong 79 \text{ kPa}$ ,  $p_0 \cong 100 \text{ kPa}$  for theoretical tissues with a half-time of desaturation/saturation  $\tau$  in the range corresponding to the  $\text{ZHL}_{12}$  model [3,37].

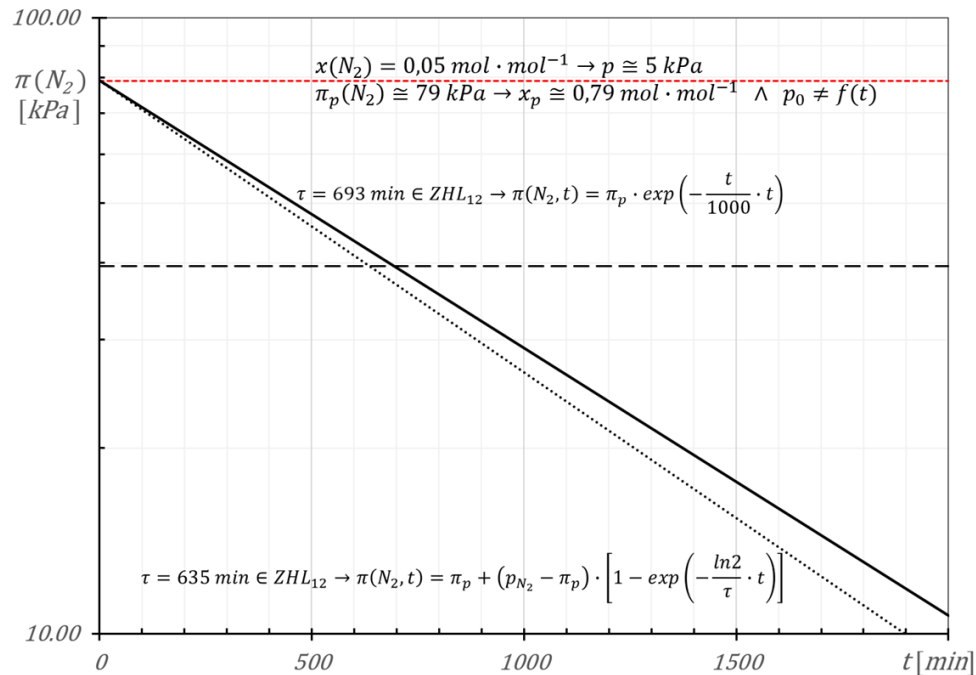


Fig. 2 Model of the process of flushing a diver's body with oxygen  $O_2$ , with residual nitrogen content:  $x(N_2) = 0.05 \text{ mol} \cdot \text{mol}^{-1}$ , under normobaric conditions:  $\pi_p(N_2) \cong 79 \text{ kPa}$ ,  $p_0 \cong 100 \text{ kPa}$  for theoretical tissues with half-time desaturation/saturation at levels:  $\tau \cong 693 \text{ min}$  and  $\tau = 635 \text{ min}$  (semi-logarithmic scale).

## PRE-OXYGENATION

The pre-oxygenation process involves ventilating the jumper's body with oxygen  $O_2$  with a residual nitrogen content<sup>27</sup>  $x(N_2) \ll 0.05 \text{ mol} \cdot \text{mol}^{-1}$ , usually carried out before the ascent begins, most often under atmospheric conditions at sea level  $p_0 \cong 100 \text{ kPa} \wedge \pi_p(N_2) \cong 79 \text{ kPa}$  – Fig. 1. This process is most often modelled using “theoretical tissues” with a half-time of desaturation/saturation  $\tau$  corresponding to the chosen model<sup>28</sup>. These times can be read directly from Fig. 1 for the nitrogen half-time pressure value – they are also described in the legend. The Naval Academy has adopted the  $ZHL_{12}$  model, although many researchers, including the author of the  $ZHL_{12}$  model, consider it unsafe for a wide range of applications [37,38]. Here, the  $ZHL_{12}$  model is used in the context of planning decompression processes for special operations personnel, who differ significantly from the average population [24,25,33]. In this case, the model seems adequate and, above all, effective, as shown by research conducted so far at the Naval Academy [3,6,29].

At the level of  $H = 30\,000 \text{ ft}$  ( $FL300$ ), the partial pressure of oxygen in the inhaled air drops to  $p_{O_2} = 5.0 \text{ kPa}$  ( $p_{O_2} = 37.5 \text{ mmHg}$ ), and the partial pressure of oxygen in the alveoli may fall below the level present in the venous blood, resulting in a reversal of the diffusion gradient and accelerated desaturation. This also leads to the important conclusion that pre-oxygenation will be supported at a higher level by decompression processes.

### Example

For theoretical tissue of  $\tau = 146 \text{ minutes}$ , it is required to calculate the decrease in nitrogen content after  $t = 60 \text{ minutes}$  of breathing oxygen at the surface, with a partial pressure of  $p_{N_2} = 5 \text{ kPa}$ , when the initial saturation of the theoretical tissue is  $\pi_p = 75 \text{ kPa}$ .

The high nitrogen content in oxygen does not necessarily come from its admixtures, but in significant amounts from “dead spaces” of the *BIBS*.

The following relationship may be used for calculations:

$$\pi(N_2, t) = \pi_p + (p_{N_2} - \pi_p) \cdot \left[ 1 - \exp\left(-\frac{\ln 2}{\tau} \cdot t\right) \right]$$

After inserting the data, the following will be obtained:  $\pi(N_2, t = 60) \cong 42.6 \text{ kPa}$ . Hence, the decrease in nitrogen content  $\Delta\pi$  in the theoretical tissue will be  $\Delta\pi \cong 32.4 \text{ kPa}$ .

