Scientific Journal of Gdynia Maritime University

No. 125/23, 54–65
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/125.04

Submitted: 08.02.2023
Accepted: 18.02.2023
Published: 31.03.2023

RISKS RELATED INCORRECT DECOMPRESSION, STAGE ASCENT PROCEDURES WITH THE USE OF DECOMPRESSION TABLES AS A TYPE OF PREVENTIVE ACTIONS AGAINST THE EFFECTS OF DECOMPRESSION

Katarzyna Mielniczek[1*], Grzegorz Rutkowski[2]

[1] Student Special Interest Group of Underwater Research 'SeaQuest',
Gdynia Maritime University, 81-225 Gdynia, Poland,
e-mail: kasiamielniczek10@gmail.com, ORCID ID: 0000-0001-7208-7027

[2] Gdynia Maritime University, Faculty of Navigation, ORCID 0000-0002-7455-7069

*Corresponding author

Abstract: The article presents what decompression is, how to perform it correctly using dive ascent tables, and the typical symptoms of decompression sickness. The article also describes typical diving accidents caused by poorly planned diving without decompression stops being performed. The article emphasises that important factors that contribute to diving safety are: proper training of the diver, a properly prepared diving plan including decompression stops, the diver's mental state and their so-called adaptive training which helps the diver to manage stress in hyperbaric conditions, preparing their body to undergo correct decompression.

Keywords: decompression, diving, staged ascent, symptoms.

1. INTRODUCTION

Statistics from August 2022 show thatthe incidence of decompression sickness is rare. In recreational diving,it is three cases per 10,000 dives. Among commercial divers, it can be higher and range from 1.5 to 10 cases per 10,000 dives. It all depends on the length and depth of the dive. The risk of occurrence is 2.5 times higher in men than in women. The disease occurs in the diver's body during poorly performed decompression during the ascent phase. The primary cause is supersaturation of the body with an inert gas (usually nitrogen or helium, the gases used to create traditional breathing mixtures). Gas bubbles then form from a solution of tissue fluids. This leads to blockage of the capillaries and subsequent disturbances in the diver's organism. As the diver ascends, the ambient hydrostatic pressure decreases, causing the gas bubbles that have accumulated in the blood vessels and/or other tissues of the body to expand. To prevent this from happening, the diver should ascend at a specific ascent rate and make mandatory decompression stops. The most common decompression stops are usually done at water depths of: 12 m, 9 m, 6 m and 3 m [Macke, Kuszewski and Zieleniec 1992]. Correct decompression involves removing excess nitrogen from the body's tissues. The length and depth of the decompression stop and the interval until the next diveare determined based on the depth and length of time underwater. In practice, however, there are depths and dive times at which it is not necessary to perform the mandatory stops.

Decompression tables are helpful in determining these parameters. There are dozens of types of tables worldwide, and they are based on proven decompression models, such as the Bühlmann model, the reduced gradient bubble model, and the variable permeability model. A distinction is also made between tables designed basedon the purpose of the dive, such as tables for recreational diving, commercial diving, or for military purposes.

Over time, so-called dive computers have come into use, which continuously assess the diver's condition. The computer measures the time and depth of the dive and also measures the body's nitrogen saturation level. In this way, it determines how long the diver can spend underwater without decompressing, but limited to a so-called safety stop.

With rapid ascent, the body produces persistent nitrogen bubbles. As the ascent and/or altitude increases, the gas pressure decreases and the size of the gas bubbles increases. Therefore, the diver's ascent rate when changing depth to the first decompression station should not exceed 15–18 m per minute.

From a practical point of view, this corresponds to a situation in which the diver ascends at or near the speed at which the smallest bubbles of exhaled air visible in the water depths are directed towards the water surface. If the diver ascends too fast or does not stop at the right place and time, the gas bubbles accumulated in the body will begin to increase in volume and eventually cause symptoms of so-called decompression sickness. Most of them will be intercepted by the body's natural shield, which is the vasculature in the lungs.

