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METHODS FOR TREATMENT OF DECOMPRESSION SICKNESS DEVELOPED DURING WRECK PENETRATION

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ABSTRACT

This article is one of the series articles relating to the *DiveSMART* project conducted to improve coordination procedures used in international underwater rescue operations in the Baltic Sea. The project *DiveSMART Baltic* has received the 'flagship status'.

The article is the third in the planned cycle of articles relating to efforts made at the Naval Academy within the framework of *DiveSMART Baltic* project. It includes scenarios of treating decompression sickness acquired by divers during a rescue operation or after completed their decompression. These issues are connected with the work package four *'Medical treatment' of the DiveSMART Baltic project: Identifies methods for different medical treatments in operational areas*.

Key words:

SAR, underwater search and rescue.

Research article

INTRODUCTION

In the course of diving a situation can occur whose consequence will be the necessity to apply a treatment procedure for divers. It follows from the previous articles that in a search and rescue operation both saturation diving and short-term intervention diving methods will be used. In these two situations, if after decompression the necessity for treatment occurs, some of the treatment procedures mentioned in the article can be applied to not only divers but to survivors rescued from a wreck. However, in most scenarios the treatment procedures will be different, which will be discussed further in the article.

The historical collection of *treatment tables TT* up to the 1980s can be found in the report by *US Naval Medical Research Center* [1]. One of the methods available in the review literature is the classification agreed upon in *NATO*. The complete list of the *TT* used by individual countries is presented in *Chapter* 5 *National therapeutic recompression tables* [9]. This document is the Annex to the *NATO Standardization Agreement* [18].

Tab. 1. Example of treatment tables *TT* apportionment [1]

Type	Example of national tables	Equivalent *US Navy* tables
Short oxygen tables	TABLE V Goodman 1 (BE) OHB (FR) HBO (GE) 9SH (NL) 60 & 61 (UK)	TT USN 5
Long, shallow oxygen tables	TABLE VI 62 (UK) Goodman 2 (BE)	TT USN 6
Long, deep oxygen tables	TABLE VII 6A (mod) (GE, CA) TABLES A and B (FR) SND (GE) 63 (UK)	TT USN 6A
Saturation or sub-saturation tables	TABLE VIII US 7 US 8 TABLE C (FR) 64 & 65 (UK)	TT USN 4
Air tables	TABLE I TABLE II TABLE D (FR) 52 (UK)	1A 2A

The existing TT can be divided into saturation, sub-saturation, and outside the saturation zone TT (tab. 1). And the last mentioned TT can be divided into those using oxygen therapy or other therapy[1].

The $US\ Navy$ procedures [21] constitute the most widespread treatment system[2]. An interesting extension of air treatment procedures is the set of the air-helium[3] tables developed by Russians [24]. However, the system which can support the whole, available for divers at present, range of depths is the system developed by $COMEX$ [17].

TREATMENT PROCEDURES

There exist different classifications of decompression sickness DCS[4]. The classification proposed by $Wienke$ has been adopted here (tab. 2). The most common cases encompass: $Type\ I\ DCS$ and $Type\ II\ DCS$. They are caused by formation of gas in free phase in tissues. They can be effectively treated by hyperbaric methods causing decrease in the size of bubbles in free gas phase occurred into tissues and caused the possibility of their reabsorption and elimination by the gas exchange through the blood into the respiratory system.

Tab. 2. Types of decompression sickness DCS [22]

$Type\ I$	**Limbs.** Symptoms: localized pain in joints, skin itching, bends, rashes, mottling, lymphatic swelling, ascending weakness in the legs, hips, elbows, muscles or skin
$Type\ II$	**Central nervous system.** Symptoms: confusion, anxiety, paralysis, dyspnoea, chest pain, breathing difficulty, loss of conscientiousness, lack of alertness, impaired balance problems in keeping upright posture, especially keeping the spine straight
$Type\ III$	**Inner ear.** Symptoms: impaired hearing, dizziness, ringing in the ears, and tinnitus or nausea. It is the result of the impact of pressure on keeping balance in the organs in the ear
$Type\ IV$	**Avascular necrosis.** Symptoms: mechanical bone injury, structural injury, local mineralization. It affects mostly long bones

[1] Air, air-helium, helium-oxygen Hx tables.

[2] Understood as a method for moving between the treatment procedures in the course of treatment decompression or when next sickness symptoms occurred after the completion of treatment.

[3] Oxygen-nitrogen-helium mixture is called *Trimix* and marked Tx.

[4] ***Dec****ompression* ***S****ickness.*

In the traditional operational diving[5] *Type I DCS* is most often caused by formation of gas in free phase in tissues, especially in blood, adipose and connective tissue and *Type II DCS* in nervous tissue. Blocked flow of blood by gas free phase can cause local ischemia leading to necrosis. Occurrence of gas in free phase in tissue usually causes neurological symptoms.

There exist a few theories relating to the probable pain inducing mechanism with regard to *Type I DCS* [10]. It occurs when bubbles in gas in free phase reach the size big enough to:

- dislocate or irritate nerve endings;
- block capillaries leading to ischemia and tissue necrosis, which while excreting chemical substances warn the brain about injuries inducing feeling of pain generated by brain;
- activate the biochemical reaction of immunoglobulins production, which also stimulates pain signaling the presence of harmful substances in living cells.

The destructive actions in tissues caused by gas existing in free phase are not the only pathological symptoms induced by it. Defensive reactions of an organism induced by gas in free phase do not have to be directly linked to the mechanical impact, but they also have biochemical origins of pain. This theory, called the complement activation[6], seems to be well documented [12].

Type II DCS can be a result of blocked blood flow to the spinal cord, which causes slowing down stimulation or inhibiting higher brain functions[7].

Type III DCS can be caused by gas in free phase, inert gas counterdiffusion and increased pressure of bodily fluids in the inner ear. Theoretically, anomalies occurring on the surface of cell membranes can be responsible for *Type III DCS*, and counterdiffusion caused by occurrence of content gradients of various gases is responsible for these anomalies. One gas can defund in one direction, whereas the other in the opposite direction. Their counter-current streams cause gas exchange disturbances on the borders of phases, which causes a change in physical conditions of gas solubility in tissue[8] [15]. Their mutual competing for presence in the solution

[5] Outside the saturation zone.

[6] Complement is a system of plasma proteins contributing to defensive reaction of that occurs on the surface of pathogens and generates active components with various effector functions.

[7] Central nervous system does not tolerate becoming deprived of the flow of information, that is why its activity dies out quickly, causing *Type II DCS*.

[8] Natural solubility is understood here as the condition in which gases occur independently.

can lead to displacing one of them[9] [16]. $Type\ III\ DCS$ symptoms can be a result of an osmotic reaction. Bodily fluids tend to balance the concentration of gases contained in it through dislocation, causing dilution of the more concentrated solution. This can entail an increase in the amount of fluids in the inner ear organs which leads to dysfunction of the labyrinth as a consequence [2].

It is difficult to determine to what extent $Type\ IV\ DCS$ is caused by wrongly performed decompression. Its formation can be influenced by the free gas phase, ischemia, embolism[10] and a combination of these factors. Statistically this sickness is important with regard to professional divers and people working in caissons. Both of these groups are often exposed to high pressure actions. The same symptoms as in $Type\ IV\ DCS$ are found in racing horses and alcoholics. In this case, this sickness is called aseptic bone necrosis. The mechanisms of formation of $Type\ IV\ DCS$ are considered theoretically and there is no exhaustive evidence based on medical observation. These symptoms are osteonecrosis that is not induced by infection[11]. If pathological hardening of bone occurs in the central part it does not affect vitals. If pathological changes occur in the end of a bone, where the head of one of the bones fits into the socket of another one, splinters can form and joints can be damaged. Probably, repeated fast compression and the content of dioxide can have an influence on inducing avascular osteonecrosis. Long exposition to partial oxygen pressure above 60 kPa can cause osteonecrosis in people predisposed to developing this sickness. The probable mechanism is associated with blocking blood flow into marrow and living bone tissue by bubbles in gas in free phase, locating themselves in capillary vessels [22]. An connection has been found of pain located in bones region with the yellow marrow, which is far less supplied by blood[12] than the red marrow. Connecting this with the generally known good solubility of inert gases in fats it can be anticipated that the difficulty in transporting the gas from the inside of a bone can be the cause of the sickness symptoms.

$Type\ III\ DCS$ and $Type\ IV\ DCS$ should not be treated with hyperbaric methods using recompression treatment. In many cases, recompression treatment can lead to worsened condition of a patient [20]. It is important as $Type\ II\ DCS$ and $Type\ III\ DCS$ are difficult to distinguish from each other.

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[9] Mechanism similar to the salting-out effect in water solutions; the addition of sodium chloride to a another solution to reduce the solubility of the latter.

[10] Gas embolism.

[11] Hence the term aseptic.

