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DESIGNING DIVING TECHNOLOGY. PART I DECOMPRESSION REQUIREMENTS

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ABSTRACT

This article is a further one in an unintended series concerning the design of diving technology [1,2,3]. It contains answers to questions raised by readers upon reading previous articles and by users of the systems described therein by way of example. The articles also refer to the discussion held at the annual NATO Working Group meeting on the various types of decompression presented by the Polish side [4,5,6,7]. The previous articles were linked to the acceptance of the results of the project No. DOB-BIO8/O9/O1/2016 carried out under the contract with the NCBiR National Centre for Research and Development entitled "Decompression schedules for MCM/EOD II diving" carried out in 2016-2021. The current article is linked to the new project No. DOB-BIO-12-03-001-2022 implemented under the contract with the NCBiR entitled: "The effects of combat effort and air transport on the safety of combat divers in the execution of underwater combat operations," scheduled for 2023-2025.

Keywords: Underwater work technology, Decompression, Taxonomy.

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INTRODUCTION

The most common method of estimating safe decompression is based on a homology between breathing space ventilation and decompression models. Classical decompression and ventilation processes are modelled using exponential functions and can therefore be combined into a model depicting ergonomic human-machine synergy [8]. Validation of such a model is performed in the process of assessing the risk of decompression sickness DCS and central oxygen toxicity CNSyn based on the results of experimental dives [4,7,9].

Under Polish conditions, it is not possible to adopt a classical approach to experimental research involving humans, due to the current lack of sponsorship opportunities for long-term research programmes/projects addressing this issue. Thus, inference at the level of combined models for ventilation, decompression and oxygen toxicity can only be carried out with a limited level of confidence and model implementation is carried out in ways that are relatively arbitrary.

PROCESS

A process is a series of activities taking place over time, oriented towards achieving a specific goal. The conditions affecting the process are the internal and the external context.

A process can only take place within a system that provides it with the homeostasis that permits its execution with an approved level of the risk *R* of failure.

SYSTEM

A system is a defined, rationally minimal set of elements together with synergistic connections between them, which guarantees the possibility of carrying out the processes defined in it.

Unlike natural systems, where the purposes of the processes running in it are not always known, a man-made system, at least in its design, should have a rational basis.

The elements of the system, together with the relations, form the structure of the system, in which the following can be distinguished: order, arrangement, series or relations, etc., constituting the basis enabling the processes defined in it to take place.

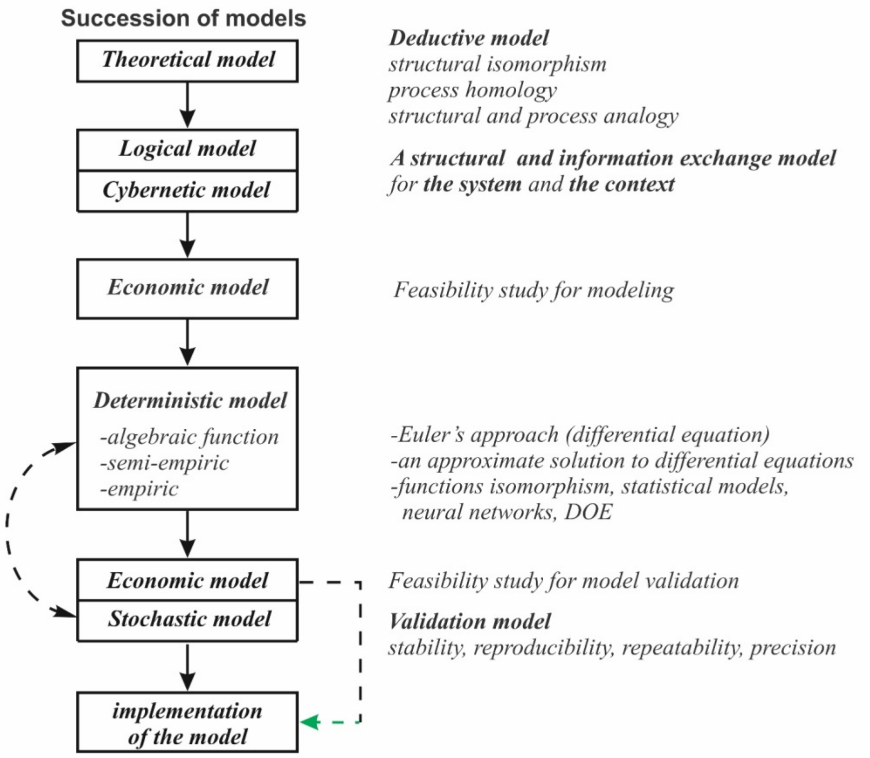

Fig. 1 The most common modeling cycle.