Fig. 1 shows that it is not necessary to perform calculations for all theoretical tissues, as conclusions can be drawn for the theoretical tissue with the longest half-saturation/desaturation time  $\tau$ . The choice of tissue can also be made arbitrarily and should not be based on the longest time occurring for the  $ZHL_{12}$  model.

### Example

The results for the tissues of  $\tau = 146 \text{ minutes}$  and the longest tissue selected in the  $ZHL_{12}$  set were compared:  $\tau = 636 \text{ minutes}$ , for the time  $t = 60 \text{ minutes}$  of oxygen ventilation on the surface.

Comparing the result from the above example  $\pi(N_2, t = 60) \cong 42.6 \text{ kPa}$  with the result for the longest tissue  $\pi(N_2, t = 635) \cong 68.6 \text{ kPa}$ , it can be seen that for the tissue with a higher saturation/desaturation time, the value obtained is higher. Therefore, it should be expected that the longest tissue will be the tissue limiting

the remaining nitrogen load (it will contain most of the nitrogen remaining after oxygen purging).

By performing complete calculations (Fig. 1), it can be concluded that the theoretical tissue with the highest half-saturation/desaturation time will accumulate the nitrogen remaining after breathing oxygen on the surface.

When considering equilibrium states in diving applications, half-saturation/desaturation times in the range of  $\tau(N_2) \in [304, 635] \text{ minutes}$ , are most commonly used for  $Nx$  dives<sup>30</sup> – as joints and bones show the least tolerance to excess inert gas and at the same time the release of this excess in these tissues is slower [37].

## REDUCED MODEL

Taking into account the equation:  $\pi(N_2, t) = \pi_p + (p_{N_2} - \pi_p) \cdot \left[ 1 - \exp\left(-\frac{\ln 2}{\tau} \cdot t\right) \right]$  and assuming:  $p_i \cong 0 \wedge k = -\frac{\ln 2}{\tau} \cong -\frac{0.693}{\tau} \rightarrow k(\tau = 693 \text{ min}) \cong -\frac{0.693}{693} \cong 0.001$ , a reduced model for calculations according to the  $ZHL_{12}$  model is:

$$\pi(N_2, t) \cong \pi_p \cdot \exp(-0.001 \cdot t) \quad | \quad p = p_0 \wedge [t] \quad (3) \\ = \min$$

### Example

Although the relationship (3) is arbitrary<sup>31</sup>, it is worth using this simplification in approximate calculations, as it can simplify the considerations.

Fig. 2 shows the difference between assuming the longest leading tissue to be  $\tau = 635$  and  $\tau = 693$ .

Fig. 2 shows calculations similar to those for Fig. 1, but in a semi-logarithmic perspective, which linearises the graphs. Fig. 2 shows that the differences between the maximum values for the theoretical tissue with half saturation time of  $\tau \cong 693 \text{ minutes}$  and  $\tau = 635 \text{ minutes}$  are small for the problems discussed here, and the deviations are on the safe side.<sup>1</sup>

Therefore, formula (3) can be used to calculate the time required to flush a diver's body with oxygen  $O_2$  under atmospheric pressure  $p_0 \cong 100 \text{ kPa}$ , for the jumper's body weight of  $m = 70 \text{ kg}$  and age  $t > 35 \text{ years}$ , at a temperature of  $T = 288 \text{ K}$  and with the initial saturation of the jumper's body with nitrogen at a level of  $\pi_p(N_2) \cong 79 \text{ kPa}$  [35].

Fig. 2 shows that the time required for a 50% reduction in nitrogen pressure in the body to residual values is approximately  $t > 700 \text{ minutes}$ . This result is consistent with data from the literature [22,35,39]. Therefore, breathing oxygen for a period of  $t \cong 1 \text{ h}$  does not significantly protect the jumper from the possibility of decompression sickness, as is commonly believed [40]. However, in the context of Norwegian research, it appears that this protection may be sufficient [19].

The relative saturation of a jumper's body with nitrogen can be estimated by reworking the formula:  $\pi(N_2, t) = \pi_p + (p_{N_2} - \pi_p) \cdot \left[ 1 - \exp\left(-\frac{\ln 2}{\tau} \cdot t\right) \right]$  and using the approximation:  $p_{N_2} \cong 0$   $\frac{\pi_p - \pi(N_2, t)}{\pi_p} = 1 - \exp\left(-\frac{\ln 2}{\tau} \cdot t\right)$ . The value  $\frac{\pi_p - \pi(N_2, t)}{\pi_p}$  represents the relative decrease in the content of nitrogen in the body when ventilated with oxygen; it can be expressed as a percentage  $\delta = \frac{\pi_p - \pi(N_2, t)}{\pi_p} \cdot 100\%$ . Hence, we can write down the following:

$$\delta = \frac{\pi_p - \pi(N_2, t)}{\pi_p} \cdot 100\% \quad (4)$$

$$= \left[ 1 - \exp\left(-\frac{\ln 2}{\tau} \cdot t\right) \right] \cdot 100\% \mid p_{N_2} \cong 0$$

where:  $\delta$  – relative decrease in nitrogen content in the body when flushed with oxygen,  $\pi_p$  – initial saturation of theoretical tissue with nitrogen,  $\tau$  – saturation/desaturation half-time,  $t$  – oxygen breathing time,  $p_{N_2}$  – partial pressure of nitrogen in respiratory oxygen.