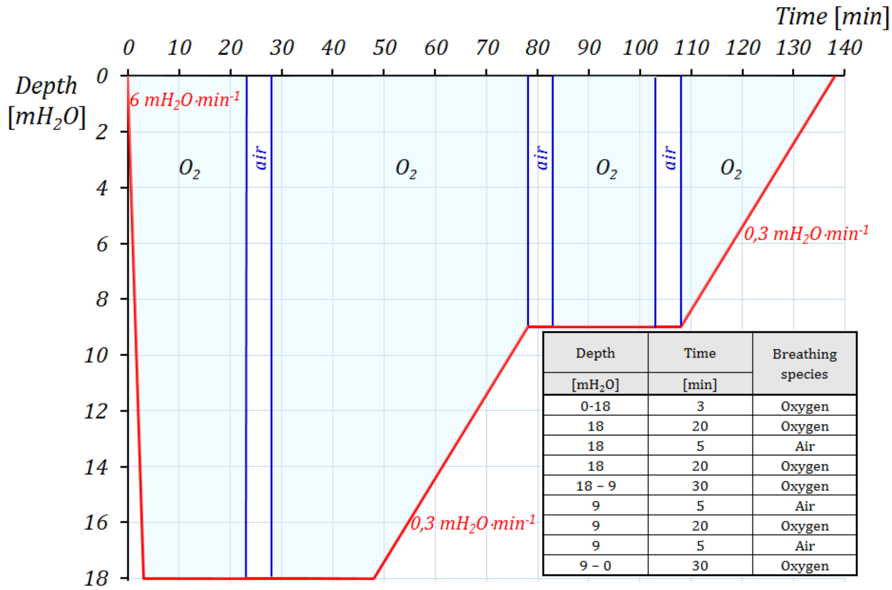
[12] Perfunded.

During saturation dives $Type\ I\ DCS$ can occur after an excursion to the depth less than the plateau of saturation or during decompression on completion of saturation. The symptoms are pain in skeletal muscle areas and joint or joints, especially knee joints. It can be preceded by itching, a rash or skin spots. Most often, at the beginning increased stiffness occurs in a knee joint area hindering movement. Then, within a few hours, the pain steadily grows in joint areas. However, divers should be able to distinguish the pain, which occurs as a result of small injuries or after some physical effort, caused by joint overload or mechanical injuries which occur during work from which the cause may be related to decompression. To this end, it is necessary to thoroughly consider the history of pain formation and its increase. It is little likely that the pain which occurred before the beginning of the decompression was caused by DCS. $Type\ I\ DCS$ formed during an excursion from the plateau of saturation and up to 60 min after the excursion over the depth of the plateau of saturation should be regarded as $type\ II\ DCS$, because $type\ I\ DCS$ symptoms are most often a signal of more serious complications.

Treatment of symptoms of diving sicknesses during saturation differs from that administered after completed decompression following saturation diving and operational diving outside the saturation zone [11]. Usually the treatment methods in saturation can also be applied as the final DCS treatment methods following diving beyond the saturation zone, as in the system developed by $Comex$ [17]. The effectiveness of saturation treatment methods should be the highest than other ones, but they are long-term methods and that is why treatment using treatment tables can be performed more effectively. Hence the $US\ Navy$ system is most common [21].

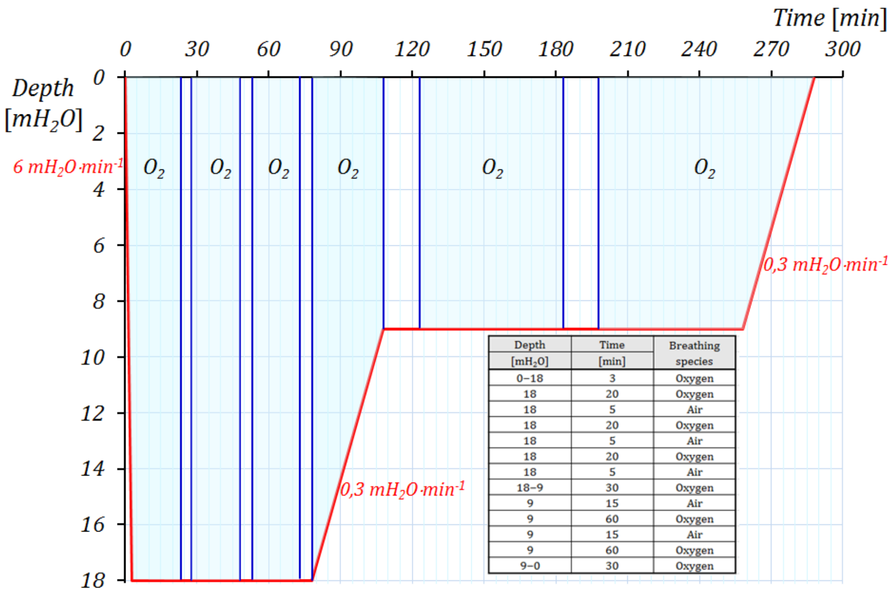
An almost complete historical review of the most important trends in the progress recorded with regard to the decompression sickness treatment can be found in some many places, but it is easy to find it in the Internet, on the webpage address[13]: http://www.wikiwand.com/en/Hyperbaric_treatment_schedules. Here a set of tables will be presented, implemented in the $US\ Navy$ and used by many $NATO$ countries together with other methods, which are interesting from the point of view of the $DiveSmart$ project.

[13] Access June 2017.



Depth [mH_2O]	Time [min]	Breathing species
0-18	3	Oxygen
18	20	Oxygen
18	5	Air
18	20	Oxygen
18 – 9	30	Oxygen
9	5	Air
9	20	Oxygen
9	5	Air
9 – 0	30	Oxygen

Fig. 1. Treatment table *TT* 5 *USN* [1]



Depth [mH_2O]	Time [min]	Breathing species
0–18	3	Oxygen
18	20	Oxygen
18	5	Air
18	20	Oxygen
18	5	Air
18	20	Oxygen
18	5	Air
18–9	30	Oxygen
9	15	Air
9	60	Oxygen
9	15	Air
9	60	Oxygen
9–0	30	Oxygen

Fig. 2. Treatment table *TT* 6 *USN* [1]