Rys. 1 Najczęściej spotykany cykl modelowania.

MODEL

A model is a maximally simplified version of a real system capable of sustaining the process of interest with the required precision and accuracy.

Theoretical models are often built on the basis of structural isomorphism[1] of known systems, homology[2] to a known process and analogy[3] to known processes occurring in known systems — Fig. 1.

At the initial stage of model building, the use of cybernetic models,[4] is common, reflecting the basic structure of the system sustaining an adequate to the original process of information exchange inside as well as outside the system.

In the current market conditions, economic modelling[5] is of utmost importance for any human activity. In project implementation, it often takes the form of a feasibility study[6].

A broader description of the various models was published at an earlier stage and hence will not be cited here [9,10].

Most often, the identification of an adequate model proceeds according to the scheme shown in Fig.1. The most important step in the procedure is the establishment of the logical and cybernetic model on the basis of the theoretical model, which usually amounts to the identification of: dependent variables, disturbance variables under control or in the absence of control, set variables and the model response, in the form of a so-called 'black box.' At times the 'black box' includes logical elements. Failure to properly establish the above elements of the system can hinder the understanding of the research object or falsify its nature. The establishment of a cybernetic model can form the basis for the search for an adequate deterministic model. It is not always possible to establish an adequate deterministic model. If this is the case, it is advisable to proceed to the search for a statistical model without establishing a deterministic model[7] — Fig. 1.

When undertaking research to search for adequate models, it is becoming increasingly necessary to convince decision makers that they can be carried out effectively based on an economic model, most often in the form of a feasibility study.

Deterministic models most often come in the form of algebraic expressions or their systems. It is not always possible to establish a strict functional relationship[8] between the explanatory variables and the explained variable in a model, although, in accordance with Leonard Euler's paradigm, we believe that such a relationship for deterministic processes always exists. When it is not possible[9] to establish an adequate model expressed in terms of a functional relationship, semi-empirical or empirical models are most often sought.[10]

PROCESS-ORIENTED APPROACH

A rational human activity can be conceptualised as a process that can only proceed in a supporting system environment, which is a set of synergetically related elements making up a system structure distinguished from the surrounding reality, defined by an internal context [1,2,3]. The external context consists of elements that are connected to the elements of the system, but lie outside its boundaries. Depending on the needs of the analyses of processes occurring in the system, the system boundaries may be shifted [3].

From the point of view of the implementation of the defined process, modelling is referred to as a process-oriented approach.

PERCEPTION

Our understanding of reality is realised through the construction of models, as the reality around us is too complex for our perception capabilities.[24]

VALIDATION

Validation is the process of confirming, in a documented and consistent manner, that a model of a system or process established on the basis of theoretical considerations is sufficiently reliable[25] for the intended purposes. If validation is carried out based on statistical models,[26] it should first be evaluated from an economic point of view – Fig. 1.

IMPLEMENTATION

Successful completion of the validation process enables model implementation.[27] Sometimes, however, implementation, although possible,[28] becomes so costly that model implementation may be abandoned or postponed – Fig. 1.

RISK AND HAZARD

Conventionally, risk and hazard most often function as synonyms. Here, hazard H is defined as the integral value of risk R: $H = f(R,t) = \int_t R\,dt$, where t is the time of exposure to risk R. The hazard function H and risk function R are here functions in the sense of survival analysis [4,7].

In the analysis of the problem situation, the function of risk R(t) and hazard H(t) should be given explicitly, as the general integration operation[29] can only be performed with the accuracy to the shift by a constant value a = const, which may be relevant in the process of risk R analysis in the problem situation considered.

Diving technologies are often based on a simple estimation of the risk of exposure to risk R_{DCS} of the occurrence of decompression sickness DCS, where the variables include only the basic parameters of the dive, such as the maximum pressure p reached[30] and the total dive time t. Some specific hazards are compensated for by varying the level of conservatism κ.