However, some of them will be too large and may then remain in various tissues of our body (e.g. in the eye, in the brain, in the knee joints, etc.) leading to numerous congestions, hypoxia in these tissues and, in extreme cases, also to their necrosis and/or permanent damage. Other gas bubbles may enter with the blood circulation, e.g. into the pulmonary artery or heart, causing their failure or damage. It is worth mentioning here that all this occurs in the human body in a very short period of time, during an uncontrolled ascent at too high a speed.

2. DIVING ACCIDENT STATISTICS WITH ASSISTANCE FROM DIVERS ALERT NETWORK

Divers Alert Network is a non-profit organisation dedicated to improving safety for all divers. Statistics are kept on the basis of reported accidents to the emergency line, available 24/7, in which diving doctors and highly skilled specialists assisted the injured.

Table 1. Summary of accidents by injury as per Alert Diver Website

Diving accident type	2018	2019	2020	2021
Decompression illness	292	271	182	200
Suspected decompression illness	129	159	70	106
Barotrauma	150	171	74	91
Suspected barotrauma	65	113	76	82
Diving death	17	12	8	15
Gas toxicity/CBG	0	1	1	3
Marine life	34	50	19	11
Near misses	13	10	4	11
Other diving	142	134	70	72
Trauma diving dry	37	39	20	18
Trauma diving wet	64	78	50	46
Total	943	1038	574	655

Source: AlertDiverWebsite, https://alertdiver.eu/pl (accessed 10.02.2023).

The statistics show that decompression causes the most accidents each year. Often, it is poorly performed decompression that leads to mishaps. Therefore, in this article, we will specifically address the issue of decompression sickness.

3. DECOMPRESSION SYMPTOMS

In addition to reactions that a person is unable to perceive, there are factors that indicate decompression sickness. These are divided into four types of symptoms:

- Central nervous system – loss of consciousness, paralysis, dizziness, visual and auditory disturbances.
- Cardiovascular and respiratory system – retrosternal pain, cough, shallow and rapid breathing, dyspnoea including respiratory and cardiac arrest, shock.
- Extremities – fatigue, numbness, weakness, pains ranging from mild to moderate to very severe, leading to shock, late bone changes.
- Skin – itching, blotchiness, rash, pallor and chilliness, warmth and sweating.

The most common cases are joint pain. Skin disorders are also very common with decompression sickness. Quite often, there are also neurological disorders resulting from impaired blood flow within the spinal cord (especially in the lower sections). Severe symptoms, i.e., brain involvement (loss of consciousness) or ‘choking’ (respiratory and circulatory disorders) are very rare.

Most symptoms occur within the first 6 hours, but this does not mean that they cannot also occur earlier or later. It must also be remembered that the intensity of the pain can mask other symptoms.

The sooner any symptoms occur, the more severe the course of the disease will be. Therefore, even the smallest of them should not be underestimated [Chomoniuk 1992].

Decompression sickness is most commonly encountered in professional divers who dive to great depths, but it is also increasingly common in relatively shallow waters where both professionals and amateurs are encountered.

Gas bubbles mainly persist in the human body in the muscles, joints and cartilages. The mere presence of gas in the form of alveoli does not directly affect the damage to the pulmonary arteries. In fact, there are the natural route for the migration of alveoli from the tissues through the right (venous) part of the heart to the lungs. This phenomenon is called gas bubble arteriolysis. This also refers to the penetration (in special cases) of a certain number of bubbles into the arterial side of the circulation and their distribution with blood stream throughout the human body (mainly into the brain and coronary system).

4. EXAMPLE OF ILLNESS

An example of this is the accident story of a 44-year-old diver with many years of practice, holding the rank of senior diver (before the amendment, resulting from the provisions of the Underwater Work Act of 17 October 2003). The weather was good, clear August skies, no cloud cover, the air temperature was 25° C, water temperature 16°C, sea state 2°B. The dive took place between 9 a.m. and 1:45 p.m. in classic equipment, at a depth of 12–15 metres. His task was to remove silt using an air injector. During the ascent, the diver had one decompression stop at a depth of 3 metres with a dwell time of 15 minutes (open-air). Approximately two hours after completion, he began to experience pain in his shoulder and knee joints, numbness in his left leg and a rash on his chest and abdomen. After informing the dive team, he was accused of simulating. No action was taken. Upon returning home, the man noticed a bluish red rash on his body and the joint pain had also increased. The numbness in his right limb subsided. After consultation with a neurologist, the decision was made to transport him to a decompression chamber. On arrival at the hyperbaric facility, the diver’s examining physician found the following on physical examination: an increased respiratory rate of up to 20/min, tachycardia of up to