Fryer D.I. equated the inverse value  $1 - \delta$  of the relative decrease in nitrogen content  $\delta$  with the percentage of protection of the jumper against decompression sickness above *FL* 350 [35]. Here, for the same data, it was proposed to model the risks using a mathematical apparatus derived from survival analysis – Table 2 [7].

Tab. 2

Useful relationships for more common functions in survival analysis [7].

$$S(t) = 1 - F(t) = \int_t^{\infty} L(t) dt$$

$$L(t) = -\frac{d}{dt} \cdot S(t)$$

$$R(t) \equiv h(t) = -\frac{d}{dt} \cdot \ln S(t)$$

$$H(t) = -\ln S(t) = \int_0^t R(t) \cdot dt \equiv \int_0^t h(t) \cdot dt$$

$$S(t) = \exp[-H(t)] = \exp\left[-\int_0^t h(t) \cdot dt\right]$$

|                                  |                           |
|----------------------------------|---------------------------|
| $F$ – distributor                | $L$ – probability density |
| $h$ – hazard function            | $R$ – risk function       |
| $H$ – cumulative hazard function | $S$ – survival function   |

Fig. 3, similarly to relations (1)-(2), shows that it is impossible to find a single model to represent the observed relations occurring during the “flushing” of nitrogen from the jumper’s body with oxygen. The strong dependence on the jumper’s age observed by researchers is puzzling [35].

Table 2 shows useful relationships used in survival analysis [7]. Comparing them with equation (4), the following relationships can be found:

$$S(t) = \exp\left(-\frac{\ln 2}{\tau} \cdot t\right) \quad (5)$$

$$H(t) = \frac{\ln 2}{\tau} \cdot t$$

$$h \equiv R = \frac{\ln 2}{\tau}$$

where:  $S(t)$  – survival function,  $h(t)$  – hazard function,  $H(t)$  – cumulative hazard function.

The survival function  $S(t)$  determines the probability of survival<sup>33</sup> longer than a certain average time  $t^{34}$ :  $\forall t \geq 0 \quad S(t) \triangleq P(T > t)$ . Here, it will be the probability of developing symptoms of decompression sickness *DCS* after a period of time  $t$  of breathing oxygen.

The hazard function  $h(t)$  is the conditional probability limit per unit of time:  $h(t) = \lim_{\Delta t \rightarrow 0} \frac{P(T \leq t + \Delta t | T > t)}{\Delta t}$ .

The hazard function  $h(t)$  represents the probability that the period  $T$  until the onset of symptoms of pressure-related illness DCS will be within the selected time frame  $t$ , however will not occur before that time.<sup>35</sup> In

general, it describes the intensity of failures for the selected time  $t$ .<sup>36</sup> The hazard function  $h(t)$  gives the probability value per unit of time, so there may be a situation<sup>37</sup> for which its value will be greater than 1.

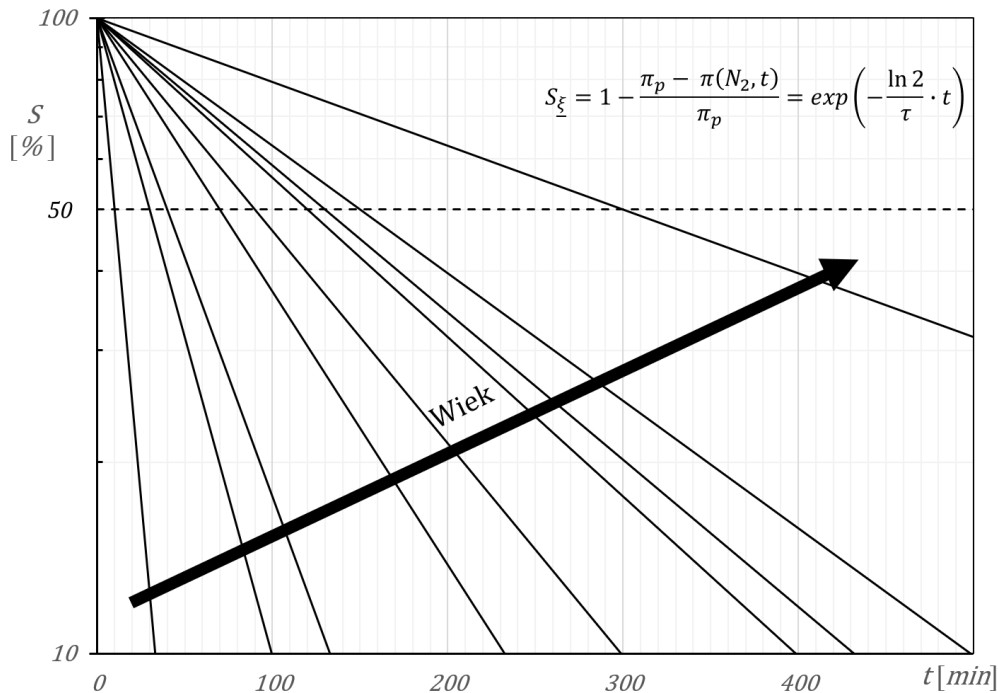


Fig. 3 Survival function  $S(t)$  - the probability of developing symptoms of decompression sickness CNS after a period of time  $t$  depending on the parameter vector  $\xi$  and the parameter  $\tau$  – Tab 3.