In order to optimise diving technologies, other specific parameters should be introduced, such as oxygen decompression, which, however, is associated with exposure to risk R_{CNSyn} of central oxygen toxicity symptoms. Sometimes, as in the case of dives conducted in the saturation zone, it i salso important to take into account the materialisation of the risk R_{PT} i.e. pulmonary oxygen toxicity PT[31]. Hence, more advanced diving technologies must be based on a multidimensional risk $\underline{R}$ analysis.

CONCLUSION

A rational human activity can be framed as a process that can only take place in a supporting system environment, which is a set of synergetically related elements that constitute a system structure distinguished from the surrounding reality, defined by an internal context. The external context consists of elements related to system elements, but lying outside the system boundaries. Depending on the needs of the analyses, the system boundaries may be adjusted. Modelling that adopts the process as the nucleus of the system structure is called the process approach.

The adopted system for the realisation of the process objective is selected, modified and supplemented when conducting the risk analysis, according to the principles of system analysis.

DECOMPRESSION

From a military point of view, the decompression process is part of the diving mission carried out for military purposes, and its basic and emergency procedures are a structural element of the diving technology subsystem, belonging to the larger system in which the military operation process is carried out. The military operation process can pursue the military objective set for it in a planned and uninterrupted manner based on the structure of the system, whose assumptions may sometimes be in contrast to the process of optimal/safe decompression.

In the first place, the decompression process should ensure adequate safety for the divers' return to reference pressure,[32] but at the same time it is almost always an element that reduces the effectiveness of the process of executing a military operation.

GRADIENTS

Decompression involves inducing a controlled disturbance of equilibrium leading to a difference $\Delta_i = \pi_i - p_i$ in the partial pressures p_i for the gases[33] present in the breathing mix inhaled by the diver and the pressure values π_i for these gases and in the tissues. Further this difference will be referred to as the gradient.

The gradient Δ_i i is the driving force of the decompression process. A rational condition for the decompression process is to maintain safe Δ_i gradients throughout the process so that the risk R_{DCS} of materialisation of the decompression sickness DCS does not exceed an accepted level. The decompression process assumes that the organism's gas balance is brought to a state of equilibrium $\pi_i - p_0 \cong 0$ during rest after a dive in the atmosphere with parameters $\{p_0, x_1..x_i\}$, to which the decompression process aims.[35] In the Polish Navy, ultrasonic detection of intravascular free gas phase is used to estimate the possibility of materialisation of the R_{DCS} risk [11].

The efficiency of the decompression process increases with an increase in the oxygen partial pressure p_{O_2} in the breathing medium inhaled by the diver. However, after sufficient exposure time at the increased oxygen partial pressure p_{O_2} present in the breathing medium inhaled by the diver, the toxic effects of oxygen on the body may become manifest. Hence the possibility of increasing the oxygen partial pressure p_{O_2} in the breathing medium for diving is limited. Planning an efficient decompression process requires a compromise between the efficiency of the decompression process and the risk R_{OSyn} of the occurrence of symptoms of oxygen toxicity[36] on the diver's organism, in particular the risk R_{CNSyn} of the neurological symptoms of CNSyn.

In most situations the materailisation of oxygen toxicity OSyn, particularly in relations to central nervous system CNSyn, is more dangerous than the symptoms of decompression sickness DCS. Hence, many strategies take the hazard level H_{CNSyn} of occurrence of CNSyn oxygen toxicity to be at a lower level $H_{DCS} > H_{CNSyn}$ than the acceptable hazard level H_{DCS} of development of symptoms of decompression sickness DCS – Fig. 2.