100/min, a blood pressure RR of 130/80 mmHg, a macular rash on the abdominal skin with a marble-like appearance; the overall clinical picture was completed by the diver's reported pain in the knee and shoulder joints, of a drilling nature, unrelated to movement of the area affected by the pain. The neurological examination did not indicate any abnormalities.

The doctor diagnosed type I decompression sickness – 'the bends'. The diver was treated by compressing the free gas bubbles and reducing their size to asymptomatic. A follow-up result after 20 minutes at maximum treatment depth showed no abnormalities, and treatment was completed. No recurrence was observed both during decompression and after completion of treatment [Olszański and Konarski 2010].

The case described shows that diving regulations were disregarded. The exact depth of the dive was not measured, but the time of the dive was determined. However, this is not sufficient to determine the time and depth of decompression. If it had been an exact depth of 12 metres and a dwell time of 285 minutes, it could have been assumed that the decompression was performed correctly.

5. TREATMENT

We can divide decompression sickness into two types. The first type is based on symptoms affecting the skin, bones, joints, and muscles through weakness, fatigue, itching of the skin, the appearance of numerous bluish-red tinges, muscle and joint pain, and restrictions of mobility. The second type of pressure disease through the influence of gas bubbles shows symptoms in organs such as the brain, middle ear or spinal cord. Vascular congestion caused by gas bubbles is also classified into this type. Symptoms include partial or complete loss of consciousness, respiratory arrest, sensory disturbances, paralysis, which can lead to hemiparesis, nausea, vomiting, tinnitus, or dizziness. All cases of the disease should initially be treated with 100% medical oxygen pending hyperbaric therapy. The aim of such therapy is to oxygenate the body in a more effective way. This is possible with the use of a special room called a hyperbaric chamber. There is a correspondingly high pressure inside, usually 2.5 times atmospheric pressure, which nullifies the physiological oxygen barriers to cell penetration. During compression, all people inside the chamber must equalise the pressure in their ears by following the instructions of the staff inside the hibernation chamber. The patients then breathe a breathing mixture with an increased content of medical oxygen, delivered by an individual respiratory system. Oxygen breathing lasts an hour, plus one or two breaks of several minutes during which breathing can be done without breathing systems. The final stage is expansion, during which the pressure in the chamber is reduced to atmospheric pressure. This increased pressure in the chamber allows much higher doses of oxygen to be delivered to the cells, which helps to treat many conditions. The patient breathes medical oxygen through the mask. Neurological, pulmonary, and skin lesions should be treated in this way. Fluids should also be given to such a person, so that dehydration does not occur. It is no longer advisable to administer aspirin, as this can reduce symptoms. The patient should be placed in a supine position or in a safe position if vomiting is present. In the first phase, first of all the so-called ABCs of medical first aid should be taken care of, i.e., patency of the airways, breathing and circulation. Before starting to dive, each person should have acquired information on the exact procedure for dealing with decompression sickness and a record of where the nearest hyperbaric treatment centre is located.

In Poland, the hyperbaric centre is located at the University Center for Maritime and Tropical Medicine in Gdynia. The person should be transferred as soon as possible to a special centre with a hyperbaric chamber. The most effective transport is by air. There are special pressurised planes, and if one is not available, they should be transported by helicopter. In this case, the flight altitude, if possible, should not exceed 300 metres.

6. DECOMPRESSION TABLES

Diving decompression tables are the result of years of scientific research, calculations, animal experiments, and human trials. Nowadays, dive computers have replaced tables almost completely in recreational diving, but it is still mandatory for every diver to have the skills to use tables. In professional diving (commercial underwater work, uniformed services diving, and training for professional diving), diving is done using tables while dive computers have a supporting use. Dive computers are an excellent training tool, easily showing how the body's gas saturation changes with depth, length of time underwater, and breathing mixture used by the divers. Each diving organisation usually has its own decompression tables. Diving decompression tables can therefore vary widely, but the principle of their use is, nevertheless, usually very similar.