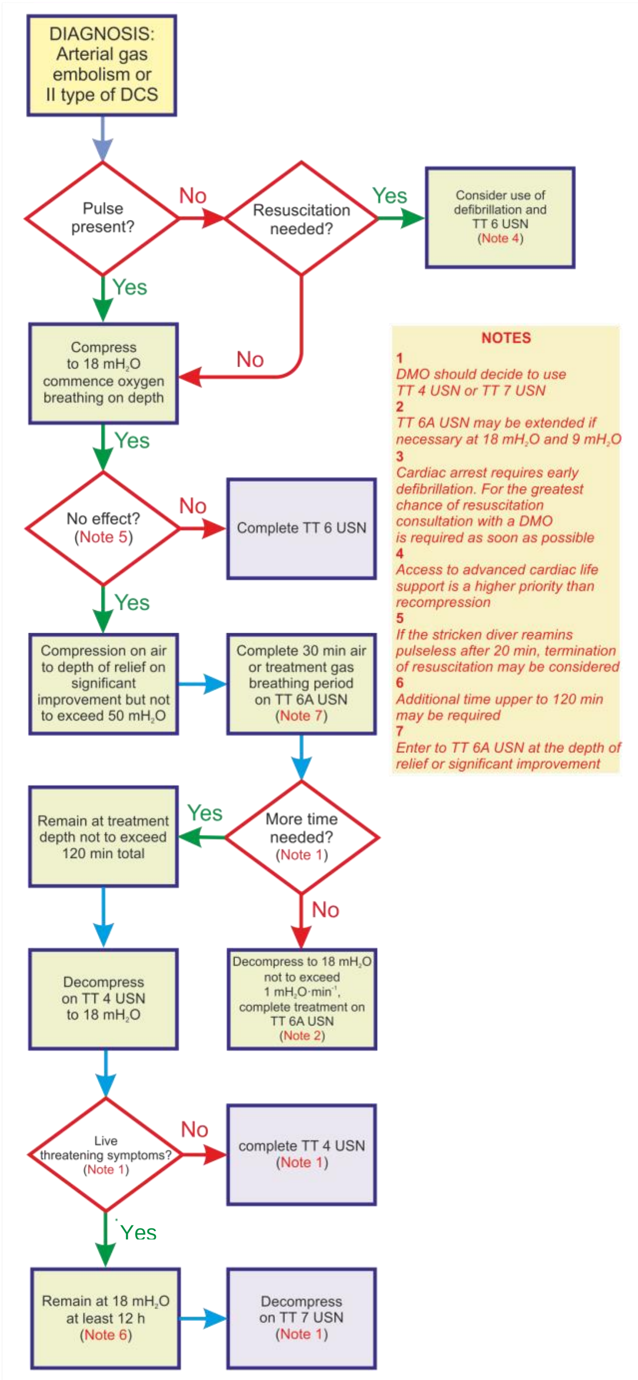
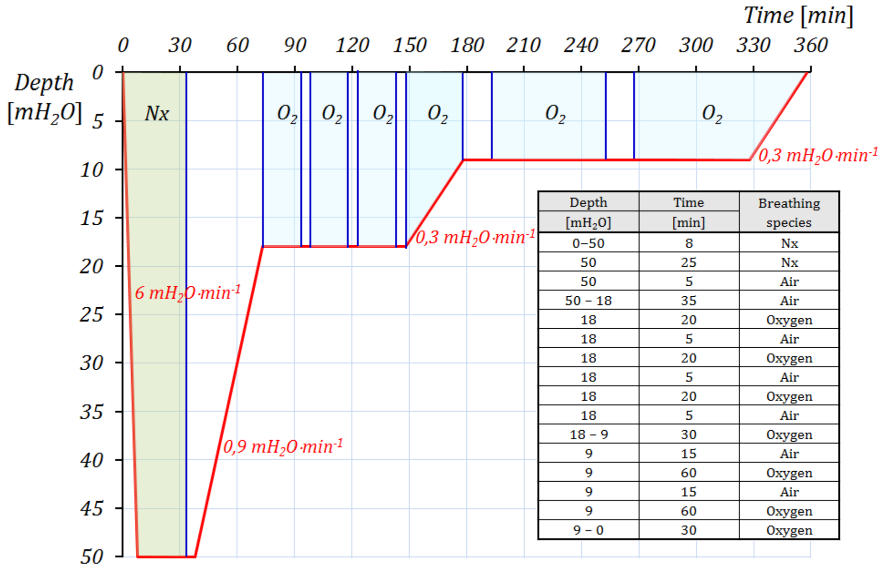
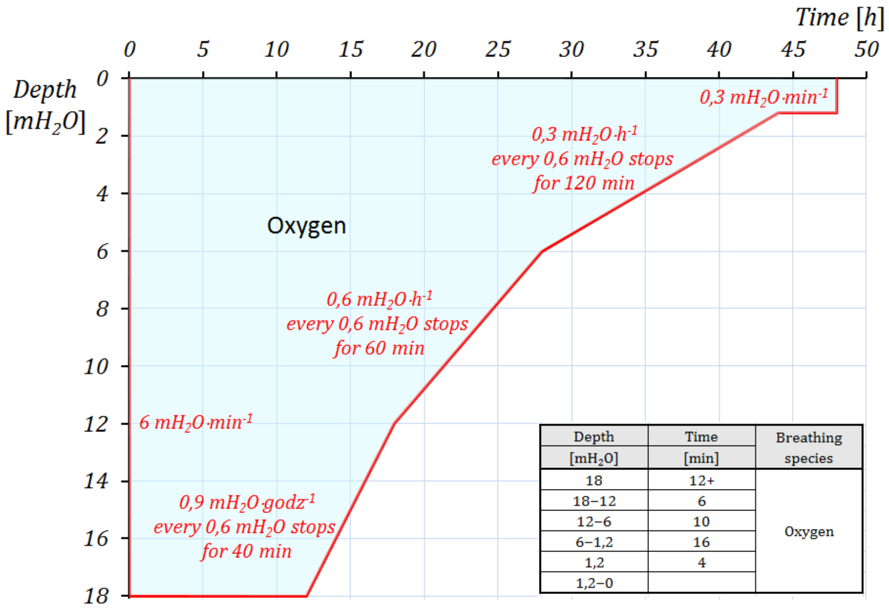


Fig. 3. Algorithm for treatment of gas embolism *Type II DCS* [own study based on 1]



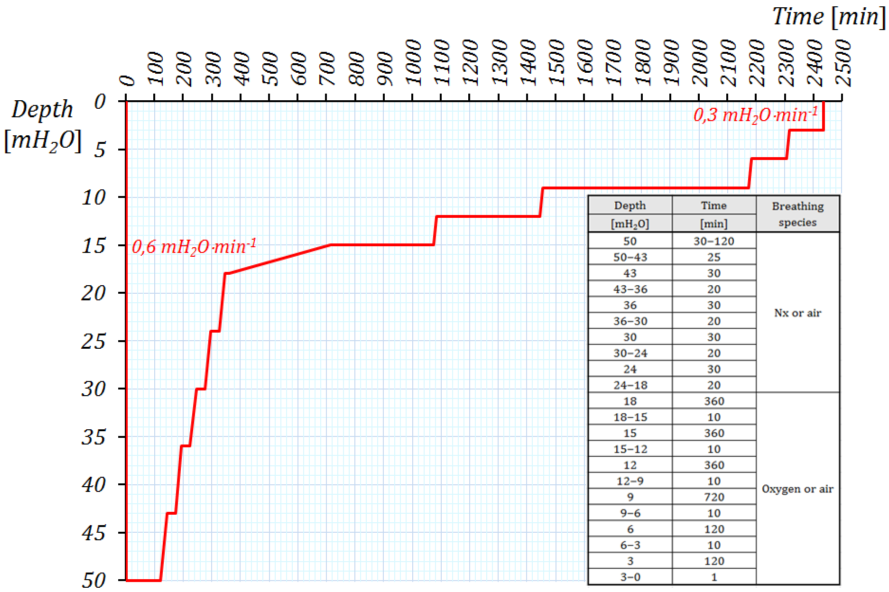
Depth [mH_2O]	Time [min]	Breathing species
0–50	8	Nx
50	25	Nx
50	5	Air
50 – 18	35	Air
18	20	Oxygen
18	5	Air
18	20	Oxygen
18	5	Air
18	20	Oxygen
18	5	Air
18 – 9	30	Oxygen
9	15	Air
9	60	Oxygen
9	15	Air
9	60	Oxygen
9 – 0	30	Oxygen

Fig. 4. Treatment table *TT 6A USN* [1]



Depth [mH_2O]	Time [min]	Breathing species
18	12+	Oxygen
18–12	6	
12–6	10	
6–1,2	16	
1,2	4	
1,2–0		

Fig. 5. Treatment table *TT 7 USN* [1]



Depth [mH₂O]	Time [min]	Breathing species
50	30–120	Nx or air
50–43	25	
43	30	
43–36	20	
36	30	
36–30	20	
30	30	
30–24	20	
24	30	
24–18	20	
18	360	Oxygen or air
18–15	10	
15	360	
15–12	10	
12	360	
12–9	10	
9	720	
9–6	10	
6	120	
6–3	10	
3	120	
3–0	1	

Fig. 6. Treatment table *TT* 4 *USN* [1]

US NAVY TREATMENT TABLES

The set of treatment tables *USN*, implemented the *US Navy*, encompasses procedures using only air[14] or air and *Nx*[15], and procedures using both air/*Nx* and oxygen alternately[16] as treatment breathing agents [21]. Procedures utilizing oxygen are more effective and should be administered first. Procedures utilizing air only should be administered when oxygen is not available[17], in emergency conditions, where the patient does not tolerate oxygen under high pressure[18] and he shows symptoms of oxygen toxicity during the treatment or the occurrence of oxygen toxicity is highly probable[19].

[14] 1*A TT USN*, 2*A TT USN*, and 3 *TT USN*.
[15] *Nx* 7 *TT USN*; nitrogen-oxygen mixture is called *Nitrox* and is marked *Nx*.
[16] 4 *TT USN*, 5 *TT USN*, 6 *TT USN*, 6*A TT USN*, 9 *TT USN*.
[17] E.g. as a result of built-in-breathing system malfunction, exhaustion of stocks, etc.
[18] Develops oxygen toxicity [21].
[19] Considered when the diver was, just before, exposed to high partial pressure of oxygen and in this case occurrence of symptoms indicating central nervous system oxygen toxicity or pulmonary oxygen toxicity is highly probable, e.g. when the dose of oxygen toxicity was clearly exceeded during the dive [10, 13, 14].