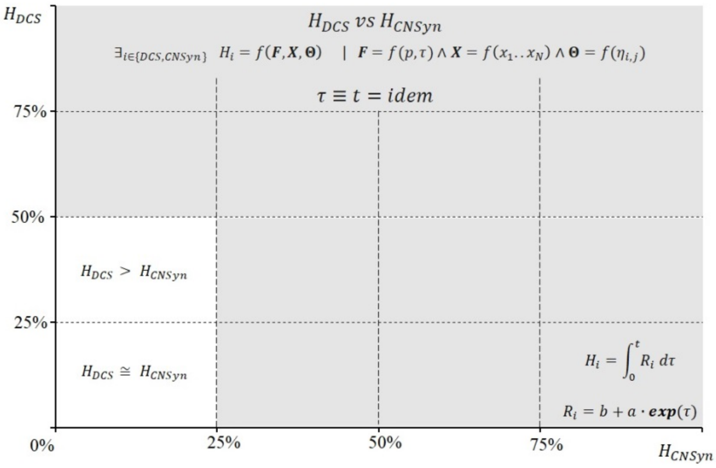

Fig. 2 Comparison of hazard H_{DCS} of the decompression sickness DCS and oxygen toxocity H_{CNSyn} in the central nervous system CNS, wheree: H is the hazard function, R is the risk function, p represents the maximum pressure dyring hyperbaric exposure, $x_{\bullet}$ is the gas proportions in the breathing mixture, τ represents the elapsed time and t tis the exposure time, $\eta_{\bullet}$ represents human and environmental factors, whereas a and b are any other modelling factors.