Tab. 3

Supplementary data for Fig. 3.

| Collection from Fig. 3 | No. | $\tau$<br>[minutes] | $\xi$                              |                                         |                                       |
|------------------------|-----|---------------------|------------------------------------|-----------------------------------------|---------------------------------------|
|                        |     |                     | $\xi_1 \sim \text{Age}$<br>[years] | $\xi_2 \sim \text{Temperature}$<br>[°C] | $\xi_3 \sim \text{Pressure}$<br>[kPa] |
| 3                      | 20  |                     | $\leq 18$                          |                                         |                                       |
| 4                      | 30  |                     | Average                            |                                         |                                       |
| 5                      | 40  |                     | 17                                 |                                         |                                       |
| 6                      | 70  |                     | 27                                 |                                         |                                       |
| J, S, B, Ba            | 90  |                     | Average                            | 15                                      | 101.325                               |
| 2                      | 120 |                     | Slowest                            |                                         |                                       |
| 7                      | 130 |                     |                                    |                                         |                                       |
| 8                      | 150 |                     | 35                                 |                                         |                                       |
|                        | 300 |                     | Slowest, individual                |                                         |                                       |

The values  $\xi_2$  and  $\xi_3$  were arbitrarily adopted.

The cumulative hazard function  $H(t)$  can be defined as the integral of the hazard function  $h(t)$ :  $H(t) = \int_0^t h(t) dt$ .

Analysing the data in Fig. 3, collected by various researchers over many years, it can be concluded that the lines drawn correspond to the round values of the half-life times  $\tau$  – Table 3.

Based on the data in Table 3, the relationship between the survival function  $S_{\xi}(t)$  vs  $(t, \xi_1)$  and constant parameters  $(\xi_2, \xi_3)$  was plotted. Relationship (5) shows that the hazard/risk function is not a function of time  $t$ :  $h_{\xi} \equiv R_{\xi} \neq f(t)$ , but is a constant value  $h_{\xi} \equiv R_{\xi} = \text{const}$ . Hence, the cumulative hazard function will be the sum of

time intervals:  $H_{\xi}(t) = \frac{\ln 2}{\tau} \cdot t$ . Using Fryer's suggestion, the cumulative hazard function can be written down as:

$$\begin{cases} S(t) = 0 & \leq FL350 \\ S(t) = \exp\left(-\frac{\ln 2}{\tau} \cdot t\right) & > FL350 \end{cases} \quad (6)$$

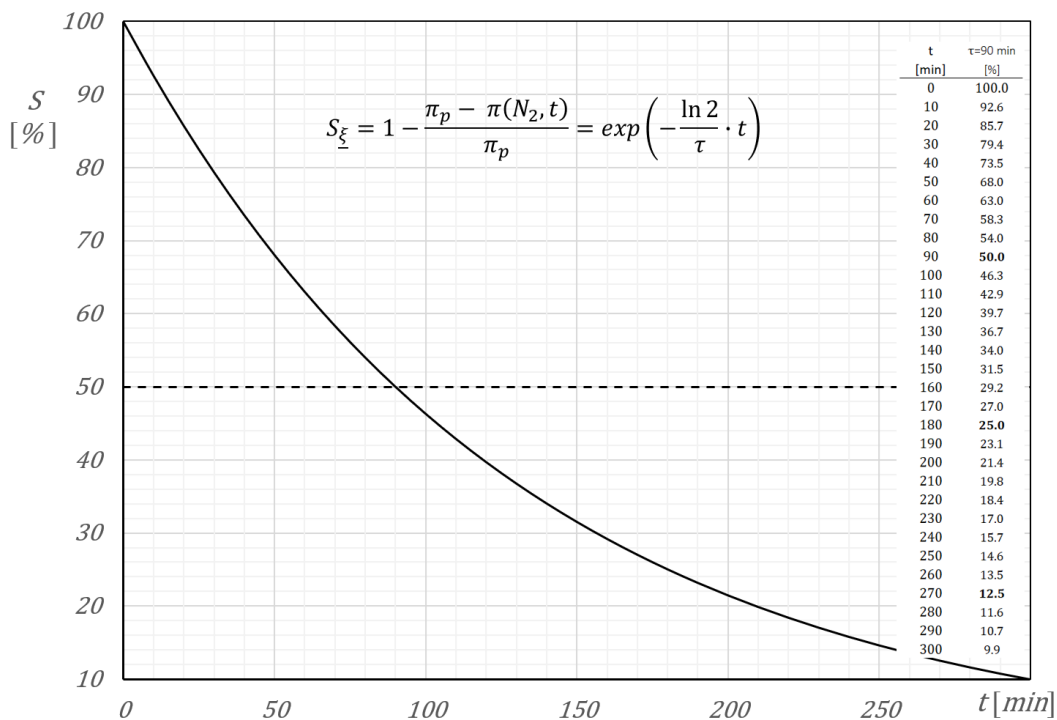
where:  $S(t)$  – survival function representing the risk of DCS above the threshold  $> FL350$ ,  $t$  – pre-oxygenation time,  $\tau$  – time value selected according to age from Table 4, for the average value  $\tau = 90 \text{ min}$ .

It is common practice to use an exponential model of risk decay of CNSyn during rest on the surface,

similar to that used for drug concentration. In these calculations, it is suggested to assume a time  $\tau$  equal to  $\tau = 90$  minutes for a 50% decay of the *CNSyn* risk time, as for the average value when estimating the risk of *DCS* at the level of  $> FL350$  after  $t$  pre-oxygenation time.