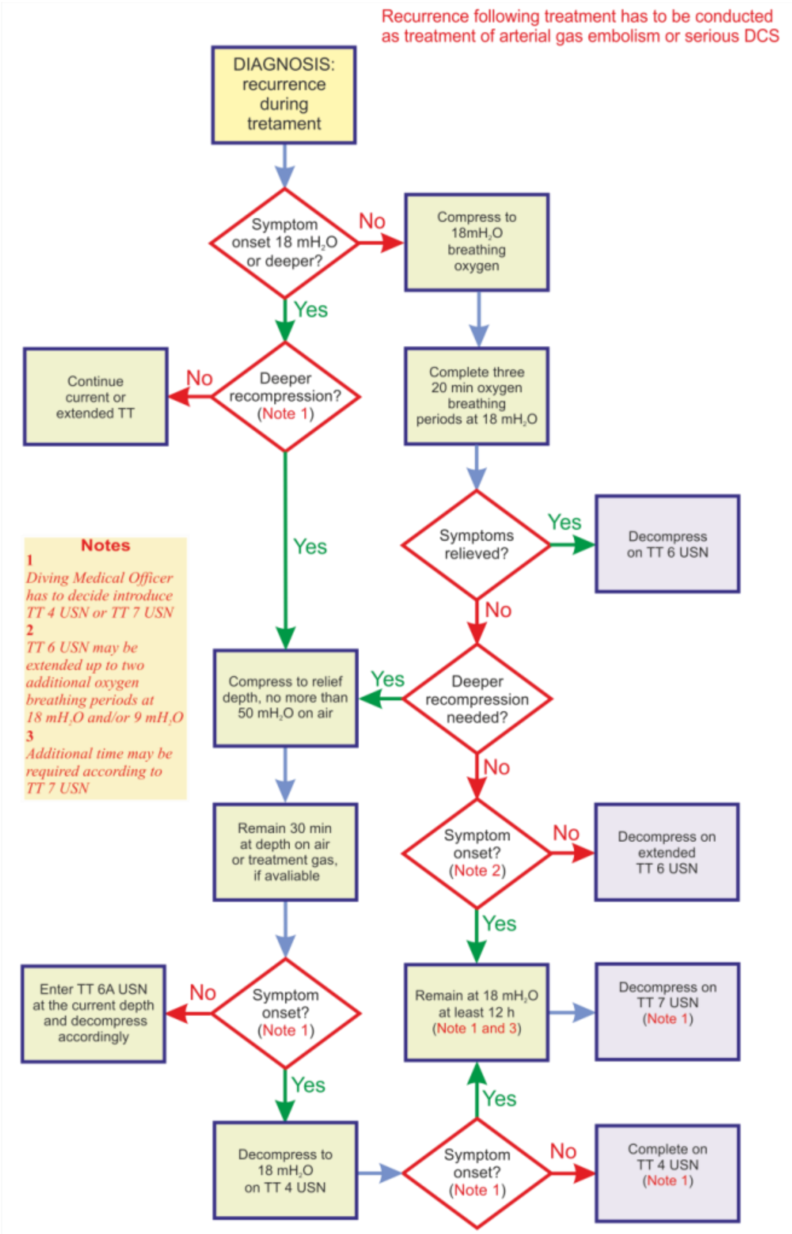
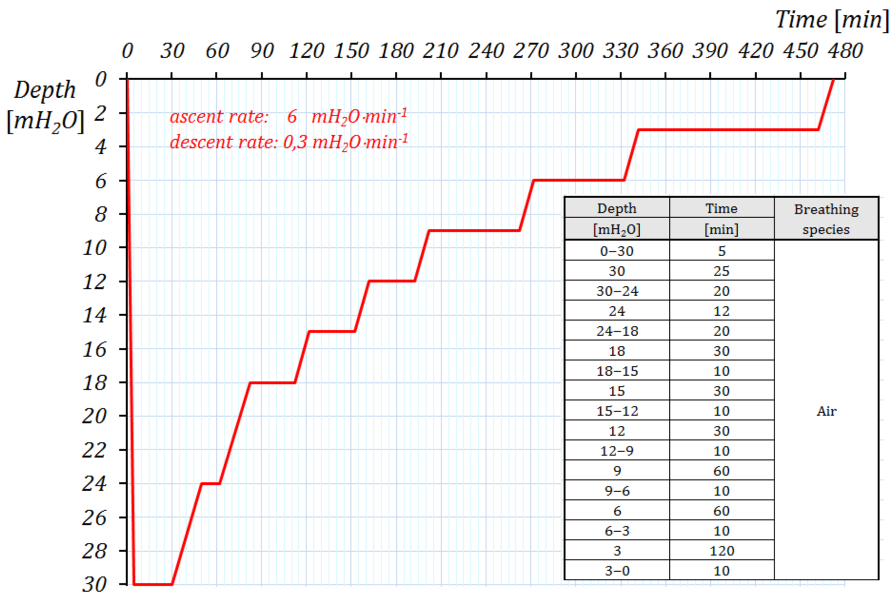


Fig. 7. *DCS* recurrence treatment algorithm [own study based on 1]

To treat *Type I DCS* the *TT 5 USN* is used (fig. 1). If after $\tau = 10\ min$ of stop at the depth $H = 18\ mH_2O$ the sickness symptoms do not disappear, the treatment has to be continued using the *TT 6 USN* (fig. 2). If after $\tau = 10\ min$ of stop at the depth

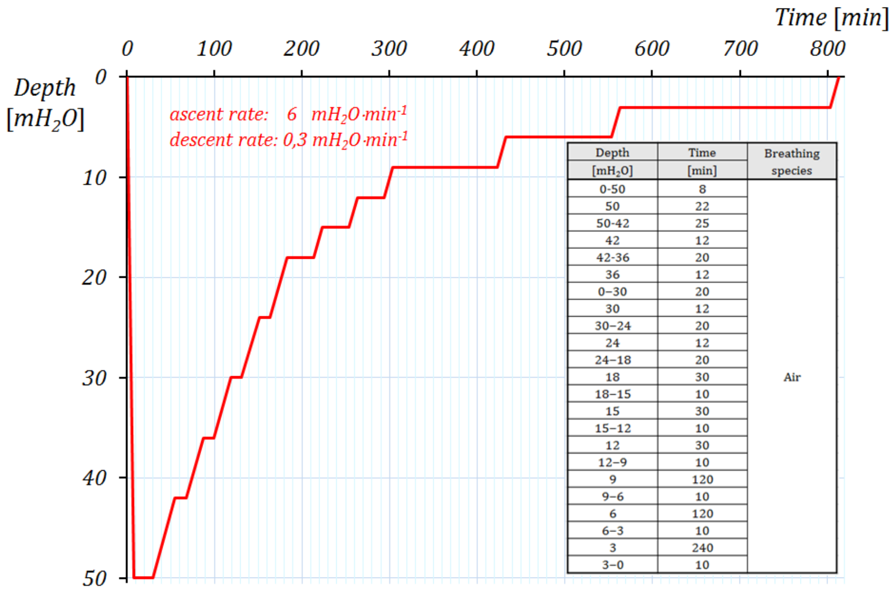
$H = 18\ mH_2O$ the sickness symptoms disappear, the treatment can be discontinued in accordance with the $TT\ 5\ USN$ or it can be prolonged by maximum two cycles $\tau_{O_2} = 20\ min$ cycle of breathing oxygen and $\tau_{air} = 5\ min$ cycle of breathing air at the depth $H = 9\ mH_2O$. Treatment using the $TT\ 6\ USN$ can be prolonged by two $\tau_{O_2} = 20\ min$ cycles of breathing oxygen and $\tau_{air} = 5\ min$ breathing air at the depth $H = 18\ mH_2O$ and two $\tau_{O_2} = 20\ min$ cycles of breathing oxygen and $\tau_{air} = 5\ min$ breating with at the depth of $H = 9\ mH_2O$. More serious cases, such as $Type\ II\ DCS$, are treated following the algorithm presented in figure 3. To treat gas embolism or $Type\ II\ DCS$ treatment tables: $4\ TT\ USN$, $6A\ TT\ USN$, $7\ TT\ USN$ are used. They are shown in figures 4–6, and the procedure in figure 7.

Treatment table $TT\ 1A\ USN$ is used to treat light symptoms of DCS, when the depth of relief does not exceed $20\ mH_2O$ (fig. 8). Tables $TT\ 2A\ USN$, and $TT\ 3\ USN$ are used interchangably to treat more serious cases (fig. 9 and 10). When the depth of relief exceeds $50\ mH_2O$, the $TT\ 4\ USN$ should be used (fig. 6).



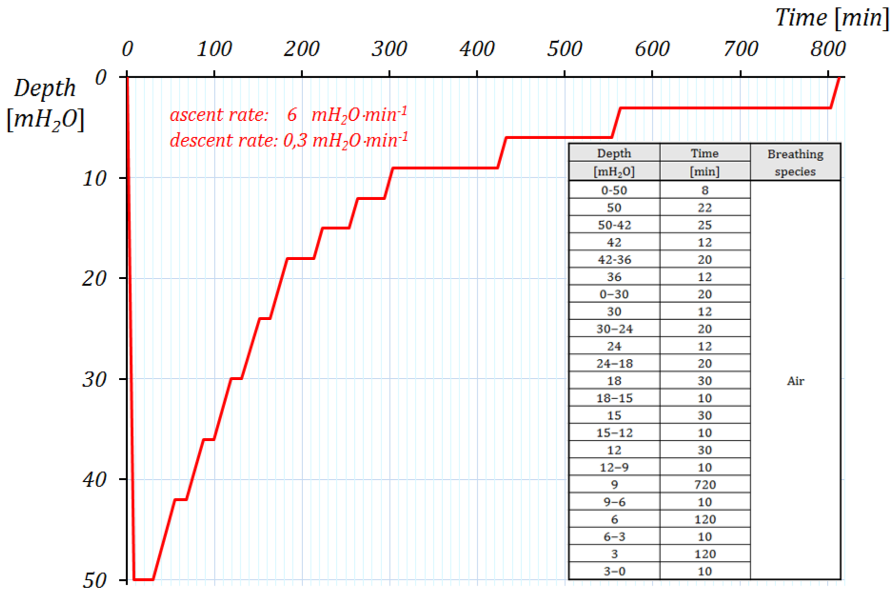
Depth [mH_2O]	Time [min]	Breathing species
0–30	5	Air
30	25	
30–24	20	
24	12	
24–18	20	
18	30	
18–15	10	
15	30	
15–12	10	
12	30	
12–9	10	
9	60	
9–6	10	
6	60	
6–3	10	
3	120	
3–0	10	