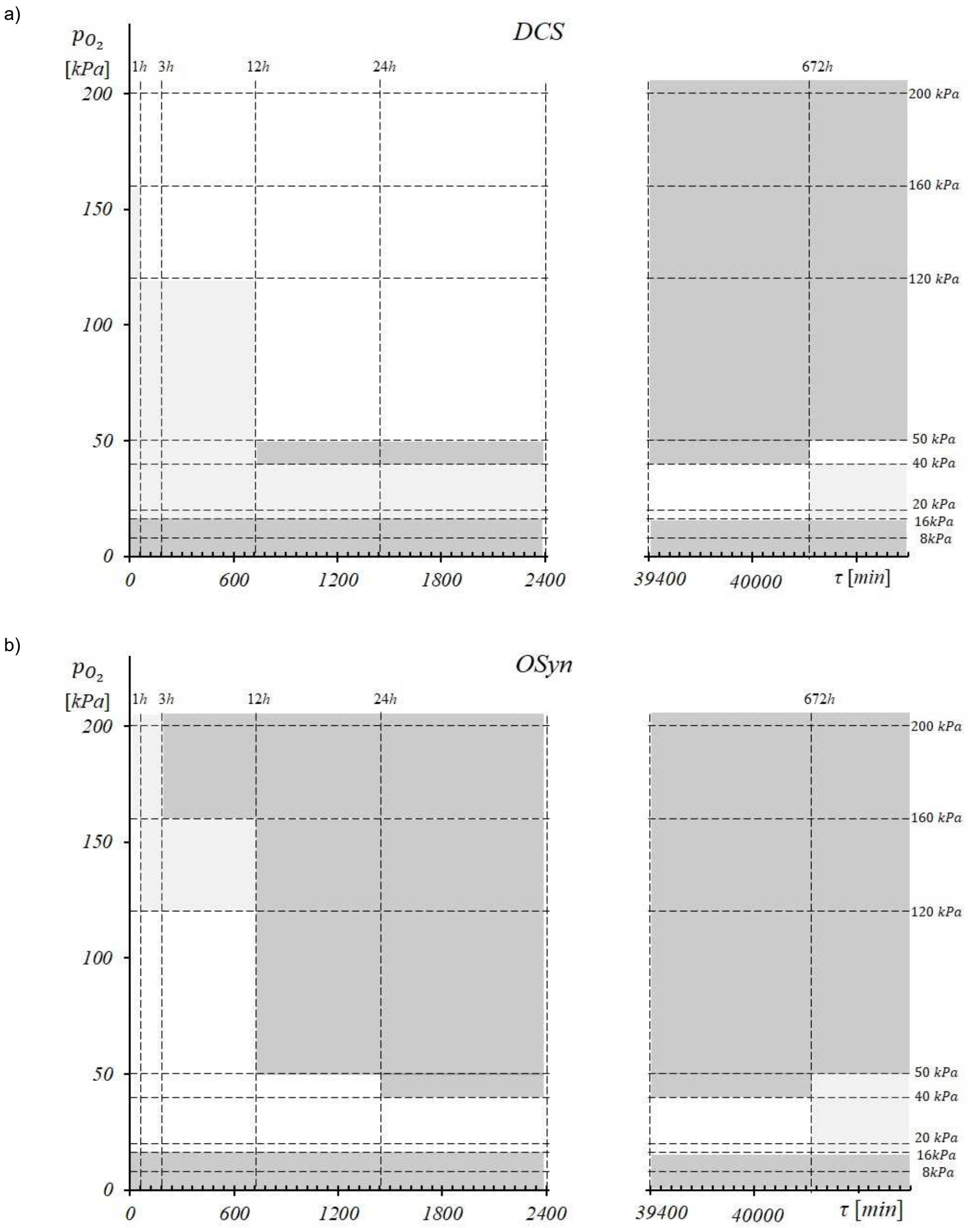

Fig. 3 The most common ranges of oxygen partial pressure p_{O_2} with respect to hazard H of: a) decompression sickness H_{DCS}, b) oxygen toxicity H_{OSyn}[37] including central oxygen toxicity H_{CNSyn} [7]. A darker colour indicates a higher hazard H.

The most commonly used ranges of oxygen partial pressure p_{O_2} with regard to the risk of decompression sickness H_{DCS} and oxygen toxicity H_{OSyn} are presented in Fig. 3.

DECOMPRESSION

The safe transition from an atmosphere with higher partial pressures p_i of the gaseous components of the breathing mix to an atmosphere with lower partial pressures p_i^0, is realised based on a scheduled decompression process, most often through variations in the total pressure $\dot{p}$ and/or the composition of the breathing mix $\dot{x}_1..\dot{x}_i$ as a function of time[38] τ[39]. The decompression proces is influenced by a larger numer of inherent[40] environmental[41] and human factors $\eta_{\bullet}$, whose values should be maintained within certain safe ranges. Exceeding of some of them beyong the established ranges induced an increase in the multidimensional residual risk[42] $\underline{R}$ of the decompression process, above the assumed value. Hazard, i.e. the integral hazard $\underline{H}$ occuring in the decompression proces should be estimated by integrating the multidimensional risk $\underline{R}$ for each realisation of the decompression process.

Any decompression system used is subject to observation and evaluation by users, and sometimes also to diagnosis[43] by established institutional supervisor yand social bodies. The analysis of the observed behaviour of the system leads to the identification of certain types of behaviour that may make up the so-called “good practices” GDP.[44] While the conclusions from such collected observations usually hold reference to current theories, they should not form the basis for absolute rules of conduct, as they have not been tested in a scientific cognitive process and validated.[45] [9] For this reason, the uncritical use of GDPs in conditions[46] different from those in which they are proven to work,[47] can degenerate into irrational or even harmful behaviour [12]. Hence, GDPs are rather unlikely to be described in the form of recommendations,[48] even though they do provide an important rationale for conducting an analysis of residual risk $\underline{R}$ dla procesu dekompresji. for the decompression process. If the conclusions do not yet constitute validated knowledge,[49] their safe transfer to other users should only take place in a system of work experience, on the basis of which the future specialist[50] acquires the necessary experience by observing the work of other, more experienced specialists.[51]

The use of ranges of gradients Δ_i, which are considered safe/acceptable, is intended to safely achieve a state of gas equilibrium of the body $\pi_i - p_i^0 \cong 0$ in the breathing atmosphere $p_1^0 .. p_i^0$ during post-dive rest. The pressure to which the decompression proces leads p^0 is usually the sea level p_0. It may be the atmosphere surrounding a body of water elevated above sea leave, where the pressure p^0 is reduced with reference to normal pressure p_0 at sea level $p^0 < p_0$. It may also be the pressure p^0 present in a cruise plane, where the pressure is usually by ¼ lower than normal $p^0 < \frac{1}{4} \cdot p_0$, a helicopter or military transport aircraft, where the difference may be even greater[52] $p^0 \ll p_0$. A reference could be the pressure p^0 in an underground cave or subterranean corridor, where the pressure p^0 may be much higher than the atmospheric pressure[53] p_0: $p^0 \gg p_0$. It may also be the pressure prevailing in the habitat to a diver returns after a trip from a saturation plateau.

During decompression, the rate of decrease in total pressure $\dot{p}$, the composition of the breathing mix $\dot{x}_1 .. \dot{x}_\imath$ or changes in other parameters of the decompression process $\eta_\bullet$, are selected in such a way that the gradients $\Delta_i = \pi_i - p_i$ accompanying the changes in these respective variables/factors guarantee that the decompression process assumed as safe, with the chosen path leading towards the final pressure p^0 of the decompression process, and that these gradients Δ_i are kept to be as efficient as possible. The decompression process may include decompression stops used to reduce the current value of the gradient Δ_i before continuing along the path of changes in these variables/factors on the way towards the final pressure p^0 of the decompression process.