In practice, the following decompression tables for recreational diving are most commonly encountered, with the names of the decompression models listed:

- The US Navy (US NAVY) tables;
- The Bühlmann/Hahn tables (an algorithm for the way gases enter and dissolve in the human body during pressure changes) tables commonly used by the International Diving Confederation CMAS (from the French: Confederation Mondiale des Activites Subaquatiques, ENG: The World Underwater Federation):
  - Bühlmann/Hahn tables 0–250 m asl,
  - Bühlmann/Hahn upland tables 251–700 m asl,
  - Bühlmann/Hahn mountain tables 701–1200 m asl,
  - Bühlmann/Hahn super-mountain tables 1201–2400 m asl,

  - DECO92 decompression tables (tables predicting descent and ascent of 0.17 m/s) EAN32 (mixture containing 32% oxygen and 68% nitrogen),
  - DECO92 decompression tables EAN36;
- RDP tables used by PADI (ENG: Professional Association of Diving Instructors):
  - RDP decompression tables (ENG: Recreational Dive Planner),
  - Nitrox tables EAN31 and EAN36;
- The 'Wheel' table used in PADI – allows for multi-level diving.

7. RULES FOR THE USE OF TABLES AND DIVING

- You may not plan a dive with parameters outside the range given in the tables you have.
- No interpolation of the tables is allowed; if you do not find the value you need in the table, assume a higher one.
- It is recommended to ascend at the speed given in the tables.
- The height of the tank above sea level affects the decompression course due to the prevailing atmospheric pressure. Tables have been designed for different altitudes above sea level. They are for lowland, upland, and mountainous areas, respectively. They have varying degrees of tightening of decompression recommendations. The most stringent tables are those for upland areas and the least stringent are for lowland areas.
- When diving in lowland areas, both upland and mountain tables can be used.
- Diving no more than twice a day is recommended.
- When diving twice a day, it is advisable to dive deeper first.
- If diving several days in a row, it is best to take a break after every 3–4 days to desaturate the body.
- If there are several dives in a row, it is best to take a break after every three to four days in order to deplete the body of gas deposits, if the surface break time between two dives exceeds the largest time on the right-hand side of the 'surface break table', the next dive is considered the first dive (additional time is 0 minutes).

8. EXAMPLE OF THE USE OF TABLES

Figure 1 shows the front of the RDP PADI table. The upper left-hand section contains the first table, from which it is necessary to determine the pressure group the diver will be in after the dive. The surface break times are in the lower right-hand section, from which it is necessary to read what pressure group the person will be in after the break. Going deeper into the translation, from the first table, the diver knows how much nitrogen they have absorbed during the dive and from the second how much they have expelled while on the surface. The third table provides information assuming the break was not long enough, and the diver is still in some pressure group. With the help of the tables, the maximum time to be underwater again and the residual time are established. These are needed, in turn, to determine the new pressure group the diver will be in after the next dive.