Fig. 8. Treatment table $TT\ 1A\ USN$ [1]



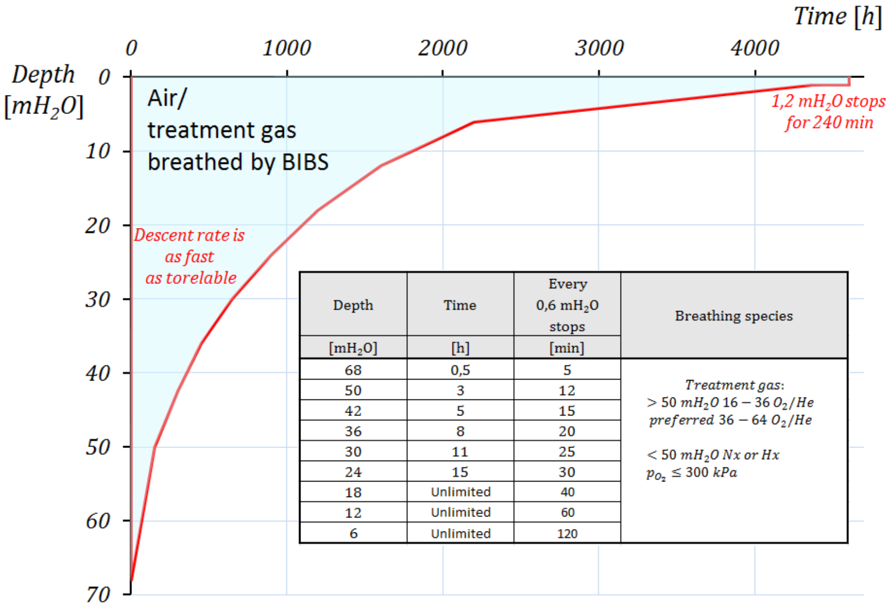
Depth [mH_2O]	Time [min]	Breathing species
0-50	8	Air
50	22	
50-42	25	
42	12	
42-36	20	
36	12	
0–30	20	
30	12	
30–24	20	
24	12	
24–18	20	
18	30	
18–15	10	
15	30	
15–12	10	
12	30	
12–9	10	
9	120	
9–6	10	
6	120	
6–3	10	
3	240	
3–0	10	

Fig. 9. Treatment table *TT 2A USN* [1]



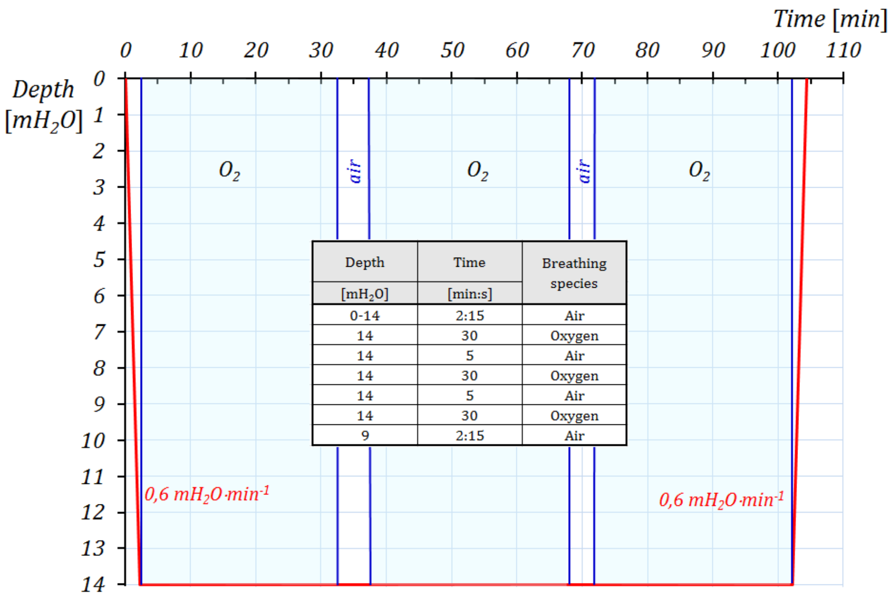
Depth [mH_2O]	Time [min]	Breathing species
0-50	8	Air
50	22	
50-42	25	
42	12	
42-36	20	
36	12	
0–30	20	
30	12	
30–24	20	
24	12	
24–18	20	
18	30	
18–15	10	
15	30	
15–12	10	
12	30	
12–9	10	
9	720	
9–6	10	
6	120	
6–3	10	
3	120	
3–0	10	

Fig. 10. Treatment table *TT 3 USN* [1]



Depth [mH₂O]	Time [h]	Every 0,6 mH₂O stops [min]	Breathing species
68	0,5	5	*Treatment gas:* $> 50\ mH_2O$ $16-36\ O_2/He$ preferred $36-64\ O_2/He$; $< 50\ mH_2O$ Nx or Hx; $p_{O_2} \leq 300\ kPa$
50	3	12	
42	5	15	
36	8	20	
30	11	25	
24	15	30	
18	Unlimited	40	
12	Unlimited	60	
6	Unlimited	120	

Fig. 11. Treatment table *TT* 8 *USN* /*RN* 65 [1]



Depth [mH₂O]	Time [min:s]	Breathing species
0-14	2:15	Air
14	30	Oxygen
14	5	Air
14	30	Oxygen
14	5	Air
14	30	Oxygen
9	2:15	Air

Fig. 12. Treatment table *TT* 9 *USN* [1]

The supplement to the DCS treatment system are two $US\ Navy$ tables: $TT\ 8\ USN$ and $TT\ 9\ USN$. The $TT\ 8\ USN$ is an adaptation of the $TT\ 65\ RN$ used in the DCS treatment system by the $Royal\ Navy$ and can be used when decompression stations have been omitted or the diver is thrown to the surface in an uncontrollable way. The $TT\ 8\ USN$ starts with compressing the diver to the depth of relief, but not higher than 68 mH_2O (fig. 11). The $TT\ 9\ USN$ is used to treat mild DCS symptoms following the previous treatment (fig. 12). It is also used to treat cases of carbon monoxide poisoning or poisoning by exhaust fumes.

RUSIAN AIR TREATMENT TABLES

An interesting supplement system to the methods for air DCS treatment used by the $US\ Navy$ are treatment tables air/Tx[20] proposed by *Военно Морский Флот России* which provide a capability of reaching the pressure of relief up to the depth of 100 mH_2O [24] (tab. 3).

Russian treatment tables $TT\ I$ ВМФ $-$ $TT\ III$ ВМФ are tables which use only air/O_2 as the treatment agent. The $TT\ I$ ВМФ is dedicated to treating light symptoms of decompression sickness $Type\ I\ DCS$ which disappear below the depth of 30 mH_2O during compression. The $TT\ II$ ВМФ is dedicated to treating light symptoms of decompression sickness $Type\ I\ DCS$, where the depth of relief occurs below the depth of 50 mH_2O during compression. The $TT\ III$ ВМФ is dedicated to treating mean symptoms of decompression sickness $Type\ I\ DCS$.

Treatment tables $TT\ IV$ ВМФ $-$ $TT\ V$ ВМФ are tables using Tx as the treatment agent, because from the depth of 70 mH_2O pure helium or Hx[21], having the content of helium within Hx: $[18;\ 20]\%_v O_2/He$, are used for compression. The $TT\ IV$ ВМФ is used to treat severe forms of decompression sickness $Type\ I\ DCS$ and the $TT\ V$ ВМФ to treat neurological $Type\ II\ DCS$ symptoms.

[20] Nitrogen-helium-oxygen mixture called *Trimix*.
[21] Helium-oxygen mixture called *Heliox*.