MODELLING

Rationally based anticipation of the value of the vector[54] of gradient $\underline{\Delta}$ is most often based on semi-empirical modelling – Fig. 1 [9]. Thus, some values of important parameters of the decompression model are determined by indirect measurements, during purposely selected experiments.

The classical neo-Haldane approach is based on a class of theoretical models used for homologous processes such as ventilation, nuclear fission, etc.

The neo-Haldane approach offers the possibility of constructing an arbitrary model expansion by using a superposition of a selected number of base models for a selected single theoretical tissue τ and gas i.

It was noted b=that for any gases $\forall_{i,j}\ i \neq j$ the ratios of theoretical saturation/desaturation half-lives of a given theoretical tissue $\tau_{0,5}^i / \tau_{0,5}^j$ correspond to the ratio of the square elements of their molar masses $\sqrt{M_i / M_j}$:

$$\forall_{i \neq j}\ \tau_{0,5}^i / \tau_{0,5}^j \triangleq \sqrt{M_i / M_j}.$$

Tab. 1

Theoretical tissue parameters for nitrogen and helium, for the model $\mathrm{ZH}-\mathrm{L}_{12}$ [13].

Theoretical tissue i no.	Nitrogen N_2			Helium He		
	saturation/desaturation half time $\tau_i(N_2)$	value $a_i(N_2)$	value $b_i(N_2)$	saturation/desaturation half time $\tau_i(\mathrm{He})$	value $a_i(\mathrm{He})$	value $b_i(\mathrm{He})$
	[min]	[ata]	[−]	[min]	[ata]	[−]
1	2,65	2,2	0,82	1	2,2	0,82
2	7,94	1,5	0,82	3	1,5	0,82
3	12,2	1,08	0,825	4,6	1,08	0,825
4	18,5	0,9	0,835	7	0,9	0,835
5	26,5	0,75	0,845	10	0,75	0,845
6	37	0,58	0,86	14	0,58	0,86
7	53	0,47	0,87	20	0,47	0,87
8	79	0,455	0,89	30	0,455	0,89
9	114	0,455	0,89	43	0,455	0,89
10	146	0,455	0,934	55	0,515	0,926
11	185	0,455	0,934	70	0,515	0,926
12	238	0,38	0,944	90	0,515	0,926
13	304	0,255	0,962	115	0,515	0,926
14	397	0,255	0,962	150	0,515	0,926
15	503	0,255	0,962	190	0,515	0,926
16	635	0,255	0,962	240	0,515	0,926

$\frac{\tau_i(N_2)}{\tau_i(\mathrm{He})} \triangleq \frac{\sqrt{M(N_2)}}{\sqrt{M(\mathrm{He})}} \cong 2{,}65$ where: M −molar mass

Tab. 2

ParTheoretical tissue parameters for nitrogen and helium, for the model ZHL – 16A [14].

Theoretical tissue i no.i	Nitrogen N_2 saturation/desaturation half time $\tau_i(N_2)$ [min]	value $a_i(N_2)$ [ata]	value $b_i(N_2)$ [−]	Hel He saturation/desaturation half time $\tau_i(He)$ [min]	value $a_i(He)$ [ata]	value $b_i(He)$ [−]
1	4	1,2599	0,5050	1,51	1,7474	0,4245
2	8	1,0000	0,6514	3,02	1,3830	0,5747
3	12,5	0,8618	0,7222	4,72	1,1919	0,6527
4	18,5	0,762	0,7825	6,99	1,0458	0,7223
5	27	0.6667	0,8125	10,21	0,9220	0,7582
6	38,3	0,5933	0,8434	14,48	0,8205	0,7957
7	54,3	0,5282	0,8693	20,53	0,7305	0,8279
8	77	0,4701	0,8910	29,11	0,6502	0,8553
9	109	0,4187	0,9092	41,2	0,5950	0,8757
10	146	0,3798	0,9222	55,19	0,5545	0,8903
11	187	0,3497	0,9319	70,69	0,5333	0,8997
12	239	0,3223	0,9403	90,34	0,5189	0,9073
13	305	0,2971	0,9477	115,29	0,5181	0,9122
14	390	0,2737	0,9544	147,42	0,5176	0,9171
15	498	0,2523	0,9602	188,24	0,5172	0,9217
16	635	0,2327	0,9653	240,03	0,5119	0,9267

Experimentally determined saturation/desaturation half times for blood nitrogen $\tau_{0,5}^{N_2}$ allow the determination of theoretical saturation/desaturation half times $\tau_{0,5}^{i}$ for other gases and for a selected theoretical tissue.