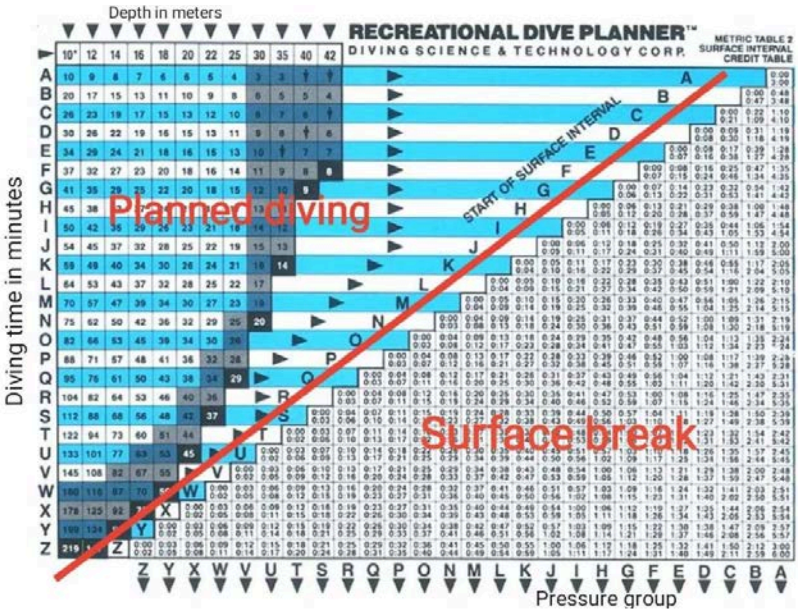

Fig. 1. Front of RDP PADI table

Source: https://www.padi.com/ (accessed 10.02.2023).

DEPTH (metres)	Z	Y	X	W	V	U	T	S	R	Q	P	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
10*	219	199 20	178 41	160 59	145 74	133 86	122 97	112 107	104 115	95 124	88 131	82 137	75 144	70 149	64 155	59 160	54 165	50 169	45 174	41 178	37 182	34 185	30 189	26 193	20 199	10 209
12	147	134 13	125 22	116 31	108 39	101 46	94 53	88 59	82 65	76 71	71 76	66 81	62 85	57 90	53 94	49 98	45 102	42 105	38 109	35 112	32 115	29 118	26 121	23 124	17 130	9 138
14		98	92 6	87 11	82 16	77 21	73 25	68 30	64 34	61 37	57 41	53 45	50 48	47 51	43 55	40 58	37 61	35 63	32 66	29 69	27 71	24 74	22 76	19 79	15 83	8 90
16			72	70 2	67 5	63 9	60 12	56 16	53 19	50 22	48 24	45 27	42 30	39 33	37 35	34 38	32 40	29 43	27 45	25 47	23 49	21 51	19 53	17 55	13 59	7 65
18				56	55	53 3	51 5	48 8	46 10	43 13	41 15	39 17	36 20	34 22	32 24	30 26	28 28	26 30	24 32	22 34	20 36	18 38	16 40	15 41	11 45	6 50
20						45	44	42 3	40 5	38 7	36 9	34 11	32 13	30 15	28 17	26 19	25 20	23 22	21 24	20 25	18 27	16 29	15 30	13 32	10 35	6 39
22								37	36	34 3	32 5	30 7	29 8	27 10	25 12	24 13	22 15	21 16	19 18	18 19	16 21	15 22*	13 24	12 25	9 28	5 32
25										29	28	26 3	25 4	23 6	22 7	21 8	19 10	18 11	17 12	15 14	14 15	13 16	11 18	10 19	8 21	4 25
30													20	19	17 3	16 4	15 5	14 6	13 7	12 8	11 9	10 10	9 11	8 12	6 14	3 17
35																14	13	12	11 3	10 4	9 5	9 5	8 6	7 7	5 9	3 11
40																				9	8	7	7	6	5 4	2 7

Fig. 2. RDP PADI table

Source: https://www.padi.com/ (accessed 10.02.2023).

From the table presented in Figure 2, we can determine the time after which a diver will be able to perform the same dive again. For example (see Fig. 3), a person dives to 18 metres for 32 minutes and then takes a 1 h break. After the first dive, they are in pressure group L, and after a 1-hour surface break, they will move to group C. They then descend to the same depth where they will be able to spend 41 minutes, plus 15 minutes of additional time. However, a safety stop (no-decompression time limit) will be required on ascent. Once out of the water, they will be in pressure group W.

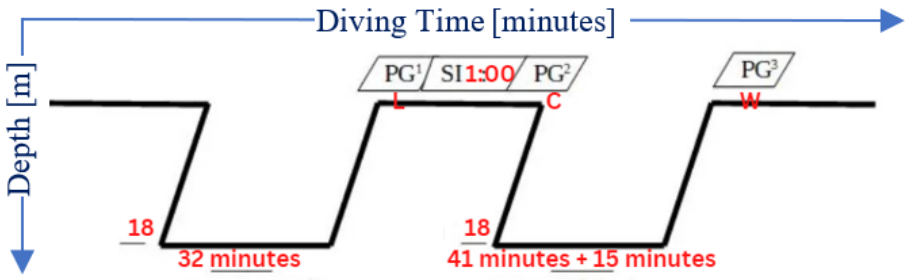

Fig. 3. Graphical representation of the dive log

Source: Own research based on RDP PADI table.