Tab. 3A. Russian air/oxygen treatment tables [24]

Recompression regime	Decompression regime	Maximum depth $[mH_2O]$	Max time at max depth $[min]$	Time to 1st stop $[min]$	1st stop depth $[mH_2O]$	Time at 1st stop $[min]$	Time to 2nd stop $[min]$	30	28	26	24	22	20	18	16	14	12
								Next decompression stops $[mH_2O]$ / Time at next decompression stops $[min]$									
I	А	50	60	20	30	30	20										
	Б		120				14								107	202	245
	В		180				10						101	166	182	202	245
	Г		360			73	2		106	112	121	130	152	166	182	202	245
II	А	70	60	20	50	30	32							65	182	203	245
	Б		90				28					39	164	179	196	218	262
	В		120				24			75	131	140	164	179	196	218	262
III	А	100	15	30	70	60	46				113	152	164	178	196	218	262
	Б					90	42		63	132	140	152	164	178	196	218	262
	В					120	40	113	123	132	141	152	164	178	196	218	262

Tab. 3A cont. Russian air/oxygen treatment tables [24]

Recompression regime	Decompression regime	10	8	6	4	2	air	O_2	Totality
		Next decompression stops $[mH_2O]$ / Time at next decompression stops on air (в) or O_2 $[min]$					Total time $[min]$		$[h:min]$
I	А	30+140в	30в+60	90в+60	180в+60	60в+60	570	270	14:00
		247в	305в	368в	235в	235в	1460	–	24:20
	Б	280в	60+35в	105в+60	210в+60	70в+60	1318	240	25:58
			328в	396в	253в	253в	2128	–	35:28
	В	280в	60+35в	105в+60	210в+60	70в+60	1656	240	31:36
			328в	396в	253в	253в	2466	–	40:16
	Г	280в	328в	396в	253в	253в	3021	–	50:21
II	А	30+150в	35в+60	105в+60	210в+60	70в+60	1347	270	26:57
		280в	328в	296в	253в	253в	2287	–	38:07
	Б	300в	60+40в	110в+60	225в+60	75в+60	1886	240	35:26
			351в	425в	271в	271в	2754	–	45:54
	В	300в	351в	60+110в	225в+60	75в+60	2500	180	44:40
				425в	271в	271в	3057	–	50:57
III	А	300в	351в	60+115в	230в+60	75в+60	2490	180	44:30
				425в	271в	271в	3037	–	50:37
	Б	300в	351в	425в	60+230в	75в+60	3048	120	52:48
					271в	271в	3285	–	54:45
	В	300в	351в	425в	271в	271в	3487	–	58:07

Tab. 3B. Russian air/Tx treatment table recompression regime IV [24]

Recompression regime	Decompression regime	Maximum depth [mH_2O]	Max time at max depth [min]	Time to 1st stop [min]	Next decompression stops [mH_2O] – Time at next decompression stops when breathing with the Tx 7% O_2 [min]: 88	86	84	82	80	78	76	74	72
IV	А	100	60	6				2	7	11	11	11	12
	Б		180	8			5	20	20	25	35	35	45
	В		360	24	90	90	100	90	100	100	110	100	110

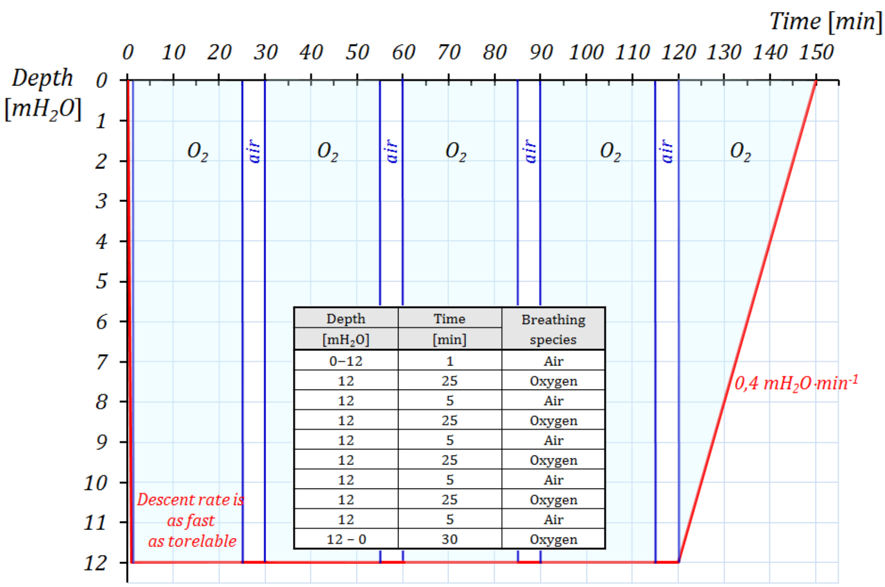
Decompression regime	Next decompression stops [mH_2O] – Time at next decompression stops when breathing with the Tx 10% O_2 [min]: 70	68	66	64	62	60	58	56	54	52	50	48	46	44	42	40	38	36	34	Time at next decompression stops when breathing with the air [min]: 32	30	28	26	24	22	20
А	8	13	18	18	19	20	29	33	35	46	54	66	79	108	136	136	144	152	159	91	94	98	102	108	117	130
Б	40	40	50	55	65	75	90	95	100	110	115	125	130	140	145	150	155	160	170	95	95	100	105	110	120	135
В	80	80	80	80	90	90	90	100	100	110	120	125	130	140	145	150	160	160	170	180	190	200	220	230	250	120

Decompression regime	Next decompression stops [mH_2O] – Time at next decompression stops when breathing with the air [min]: 18	16	14	12	10	8	6	4	2	Total time: Tx 7% O_2	Tx 10% O_2	air	Totality: [h]	[min]
А	146	162	181	202	227	255	290	334	394	60	1273	2931	71	64
Б	150	170	190	210	240	270	310	360	430	193	2010	3090	88	13
В	140	160	170	210	250	300	370	470	610	914	3470	2800	119	44

COMEX TREATMENT TABLES

Treatment tables of the French firm *COMEX* constitute the base for treating the most severe *DCS* forms which can occur during both saturated diving and outside the saturation zone, to the maximum operational depth of 450 mH_2O [17]. Light cases are treated out of saturation zone but more severe ones require facilities for providing saturation.

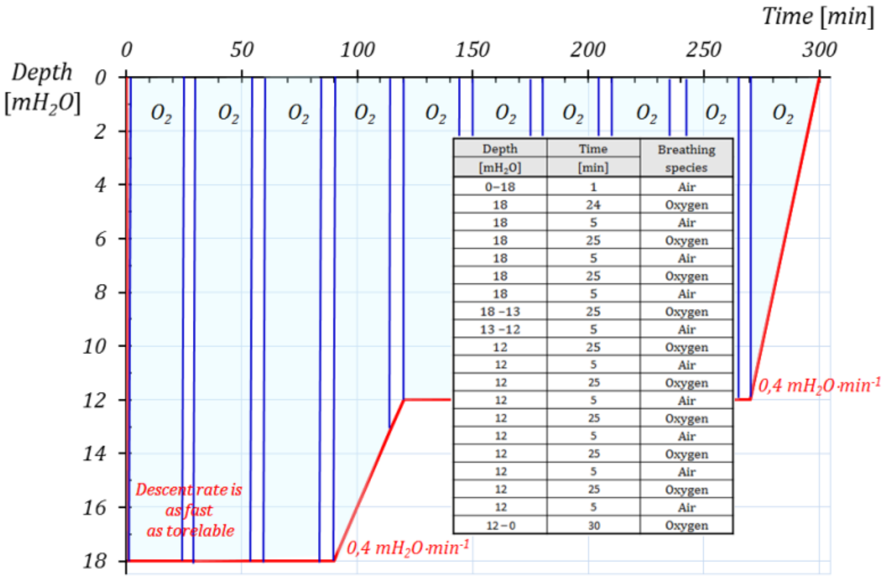
Treatment tables: $TT\ 12_{86}\ Cx$, $TT\ 18_{86}\ Cx$ and $TT\ 30_{86}\ Cx$ are similar to the *US Navy* oxygen treatment tables [21]. The $TT\ 12_{86}\ Cx$ is used to treat light *DCS* symptoms and the $TT\ 18_{86}\ Cx$ to treat more severe *Type I DCS* (fig. 13 and 14). The $TT\ 30_{86}\ Cx$ is used to treat neurological symptoms *Type II DCS* (fig. 15). These tables assume pharmacological support through administering acetylsalicylic acid[22] and in the case of the $TT\ 30_{86}\ Cx$ also an anti-inflammatory medication, hormone medicine having inflammatory properties, and isotonic infusion liquids[23].



Depth [mH₂O]	Time [min]	Breathing species
0–12	1	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12 – 0	30	Oxygen

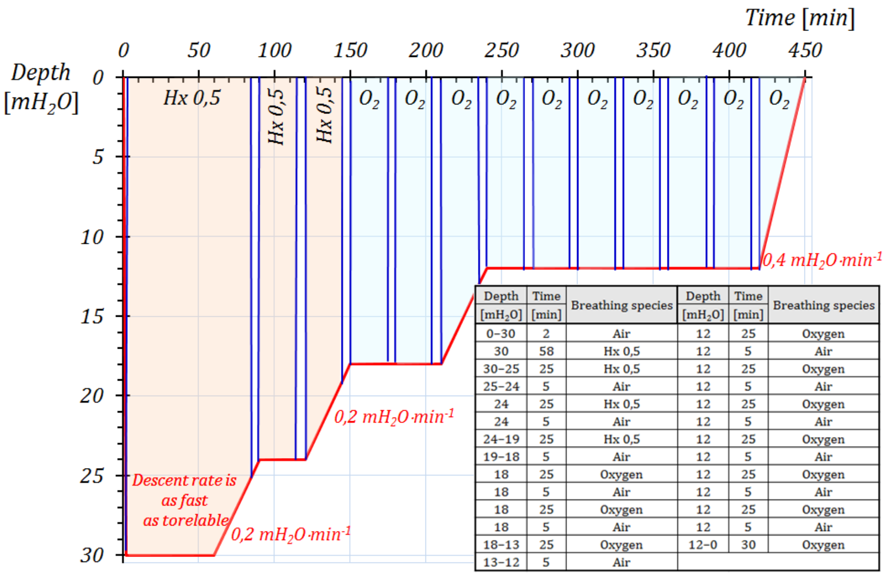
Fig. 13. Treatment table $TT\ 12_{86}\ Cx$ [17]

[22] *Aspirin* (Germany), *Aspegic* (France), *Polopiryna* (Poland) etc.
[23] Ringer's solution or balanced salt solution (physiological pH and isotonic salt concentration).