#### Example

To estimate the risk of *DCS* at a level above  $FL350$ , the survival function can be assumed to be:  $S(t) = \exp\left(-\frac{\ln 2}{\tau} \cdot t\right)$  for the half-life  $\tau = 90$  min, hence the risk of *DCS* after  $t = 90$  minutes will be  $S(t) = \frac{100\%}{2} = 50\%$ , after  $t = 2 \cdot 90$  minutes = 180 minutes it will be  $S(t) = \frac{100\%}{2^2} = 25\%$ , and after  $t = 3 \cdot 90$  minutes = 270 minutes it will be  $S(t) = \frac{100\%}{2^3} = 12.5\%$ .



#### SUMMARY

During HAAMS operations, strict adherence to safety standards is required within the following scope [28,32].

1. Preparation of the jumper:
  - ✓ The pre-oxygenation procedure is used for at least  $t \in [30, 60]$  minutes prior to the jump to eliminate nitrogen from the body
  - ✓ Specialised equipment is used (pressure suits, oxygen systems and emergency parachutes, etc.).
2. Aircraft depressurisation rate:
  - ✓ The pressure in the cabin is gradually equalised to the external pressure.
  - ✓ In the case of *HALO* and *HAHO* jumps, the aircraft is exited from an altitude above  $H > 9\,000$  m ASL.
3. Flight parameters:
  - ✓ *HALO* jumps are performed from an altitude of  $H \in [9\,000, 12\,000]$  m ASL and the parachute

is opened at an altitude of approximately  $H \in [800, 1\,000]$  m ASL, while the descent velocity is in the range of  $\dot{v} \in [200, 220]$  km  $\cdot$  h $^{-1}$ .

- ✓ *HAHO* jumps are performed from an altitude of  $H \in [9\,000, 12\,000]$  m ASL, and the parachute is opened at an altitude of approximately  $H \in [7\,000, 8\,000]$  m ASL, which allows for a long glide to the target
- 4. Descent speed:
 

For *HALO* and *HAHO* parachute jumps, the average descent speed varies depending on the altitude, type of parachute and the weight of the jumper

  - ✓ *HALO*

Free fall: approx.  $\dot{v} \in [200, 220]$  km  $\cdot$  h $^{-1}$  (approx.  $\dot{v} \in [55, 60]$  m  $\cdot$  s $^{-1}$ ) in a flat position.

After the parachute opens:  $\dot{v} \in [4, 6]$  m  $\cdot$  s $^{-1}$  (approx.  $\dot{v} \in [14, 22]$  km  $\cdot$  h $^{-1}$ , depending on the type of parachute)
  - ✓ *HAHO*

After the parachute opens:  $\dot{v} \in [3, 5]$  m  $\cdot$  s $^{-1}$  (approx.  $\dot{v} \in [10, 18]$  km  $\cdot$  h $^{-1}$ ) – gliding

parachutes can allow for greater flight control, which reduces the vertical descent speed. Gliding parachutes are often used in *HAHO* jumps, allowing coverage of large distances.

1. Application:

- ✓ *HALO* – used for infiltration into enemy territory with minimal detection.
- ✓ *HAHO* – used in missions requiring long gliding flights and discreet arrival at the landing zone.

The pre-oxygenation procedure is crucial for the safety of *HAAMS* operations, hence it raises questions and interpretative controversies<sup>38</sup> – here we specified the estimation methods used at the Naval Academy.

Currently, despite the passage of time and the increased interest of scientists in modelling the mechanism of decompression of the body from inert gases, we are still forced to seek answers to questions that should have been known long ago. Certainly, methods for modelling this process were defined for operations *HAMMS*, but over the years they were kept secret until they were lost.

At the  $H = 30\,000\text{ ft}$  altitude, the partial pressure of oxygen in the inhaled air drops to  $p_{O_2} = 5.0\text{ kPa}$  ( $p_{O_2} = 37.5\text{ mmHg}$ ), and the partial pressure of oxygen in the alveoli may fall below the level present in venous blood, resulting in a reversal of the diffusion gradient and accelerated desaturation. In the event of a failure of the oxygen system *BIBS*, rapid hypoxaemia occurs, causing loss of consciousness after just  $t \in [3, 4]\text{ minutes}$ , even in healthy, athletic operators. The risk of loss of consciousness increases above  $FL250$ .

As a recommendation, training in emergency procedures in *HAHO* conducted in a hypobaric chamber, with appropriate personnel on hand, can be adopted. However, specialists participating in *HAHO* training should carefully assess the risk-benefit ratio during training above  $FL > 250$ , especially due to the risk of loss of consciousness in the event of oxygen equipment (*BIBS*) failure. Owing to the limited number of trials available in the literature, it is not possible to accurately estimate the risk of loss of consciousness.

*BIBS* system failure during the jump from  $FL300$  leads to very rapid and severe hypoxaemia, indicating a limited time window for response and problem solving during flight. However, if adequate heart rate and cardiac output are maintained, healthy and fit soldiers can temporarily tolerate even extremely low arterial oxygen levels. During training, it is worth emphasising the important role of hyperventilation in improving pre-oxygenation, which has a compensatory effect.