Going forward (see Fig. 4), the first dive will be performed at a depth of 20 metres for 31 minutes, and after a 29-minute surface break, the second dive will be started at 30 metres. After 31 minutes, the diver will be in pressure group N, while after the break, they will move to group H. After descending to 30 metres, they will be allowed to spend 7 minutes there, while the safety time will be another 13 minutes. On ascent they will be required to make a 3-minute safety stop. On the surface, they will be in pressure group N again.

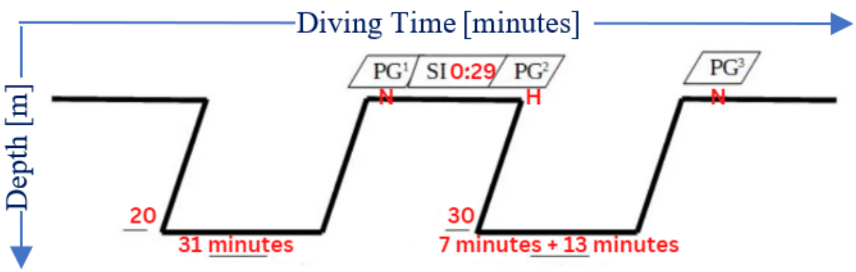

Fig. 4. Graphical representation of the dive log

Source: Own research based on RDP PADI table.

9. CONCLUSIONS

Training and diver awareness are important factors in reducing diving accidents. Conscious and voluntary training leads to greater attention to work rules and less stress before and during the dive. A good diver will not allow him/herself to break rules that may affect their life. By doing so, they will contribute to increased safety.

Decompression sickness is also influenced by factors such as:

- water temperature – cold, resulting in hypothermia (decompression in the water is carried out with minimum energy expenditure of the divers);
- yo-yo diving (diving again and again with short breaks);
- dehydration;
- obesity;
- exertion during the dive;
- old age;
- consumption of alcohol before diving;
- carbon dioxide poisoning due to, inter alia, poor diving condition, exertion, high density of the breathing medium;
- high exertion before diving, muscle acidification after exertion;
- injuries such as interrupted tissue continuity. A slow gas phase may develop at the sites of injury.

Adaptive training helps divers to maintain their body's readiness to undergo decompression and contributes to an improved mental state under hyperbaric conditions. Before putting decompression tables into use, the diver should become very familiar with them and follow them.

10. ACKNOWLEDGEMENTS

The Student Special Interest Group of Underwater Research 'SeaQuest' operating at Gdynia Maritime University would like to thank the reviewers for their kind evaluations, substantive comments and the time devoted to evaluating our work. Our students have been actively involved in research analysis of the risks associated with decompression sickness in scubadiving. 'SeaQuest' is currently participating in research project No. SKN/SP/535575/2022 called MUDS Base – the Mobile Underwater Diving Support Base, which was submitted as part of a scientific competition organised by the Ministry of Science and Higher Education in October 2021 as the new initiative: 'Student Circles Create Innovations'. The members of 'SeaQuest' hope that their new project will gain extra financial support in this initiative, which will enable them to continue their research work on their new mobile diving base project with a flexible diving bell called Batychron. As a result of the planned research work in 2023, 'SeaQuest' would like to create a mobile MUDS Base device, which will be widely used in hydrotechnics for underwater

transport and securing exploratory and tourist dives while maintaining the safety of human life. In addition, we also plan to familiarise ourselves with the equipment available at MUG's Division of Hyperbaric Medicine &Maritime Rescue – National Centre for Hyperbaric Medicine in Gdynia.

REFERENCES

Brubakk, A.O., Neuman, T.S., 2003, *Bennett and Elliott's Physiology and Medicine of Diving*, Saunders-Elsevier Science Ltd. Edinburgh, Scotland.