Depth [mH2O]	Time [min]	Breathing species
0–18	1	Air
18	24	Oxygen
18	5	Air
18	25	Oxygen
18	5	Air
18	25	Oxygen
18	5	Air
18 –13	25	Oxygen
13 –12	5	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12	25	Oxygen
12	5	Air
12 – 0	30	Oxygen

Fig. 14. Treatment table $TT\ 18_{86}\ Cx$ [17]



Depth [mH2O]	Time [min]	Breathing species	Depth [mH2O]	Time [min]	Breathing species
0–30	2	Air	12	25	Oxygen
30	58	Hx 0,5	12	5	Air
30–25	25	Hx 0,5	12	25	Oxygen
25–24	5	Air	12	5	Air
24	25	Hx 0,5	12	25	Oxygen
24	5	Air	12	5	Air
24–19	25	Hx 0,5	12	25	Oxygen
19–18	5	Air	12	5	Air
18	25	Oxygen	12	25	Oxygen
18	5	Air	12	5	Air
18	25	Oxygen	12	25	Oxygen
18	5	Air	12	5	Air
18–13	25	Oxygen	12–0	30	Oxygen
13–12	5	Air			

Fig. 15. Treatment table $TT\ 30_{86}\ Cx$ [17]

Treatment tables: $TT\ 12_{86}\ Cx$, and $TT\ 18_{86}\ Cx$ constitute a treatment recompression system for symptoms $Type\ I\ DCS$ occurring after air or Hx diving. If after

$\tau = 15\ min$ from compression to $12\ mH_2O\ DCS$ symptoms disapper the treatment is based on the $TT\ 12_{86}\ Cx$. If this is not the case, treatment continuation is based on the $TT\ 18_{86}\ Cx$. Symptoms $Type\ II\ DCS$ are treated following the $TT\ 30_{86}\ Cx$.

When decompression stations have been omitted or the diver has been blow up to the surface during an air dive outside the saturation zone, for $Type\ I\ DCS$ the $TT\ 18_{86}\ Cx$ is used and for $Type\ II\ DCS$ symptoms treatment is based on the $TT\ 30_{86}\ Cx$. If there exists a need for extending the treatment time in accordance with the $TT\ 30_{86}\ Cx$, the time of stop at the depth $H = 30\ mH_2O$ can be prolonged to maximum $\tau = 3\ h$.

When DCS occurs during air saturation or Hx saturation dives, or operational Hx diving outside the saturation zone, for $Type\ I\ DCS$ symptoms the $TT\ B_{86}\ Cx$ is used, if the symptoms disappear within $15\ min$ with standard decompression, if not, the $TT\ SB_{86}\ Cx$ is used with standard decompression also (tab. 4). When the condition of the diver worsens, special saturation table $TT\ N_{86}\ Cx$ should be used (tab. 5).

Tab. 4. Treatment tables $TT\ B_{86}\ Cx$ i $TT\ SB_{86}\ Cx$ [17]

$TT\ B_{86}\ Cx$			$TT\ SB_{86}\ Cx$				
Depth of treatment $[mH_2O]$	Hx bounce dive and saturation	Air saturation	Depth of accident $[mH_2O]$	Depth of treatment $[mH_2O]$	BIBS breathing duration $[min]$	Hx bounce dive and saturation	Air saturation
0−12	Oxygen	Oxygen	0−12	+6	120	Oxygen	Oxygen
19−40	Hx 0,50	Nx 0,50	13−31	+9	120	Hx 0,50	Nx 0,50
41−110	Hx 0,20		32−98	+12	120	Hx 0,20	
111−210	Hx 0,10		99−195	+15	120	Hx 0,10	
211−360	Hx 0,05		196−345	+15	120	Hx 0,05	
361−450	Hx 0,03		346−450	+15	120	Hx 0,03	

Tab. 5. Treatment table $TT\ N_{86}\ Cx$ [17]

$TT\ N_{86}\ Cx$			
Depth of accident $[mH_2O]$	BIBS breathing duration $[min]$	Hx bounce dive and saturation	Air saturation
20−40	120	Hx 0,50	Nx 0,50
41−110	180	Hx 0,20	
111−210	240	Hx 0,10	
211−360	300	Hx 0,05	
361−450	360	Hx 0,03	

Saturation table $TT\ N_{86}\ Cx$ is also used to treat $Type\ II\ DCS$ symptoms following air or Hx saturation, or operational dives Hx outside the saturation zone. When using saturation table $TT\ N_{86}\ Cx$ for treating cases of DCS developed during or after Hx dives, both saturated and outside the saturation zone, decompression is conducted on the continuous basis, with the time passage through the individual depth $t = 60\ min \cdot mH_2O^{-1}$ within the depth range $H \in [15; 200]\ mH_2O$, keeping the oxygen partial pressure at the level $p_{O_2} \in [60; 63]\ kPa$ in Hx making the atmosphere of complex. Decompression from the depth $H = 15\ mH_2O$ to the surface is conducted with the time passage through the individual depth $t = 80\ min \cdot mH_2O^{-1}$, keeping the oxygen volume content at the level $C_{O_2} \in [23; 24]\%_v$ in Hx making the atmosphere of complex. When treating DCS cases developed during or after saturation dives based on nitrox Nx, for the depth range $H \in [15; 30]\ mH_2O$ decompression is conducted on the continuous basis with the time passage through the individual depth $t = 120\ min \cdot mH_2O^{-1}$, keeping the oxygen partial pressure in Nx making the atmosphere of complex at the level $p_{O_2} \in [60; 63]\ kPa$. From the depth $H = 15\ mH_2O$ to the surface decompression is conducted with the passage time through the individual depth $t = 180\ min \cdot mH_2O^{-1}$, keeping the oxygen volume content in Nx making the atmosphere of complex at the level $C_{O_2} \in [23; 24]\%_v$.

As there are no special procedures for cases when DCS symptoms appear during decompression in water, as is the case in other systems[24], when they appear, the decompression is discontinued. The diver is brought to the surface as quickly as possible and further treatment is administered as in the case when a diver is blow up to the surface.

DISCUSSION

The commonly used worldwide dive decompression tables usually allow for only a low workload of the diver underwater[25]. This is caused by the existence, in hyperbaric conditions, of an additional workload of the respiratory system and action of the water environment itself. For example, divers use suits in which work requires additional effort, or because they cannot breathe water divers have to carry substantial amount of breathing agent, which requires additional effort concerned

[24] For example [21].

[25] Almost without doing any extra work except diving.

with carrying it, etc. Only some of the decompression tables take into account additional effort dedicated to useful work under water determining its maximum border as a mean load. This limitation is associated not only with performing work concerned with staying in the water environment itself but also with the necessity to later undergo decompression. The decompression process will be disturbed by metabolism products, which occur after the high effort is undertaken. For example, acidification of muscles with lactic acid caused by anaerobic changes leads to acidification of blood and because of this hemoglobin loses its capacities of carrying oxygen [13]. This hampers gas exchange and as a result it disturbs the process of decompression. The precise consideration of the effect workload on the panned decompression is very difficult. Only saturation dives give divers the possibility to make relatively big efforts as their decompression process is separated from the work period by suitably long rest period dedicated to stabilization.

As it was mentioned in the previous articles of the series dedicated to the issues of rescuing survivors who have been stuck in air traps in a wreck of a sunken surface vessel, mobilization of search and rescue assets fast enough to prevent the casualties from the Nx saturation[26] is not possible. Work in the wreck will be connected with necessary mechanical separation actions[27] or other requiring much physical effort. There exists a high probability for a diver to get stuck inside the wreck during the penetration. In a rescue operation support, divers, who work outside the saturation zone, due to bad decompression, face a hazard of e.g. blow up to the surface without decompression or emergency omitting some elements of decompression. The issues concerned with adopting appropriate treatment procedures with regard to divers taking part in a rescue operation is an important element of the preparation for conduct of underwater rescue. Hence the above analyses of the possible to apply treatment tables systems have been focused on these issues. The issues relating to decompression of casualties who were exposed to Nx saturation inside the wreck of a sunken vessel will be presented further in the series of the articles.