As adequate models for values of maximum saturation gradients Δ_i^M the following linear combinations were adopted $\forall_{a_i=f(\tau_i)\wedge b_i=f(\tau_i)}\ \Delta_i^M=(\Delta_i-a_i)\cdot b_i$, where values a_i, b_i are consnant and specific to the given theoretical tissue τ_i, and the modelling approach adopted [13,14]. For instance, for nitrogen: $a_i=2\,\mathrm{atm}\cdot(\tau_{0,5}^{i}\cdot\mathrm{min}^{-1})^{-\frac{1}{3}}\ \wedge\ b=1{,}005-(\tau_{0,5}^{i}\cdot\mathrm{min}^{-1})^{-\frac{1}{2}}$, where: $[\tau_{0,5}^{i}]=\mathrm{min}$ [14]. The basic twelve-tissue theoretical model of Bühlmann ZHL_{12}, is used in the Polish Navy in the wor on decompression systems for the military – Tab.1. However, it has been abandoned in other countries, in favour of its modifications:

- ZHL – 16: basic sixteen-tissue theoretical model,
- ZHL – 16A: basic model with zero conservatism[55] $\kappa=0$ – Tab. 2,
- ZHL – 16B: sixteen-tissue model with increased conservatism κ for tissues with average saturation/desaturation half-times, most commonly used for decompression tables,
- ZHL – 16C: sixteen-tissue model with modified conservatism κ in relation to ZHL – 16C model, most commonly used in electronic decompressiometers without the possibility to change the model parameters,
- ZHL – 16 ADT DD: sixteen-tissue model with modified conservatism κ in relation to model ZHL – 16C, most commonly used in electronic decompressiometers with the possibility to adapt some parameters of the model, especially conservatism
- ZHL – 8: a scaled-down, eight-tissue model introduced to reduce the computational load on personal diving computers; its modifications relate to increasing the adaptability and use of different gases and, components of the breathing mix.

Nowadays, neo-Haldane algorithms are often replaced by others, such as: VPM[56], RGBM[57] TBDM[58] VVAL18[59] etc., which are considered more conservative, hence safer than neo-Haldane models by Workman or Bühlmann. The Hempelman Prt model is also used in the Polish Navy to assess decompression load [4,6,15].

INITIAL STATE

In order to estimate the level of value, a controlled disturbance of the equilibrium state by changing the environmental parameters η., _-, leading to safe and effective gradients $\Delta_i=\pi_i-p_i$ between the partial pressures p_i for gas in the breathing atmosphere and its pressures π_i in particular theoretical tissues, an estimate of the initial saturation state is needed. The initial saturation state is estimated from the profile of the course of the previous dive[60] and the surface decompression course during the rest/stress immediately preceding the start of the decompression process.

Most often, the initial saturation state is determined by a rough estimate using the decompression table, taking into account the maximum pressure reached during the dive process p_{max}, e time of exposure to the maximum pressure and the time interval between the end of the previous dive and the planned commencement of the next dive process. This procedure allows the estimation of the inert gas pressures π_i remaining in the theoretical tissues from the previous dive and their influence on the next dive process.

As the decompression process progresses, further changes in the decompression parameters should be predicted based on the model, taking into account the current situation - estimating the departure from the baseline plan envisaged for the dive being carried out. It is tempting to make estimates for every, even the smallest, change in the dive parameters, as electronic decompressiometers allow. However, that capability characteristic of electronic decompressiometers can be both their greatest advantage as well as their main flaw[61]

PREVENTION

Decompression procedures included in the structure of the decompression subsystem, which is part of the underwater work technology system, are used to prevent the onset of symptoms of decompression sickness DCS. Commonly encountered descriptions of the decompression system are laconic, as it is assumed that the necessary knowledge for the correct use of the decompression system has been acquired and consolidated through mandatory courses and training at the different levels of a professional diver's career development.