The following detailed training recommendations should be adopted:

- Inclusion of realistic oxygen system (*BIBS*) failure scenarios in *HAHO* training.
- Simulations involving medical personnel and *NIRS* equipment<sup>39</sup>.
- Monitoring of cerebral saturation and cardiovascular parameters during exercises.
- Implementation of procedures for rapid transition to a backup oxygen source.
- Limiting training altitude to safe limits (below  $FL250$  unless there is a strong operational need for training at higher altitudes)

*HAHO* simulation in a hypobaric chamber, like any simulation, does not fully reflect the conditions of a high-altitude jump. In a real situation, the jumper is suspended in a harness in an upright position, which increases haemodynamic risk, especially in cases of bradycardia and loss of consciousness. Venous compression and reduced venous return may limit cardiac output and the ability to spontaneously regain consciousness. In real-life conditions, physical exertion occurs associated with parachute control, possible attempts to repair equipment in flight, operational stress, etc. These factors can significantly worsen hypoxia tolerance compared to resting conditions in a chamber<sup>40</sup>.

A strong correlation was observed between the partial pressure of carbon dioxide  $p_{CO_2}$  and the calculated value of the oxyhaemoglobin dissociation curve shift index  $p50$  [41]. Significant differences in saturation at the same values of  $p_{O_2}$  were recorded, indicating high individual variability in physiological response. An inverse relationship was observed between the partial pressure of carbon dioxide  $p_{CO_2}$  and other blood gas parameters in severe hypoxia. Higher partial pressure of carbon dioxide  $p_{CO_2}$  was associated with lower partial pressure of oxygen  $p_{O_2}$  and lower oxygen saturation  $SpO_2$  [19].

Other studies have reported loss of consciousness and brief asystole in 2% of participants in a hypobaric chamber at an altitude  $H = 20\,000\text{ ft}$ , however, all participants received immediate intervention after their heart rate dropped below 20% [42].

It was found that exposure to acute hypoxia is a sufficient cause of fainting in healthy individuals, leading to vascular collapse, bradycardia or asystole. Those exposed to hypobaric conditions recover fully in the Trendelenburg position with oxygen administration, requiring no further clinical examination.

## INFORMATION

The study was conducted as part of the project entitled: "The impact of combat effort and air transport on the safety of combat divers during underwater combat operations" agreement no.: DOB-BIO-12-03-001-2022 implemented as part of competition no. 12/2022 (Round 1) for the implementation and financing projects in the field of scientific research or development work for national defence and security.