It follows from the carried out analysis that it is relatively easy to select the treatment recompression system for DCS cases, which occurred in the course of short-term operational dives[28] outside the sub-saturation or full saturation zone. Out of many existing systems the most common is the system developed and published by the $US\ Navy$ [21]. It can be used to support the DCS treatment process in divers,

[26] Even if mobilization is carried out relatively quickly , actions conducted by SAR will not enable fast commencement of underwater rescue [6].

[27] Counter fencing, removing separation barriers.

[28] Except for severe cases when the diver was thrown to the surface.

providing support to saturation divers in the course of wreck penetration. Such divers can be employed to provide assistance in straightening and winding umbilicals[29] of the saturation diver and underwater vehicles, deliver tools, render assistance in transporting casualties and in other support actions carried out outside the sub--saturation and full saturation zone. These methods can also be used to treat light DCS occurred after saturation diving with Nx. The $US\ Navy$ system does not allow exceeding $70\ mH_2O$ to produce the relief effect in a patient. Such situations occur rarely and theoretically, and in the case of the considered operational scenario, assuming the maximum operational depth of $30\ mH_2O$ they probably not occur. Extending the $US\ Navy$ system by air tables system ВМФ offers additional treatment capabilities, enabling covering the cases of DCS which can potentially occur during $DiveSMART$ operations. However, the treatment is conducted in difficult conditions, hard to accept without any doubt. Complications will appear when respiratory failure occurs in in the casualty, e.g. as a result of pulmonary barotrauma[30], which occurs when the diver is blow up to the surface. In such a case effective breathing Tx, Nx or oxygen under high pressure can cause airway resistance in the patient so high that it not only will hamper the treatment process but it also may prevent him from breathing and induce asphyxia[31]. When this is the case, using Hx may turn out necessary. It should be borne in mind, however, that transfer from the heavy breathing agent to a lighter one often causes occurrence of DCS symptoms through counterdiffusion, even if this is not accompanied by change in pressure [3–5, 8]. It seems that in the case of the $DiveSMART$ project the use of all the three presented systems should be given a serious consideration. A comparative analysis of the proposed tables, based on one selected approach to estimation of DCS hazard, is worth conducting.

Treatment of $Type\ I\ DCS$ and $Type\ II\ DCS$ cases is based, first of all, on hyperbaric method. The first treatment parameter is pressure causing compression of gas in free phase precipitated in tissues allowing it to dissolve in fluids existing in tissues. This causes a decrease in mechanical impact of gas on tissues, unblocking blood flow through capillaries, cessation of response reaction of the immunity system identifying gas bubbles as aggressors.

The second parameter is time needed for homeostasis, resorption of gas in tissues and bodily fluids, and transport of dissolved gas excess to the blood. Then eliminating the gas excess from the body during the decompression by the blood prefunding the bodily tissues and lung tissue (fig. 16).

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[29] Umbilicals.

[30] Pulmonary barotrauma.

[31] Insufficient amount of oxygen in the body leading to loss of consciousness.

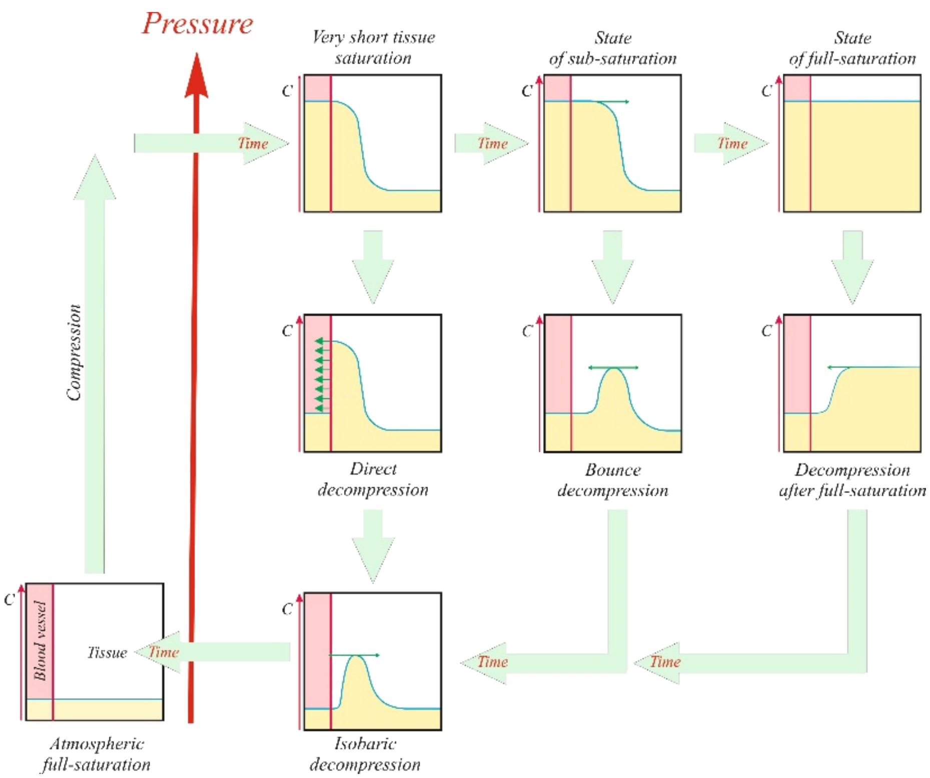

Fig. 16. Main overview for overload of inert gas in body tissues in the hyperbaric environment and its elimination during the decompression process [own study]

The factor intensifying the treatment process is the use of oxygen or mixtures enriched with oxygen. Oxygen is rapidly metabolized in the body tissues leaving a free space to transport inert gas by the blood. Sometimes, other drugs are needed in emergency cases and for the treatment intensification. The therapeutic recompression process can be supported pharmacologically by blood thinning, maximizing hydration, administering pain killers, anti-coagulants[32] and anti-inflammatory medication.

Described here, the systems of treating *DCS* with therapeutic recompression constitute a vivid example of uses of these briefly presented parameters. But free use of pressure, time and composition of breathing agent is often made difficult because of the phenomenon of oxygen toxicity, counterdiffusion, respiratory failure, etc.

[32] Anticoagulants are medicines that reduce the ability of the blood to clot.

Modelling counterdiffusion has, so far, not resulted in developing a comprehensive theory taking counterdiffusion into account during the decompression process, despite the fact that counterdiffusion cases often occur in diving [7, 23]. The occurrence of DCS cases accompanied by counterdiffusion can be divided into two forms: $SICD$[33] and $DTICD$[34]. The $SICD$ symptoms occur when the diver is breathing a gas different than gas surrounding the body [15]. For example, in the $Polish\ Navy$ the deep diving technology is used with Tx as a breathing agent during work performed under water, and the drysuit is inflated with air. During decompression the diver changes the breathing agent into air during the transfer under pressure and then into oxygen decompression. In all divers light skin DCS symptoms occur, e.g. general skin itching. The $DTICD$ symptoms accompany sequential changes in the breathing agent, usually during decompression. The sequential changes in the breathing agent from lighter to heavier mixture and from heavier to lighter mixture can cause DCS, even if they are not accompanied by changes in depth — ICD[35]. A combination of counterdiffusion phenomena through cell membranes and dissolution of gases in tissues can lead to exceeding the dissolution border and the precipitation of gas in free phase in tissues, causing DCS, due to the differences in diffusion and solubility coefficients especially of helium and nitrogen [9].

A possible counterdiffusion occurrence has to be taken into account when the $US\ Navy$ method is used for treatment after an accident during deep diving or saturation diving. When the treatment methods recommended by the French firm $COMEX$ are used the probability of counterdiffusion occurrence can be minimized by choosing for treatment the breathing agent on which DCS symptoms occurred.

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[34] ***D**eep **T**issue **I**sobaric **C**ounter**d**iffusion.*

[35] ***I**sobaric **C**ounter**d**iffusion.*

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METODY LECZENIA CHOROBY DEKOMPRESYJNEJ ZAISTNIAŁEJ PODCZAS PENETRACJI WRAKU

STRESZCZENIE

Artykuł należy do serii dotyczącej projektu *DiveSMART*, który jest związany z zapewnieniem lepszej koordynacji międzynarodowej akcji ratownictwa podwodnego w rejonie Morza Bałtyckiego. Projekt ten otrzymał status „projektu flagowego”.

Artykuł jest trzecim z cyklu artykułów opisujących zadania realizowane przez Akademię Marynarki Wojennej w ramach projektu *DiveSMART Baltic*. Zawiera opis scenariuszy leczenia potencjalnych przypadków choroby dekompresyjnej zaistniałej u nurków podczas akcji ratowniczej lub po dekompresji. Tematyka ta dotyczy realizacji zadania czwartego *‘Medical treatment’ of the DiveSMART Balitc project: Identifies methods for different medical treatments in operational areas*.

Słowa kluczowe:
SAR, poszukiwania i ratownictwo podwodne.

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