Bühlmann, A.A., 1984, *Decompression-Decompression Sickness*, Springer-Verlag, Berlin.

Buzzacott, P., MPH, PHD, Denoble, P.J., 2018, *Annual Diving Report 2018*, Divers Alert Network, Durham, NC.

Chomoniuk, W., 1992, *Tabele dekompresyjne,* Alldiv.

Denoble, P.J, MD, DSC, 2019, *Annual Diving Report 2019*, Divers Alert Network, Durham, NC.

Jurczyński, M., Rutkowski, G., 2021, *Analysis of Maritime Accidents in the Context of Demand for MoB MEDS the Mobile Base of the Marine Emergency Diving Service*, TransNav the International Journal on Marine Navigation and Safety of Sea Transportation, vol. 15, no. 1, March 2021, pp. 209–214, TransNav 2021, 14th International Conference on Marine Navigation and Safety of Sea Transportation, 16–17 June 2021, Gdynia, Poland.

Kłos, R., 2006, *Walidacja tabel dekompresyjnych w oparciu o rozkład dwumianowy*, Polish Hyperbaric Research, no. 14, pp. 59−78.

Kłos, R., 2007, *Niektóre problemy związane z wyborem sposobu dekompresji*, Polskie Towarzystwo Medycyny i Techniki Hiperbarycznej Polish Hyperbaric Research, No. 1(18).

Kłos, R., 2018, *Methods for Treatment of Decompression Sickness Developed During Wreck Penetration*, Zeszyty Naukowe Akademii Marynarki Wojennej, March 29, Gdynia.

Kot, J., Lenkiewicz, E., 2022, *Hyperbaric Oxygen Therapy in Necrotizing Soft Tissue Infections Caused by Vibrio Species from the Baltic Sea – Three Clinical Cases*, International Maritime Health, vol. 73, pp. 52–55.

Kot, J., Lenkiewicz, E., Lizak, E., Góralczyk, P., Chreptowicz, U., 2021, *Spinal Cord Decompression Sickness in an Inside Attendant After a Standard Hyperbaric Oxygen Treatment Session,* Diving and Hyperbaric Medicine, vol. 51, pp. 103–106.

Macke, J., Kuszewski, K., Zieleniec, G., 2007, *Nurkowanie*, Warsaw.

Olszański, R., Konarski, M., 2010, *Choroba dekompresyjna u nurka po długotrwałym nurkowaniu powietrznym na małej głębokości – opis przypadku*, Polish Hyperbaric Research, pp. 89–96.

Rutkowski, G., Kosiek, J., Nasur, J., 2022, *Analysis of the Batychron Research Project*, Scientific Journal of Gdynia Maritime University, no. 121, March 2022, pp. 20–27, https://sj.umg.edu.pl/issues.

Shilling, C.W., 1981, *A History of the Development of Decompression Tables*, Undersea Medical Society, Inc. Bethesda.

Siewiera, J., Szałański, P., Tomaszewski, D., Kot, J., 2020, *High-Altitude Decompression Sickness Treated with Hyperbaric Therapy and Extracorporeal Oxygenation*, Aerospace Medicine and Human Performance, vol. 91, pp. 106–109.

US Navy Diving Manual, 2001, The Direction of Commander, Naval Sea Systems Command.

Wienke, B.R., 2009, *Diving Above Sea Level*, Best Publishing Company, Wielki Błękit, Warsaw, Poland.

Internet sources

https://alertdiver.eu/pl (accessed 10.02.2023).

https://idiver.wordpress.com/tablica-rdp/ (accessed 10.01.2023).

https://medycynatropikalna.pl/ (accessed 12.01.2023).

https://www.instructables.com/Reading-Dive-Tables/ (accessed 15.01.2023).

https://www.ncbi.nlm.nih.gov/ (accessed 10.01.2023).

https://www.nurkomania.pl/nurkowanie_tabele_dekompresyjne_pojecia_podstawowe.htm (accessed 10.01.2023).

https://www.padi.com/ (accessed 10.02.2023).