## REFERENCES

1. Kłos R. 2019 a. Designing of diving technologies – process approach. *Polish Hyperbaric Research*. 1, 2019 a, Tom 66, DOI: 10.2478/phr-2019-0001, strony 7-24.
2. Kłos R. 2019 b. Context analysis in the development of diving technologies. *Polish Hyperbaric Research*. 2, 2019 b, Tom 67, DOI: 10.2478/phr-2019-0005, strony 7 – 58.
3. Kłos R. 2011. *Możliwości doboru dekompresji dla aparatu nurkowego typu CRABE*. Gdynia : Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej, 2011. ISBN 978-83-924989-4-0.
4. Barański St. (red.). 1977. *Medycyna lotnicza i kosmiczna*. Warszawa : Państwowy Zakład Wydawnictw Lekarskich, 1977.
5. Kłos R. 2012. *Możliwości doboru dekompresji dla aparatu nurkowego typu AMPHORA*. Gdynia : Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej, 2012. ISBN 978-83-924989-8-8.
6. Kłos R. 2016. *System trymiksowej dekompresji dla aparatu nurkowego typu CRABE*. Gdynia : Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej, 2016. ISBN 978-83-938322-5-5.
7. Kłos R. 2023. *Oxygen Diving*. 1st Edition. Boca Raton : CRC Press (Taylor & Francis Group, LLC ), 2023. str. 236. ISBN: ISBN 978-1-032-31389-4 (hbk), ISBN: 978-1-032-31390-0 (pbk), ISBN: 978-1-003-30950-5 (ebk), DOI: 10.1201/9781003309505.
8. Netzer N.C., Rausch L.K., Frieß M., Strohl K.P., Schilz R., Decker M., Pramsohler S. 2022. Expiratory Peak Flow and Minute Ventilation Are Significantly Increased at High Altitude versus Simulated Altitude in Normobaria. *Life*, 2, 2022, Tom 12, str. 306.
9. Vinetti G., Turner R., Taboni A., Rauch S., Seraglio P.M.E., Netzer N., Strapazzon G., Gatterer H. 2025. Cardiorespiratory Responses to Exercise in Hypobaric versus Normobaric Hypoxia: A Randomized, Single-Blind, Crossover. *Medicine & Science in Sports & Exercise*. 2025, Tom 57, 3, strony 632-640.
10. Bourdillon N., Saugy J., Schmitt L., Rupp T., Yazdani S., Vesin J-M, Millet G.P. 2017. Acute and chronic changes in baroreflex sensitivity in hypobaric vs. normobaric hypoxia. *European Journal of Applied Physiology*. 117(2017), 2017, strony 2401–2407.
11. Stevenson K. 2019. *Hypoxia: An Analysis of Hypobaric Chamber Training*. Tampa : Arizona State University, 2019. repozytorium dysertacji: <https://repository.asu.edu/items/53623>.
12. Xie J., Zhong Z., Dong H., Huang P., Zhou S., Tian H., Wu Y., Li P. 2023. Hypoxic Preacclimatization Combining Intermittent Hypoxia Exposure and Physical Exercise Significantly Improves Hypoxic Tolerance. <https://www.researchsquare.com/article/rs-2577458/latest.pdf>. [Online] 2023. [Zacytowano: 06 06 2025.] DOI: <https://doi.org/10.21203/rs.3.rs-2577458/v1>.
13. Ferguson S., Miller M., Yeager L., Wislowski A., Subudhi A., Roach R. 2024. Impact of Respiratory Muscle Training on Exercise Tolerance in Hypobaric Hypoxia. *Physiology*. S1, 2024, Tom 39.
14. Federal Aviation Regulations. Title 14 Chapter I Subchapter C Part 25 Subpart D Pressurization §25.841 Pressurized cabins. *eCFR :: 14 CFR 25.841 -- Pressurized cabins. (FAR 25.841)*. [Online] [Zacytowano: 06 06 2025.] FAR 25.841.
15. Morgagni F., Autore A., Landolfi A., Ciniglio Appiani M., Ciniglio Appiani G. 2012. Predictors of ear barotrauma in aircrews exposed to simulated high altitude. *Aviation, Space, and Environmental Medicine*. 2012, Tom 83, 6, strony 594–597.
16. Brubakk A.O., Neuman T.S. 2003. *Bennett and Elliott's physiology and medicine of diving*. Philadelphia : Saunders, 2003. ISBN 0-7020-2571-2.
17. Strauss R.H. 1976. *Diving medicine*. New York : Grune & Stratton Inc., 1976. ISBN 0-8089-0699-2.
18. Sastranegara Y. T., Basuki B., Muljadi H. 2008. Septal deviation and other factors increase the risk of barotitis media in high altitude high opening training. *Medical Journal of Indonesia*. 2008, Tom 17, 1, strony 37–42.
19. Bloch, A., Kersten, N., Short, E., Stevens, P., Simonson, B., & Hoyer, B. 2023. Physiological Sensing in HALO/HAHO. *Environment*. 2023.
20. Skrzypkowski A. 2012. *Medycyna lotnicza: Fizjologia i trening lotniczy*. [Online] 2012. [Zacytowano: 03 czerwiec 2025.] <https://docplayer.pl/905680-Adam-skrzypkowski-fizjologia-i-trening-lotniczy.html>.
21. Behnke A.R. 1974. *Environmental Physiology*. [aut. książki] N.B. (ed.) Slonim. *Marine and other hyperbaric environments*. Saint Louis : The C.V. Mosby Co, 1974, strony 399-418.
22. Luft U.C. . 1974. 10. Aerospace environments. [aut. książki] N.B. Slonim. *Environmental physiology*. Saint Louis : the C. V. Mosby Company, 1974.
23. Miller A.T., Jr. . 1974. 9. Altitude . [aut. książki] N.B. Slonim. *Environmental physiology*. Saint Louis : the C. V. Mosby Company, 1974.
24. Kłos R. 2020a. Selected risks of the decompression process. part I: selected inherent residual risks in the decompression process. *PolHypRes*. 2020a, Tom 71, 2, strony 7 – 36.
25. Kłos R. 2020. Selected Risks of the Decompression Process, Part II: Analysis of Selected Types of Risk. *Polish Hyperbaric Research*. 2020, Tom 72, 3, strony 7-23.
26. North Atlantic Treaty Organization: Allied diving publication. September 2019. *Allied guide to diving operations*. Edition C Version 3 . Brussels : NATO Standardization Office, September 2019. NATO standard ADivP-01.
27. Ottestad W., Hansen A., Pradhan G., Stepanek J., Høiseth L.Ø., Kåsin J.I. 2017. Acute hypoxia in a simulated high-altitude airdrop scenario due to oxygensystem failure. *J Appl Physiol*. 2017, Tom 123, doi:10.1152/japplphysiol.00169.2017, strony 1443–1450.
28. MON. 2022. Zak. 17. Wymaganie dla saturacji oraz ograniczenia ekspozycji podczas operacji spadochronowych na dużych wysokościach. [aut. książki] Zbrojnych Dowództwo Rodzajów Sił. *Instrukcja organizowania i prowadzenia szkolenia spadochronowo-desantowego w Siłach Zbrojnych RP*. Warszawa : MON, 2022.
29. Kłos R.. 2025. *Rebreathers in Diving Science: Semi-Closed and Closed Circuit Diving Apparatuses*. Abingdon, Oxon : CRC Press (Taylor & Francis Group, LLC ), 2025. ISBN: 978-1-032-59608-2 (hbk), ISBN: 978-1-032-64919-1 (pbk), ISBN: 978-1-032-64920-7 (ebk), DOI: 10.1201/9781032649207.
30. NSO. 2020. *Allied guide to diving medical disorders – national information*. Edition A Version 1. Brussels : NATO Standardization Office (NSO), 2020. Standards Related Document ADivP-02.1 (STANAG 1432).
31. Kłos R.. 2018. Securing the hyperbaric treatment of decompression sickness in the Polish Navy. *Polish Hyperbaric Research ISSN 1734-7009; e-ISSN 2084-0535*. 2018, Tom 65, 4, strony 7-23. Polish-English Bilingual Publication.
32. Department of the Army. 2005. *Special Forces Military Free-Fall Operations*. Fort Bragg : Headquarters Department of the Army, 2005. FM 3-05.211 (FM 31-19); MCWP 3-15.6; NAVSEA SS400-AG-MMO-010, AFMAN 11-411(I).
33. 2022. Designing diving technology - decompression requirements. *Polish Hyperbaric Research*. 4, 2022, Tom 81, DOI: 10.2478/phr-2022-0019, strony 7 – 52.
34. Fulton J.F. 1948. *Aviation Medicine in its Preventive Aspects*. London : Geoffrey Cumberlege Oxford University Press, 1948.
35. Fryer D.I. 1969. *Subatmospheric Dekompression Sickness in Man*. Slough : The Advisory Group for Aerospace Research and Development NATO Technivision Services, 1969. AGARDograph Number 125.
36. Hardin B.J. 1951. Molecular Exchange and Blood Perfusion through Tissue Regions. [aut. książki] Lawrence J.H. Hamilton J.G. *Advances in Biological and Medical Physics*. New York : Academic Press Inc., Publishers, 1951, Tom II.
37. Bühlmann A.A. 1984. *Decompression-Decompression sickness*. Berlin : Springer-Verlag, 1984. ISBN 3-540-13308-9; ISBN 0-387-13308-9.
38. Kłos R.. 1995. *Tauchmedizin*. Berlin : Springer-Verlag, 1995. ISBN 3-540-58970-8.
39. Jones H.B. 1948. Respiratory System: Nitrogen elimination. [aut. książki] O. Glasser. *Medical Physycs*. memorandum report of the US AirForce : brak nazwiska, 1948, strony 855-871.
40. STANAG 7056. 1997. *Functional requirements for physiological protection during high altitude parachuting operations*. EDITION 1 . Brussels : NATO Military Agency for Standardization, 1997. STANAG 7056 AMD.
41. Kłos R. 2007. *Zastosowanie metod statystycznych w technice nurkowej*. Gdynia : Polskie Towarzystwo Medycyny i Techniki Nurkowej Gdynia 2007, 2007. ISBN 978-83-924989-2-6.
42. Westendorp RG, Blauw GJ, Frölich M, Simons R. 1997. Hypoxic syncope. *Aviat Space Environ Med*. 1997, Tom 68, strony 410–414.

**dr hab. inż. Ryszard Kłos, prof. nadzw. AMW**  
Akademia Marynarki Wojennej im. Bohaterów Westerplatte  
Zakład Technologii Prac Podwodnych  
81 – 103 Gdynia 3,  
ul. Śmidowicza 69  
Tel.: +58 626 27 46

1 significant in a given context; relating to a topic, issue or problem,  
2 normal conditions,  
3 theoretically, this technique can be used to extinguish a fire in a hypobaric complex, analogous to the use of Inergen to extinguish fires under normobaric conditions [7],  
4 e.g. in a hypobaric chamber,  
5 Annex 2.a Transport and use of oxygen to announcement No. 6/2024 of the President of the Civil Aviation Authority of 13 March 2024 on the publication of the text of Annex 6, Part II to the Convention on International Civil Aviation, drawn up in Chicago on 7 December 1944. [Journal of Laws 10.2024, as amended],  
6 Similarly, diving technology often refers to the pressure prevailing at a depth,  
7 e.g. in the middle ear, lungs, stomach,  
8 most often to the surface of the body of water,  
9 hypoxia,  
10 for every 1,000 ft, the temperature drops by approx. 2°C,  
11 High-Altitude Group Readiness Profile,  
12 in certain operational conditions when performing HALO jumps, BIBS oxygen breathing equipment may be omitted if the pre-oxygenation process has been carried out correctly,  
13 Mean Sea Level,  
14 regardless of the altitude of the terrain below or above sea level,  
15 flight level – the conventional altitude at which an aircraft is located in airspace, expressed in hundreds of pressure feet, i.e. based on atmospheric pressure at given altitudes,  
16 Physiology Technician,  
17 in order to properly adjust equipment,  
18 including operational documents and thematic publications,  
19 before or after a high-altitude jump,  
20 incorrectly referred to as: zero decompression (incorrect, as some form of decompression always accompanies the ascent procedure),  
21 surface decompression time does not apply,  
22 Military Free-Fall Operations,  
23 [32],  
24 provided in the process of *homeostasis*,  
25 mountains, high-altitude lakes,  
26 e.g., caves or deep mines,  
27 it is rarely taken into account, although its residual content in the oxygen used or its recirculation from the dead space of the mask must always be considered,  
28 there are other possible approaches to this modelling, but this is the most common,  
29 of course, taking into account models other than  $ZHL_{12}$ , the ranges of half-life saturation/desaturation may be different, e.g. for the Workman model – Table A.8,  
30 the corresponding  $\tau(He) \in [115, 240]minutes$  times for helium,  
31 results from the convergence of numerical values for  $ln2$  and theoretical tissue  $\tau = 1000 \cdot ln2$ ,  
32 the results are overestimated,  
33 probability of failure-free operation, survival, occurrence of another defined event, etc.,  
34 for example,  $S(t)$  is the probability that a given person will live until  $t$ ,  
35 The value of the  $h(t)$  function should be treated as the potential for an expected event (most often a failure) to occur, complementing the analysis of a problem situation characterised by the survival function  $S(t)$  – when the  $S(t)$  function decreases,  $h(t)$  increases. The function  $h(t)$  can be vividly compared to the operation of a car speedometer. Based on its constant reading, it is possible to conclude what distance will be travelled after a selected period of time – based on the constant value of the function  $h(t)$ , it is possible to anticipate the number of expected events within a selected period of time,  
36 In safety engineering, the hazard function  $h(t)$  is defined as *the intensity of safety failure* and is often referred to as  $\lambda_B(t)$  (Jaźwiński J. and Ważyńska-Fiok K., 1993),  
37 depending on the units of time adopted,  
38 especially since different authors assess its effectiveness differently,  
39 NIRS (Near-Infrared Spectroscopy) equipment uses near-infrared spectroscopy for non-invasive measurement of tissue oxygenation,  
40 it is, of course, possible to make the simulation conditions much more realistic.