Exhaustive commentaries are found in studies of the results of research on decompression systems, however, access to these is not universal. The necessary knowledge is rarely communicated openly, in a comprehensive manner, as in the case of the decompression system developed by Bühlmann [13]. Occasionally, some works are published that generalise the approach to decompression [16,17]. The knowledge imparted in training courses is contained in course materials [18,19]. Such textbooks are not fully useful for acquiring knowledge outside the training system. Sometimes these are assigned to the trainee with the indication that only the person signed on the cover can legally use the information contained therein [20,21]. This is not only due to the desire to protect the know-how, but above all for the protection against misinterpretation of the information contained therein by an untrained user.

Usually, the designer of a decompression system assumes a high level of knowledge of the future user, which justifies the inclusion of only a concise comment [22]. Often it is narrowed down only to the disclaimer[62] of the developer of the decompression system.

This particular way of implementing the process of introducing professionals to the use of the decompression system is justified by certain barriers in perception. Diver's skills should rather be considered in terms of highly skilled craft skills[63], the learning of which takes place through an appropriate practical training system. This does not only apply to the ability to use diving equipment and gear, but also the decompression systems. It is possible to describe many determinants of the correct approach to underwater work planning [23], but the number of special situations is nevertheless so large that teaching it within a single cycle would be long and tedious and the consolidation of such acquired knowledge problematic. This can be compared to learning in detail all the options and capabilities of a multifunctional electronic device, like a smartphone, prior to starting to use it. Usually, the user is not given complete knowledge of such a system, as functions not used on a daily basis will quickly be forgotten.

One may for a moment imagine that divers could be selected and trained in the same way as cosmonauts. Professional cosmonauts are highly educated individuals in several fields of knowledge, with considerable practice in aviation and specially trained to achieve extraordinary fitness[64]. Following this line of thought, one could assume for a moment that a car driver should be a trained mechanic, instructed similarly to professional passenger aircraft pilots. Postulating such approaches would rather be met with ostracism and, in a worse scenario, with the accusation of a lack of adequate reference to reality, bordering on madness.

Modern cars are no longer supplied with technical manuals for servicing them[65]. They are not even supplied with accurate technical descriptions. The same happens with decompression systems. At times, decompression systems are classified and their implementation requires the involvement of assistance from the first user or the developer of the decompression system. Other times, information on the assumptions behind decompression systems is patented, but even then the extent of the know-how disclosed is as limited as possible [24].

In military systems and high-tech commercial institutions, efforts are made to communicate in as much detail as possible the knowledge of the decompression systems in use. But even in such cases, decompression systems are not provided with sufficiently comprehensive comments.

They are replaced by a mandatory operational risk analysis [25]. This forces the user to undertake their own studies or attend additional courses so as to acquire the skills to conduct such an analysis. In the event of an accident or potentially hazardous situation, the absence of such a document, or the perfunctory preparation of such a document, constitutes a compounding factor for the person responsible for planning the diving operation.

More often than not, the user would like the instruction to be as brief as possible and exhaustive to the extent that it would cover all possible situations in a comprehensible manner. These requirements are in mutual contradiction[66] and therefore such an instruction probably does not exist in any field.

An attempt to describe the air decompression system currently in use by the Polish Navy will be presented in the second part of the article. Testing of said description has revealed deliberate distortion by users of the content thereof, causing greater cognitive dissonance than would occur without it being developed. Hence, it appears that the traditional method of progressively introducing users to decompression systems on mandatory, graded specialist courses should still be the preferred route for admission to the use of diving technology.

CONSERVATISM

In the case of the presence of factors compounding the possibility of symptoms of the decompression sickness DCS, the anticipated or materialised risk R can be compensated for by using extended decompression [26,27]. Such a procedure is termed conservative or simply conservatism. Conservatism κ can be implemented in various forms. As an example, one could take the selection of the next greater depth in the decompression table from the exposure depth67. Most commonly, for a selected decompression schedule, the level of conservatism κ is increased by artificially assuming a longer stay time Δt for a corresponding exposure pressure p, as in the air diving system used in the Polish Navy [22].

When researching acceptable values of gradients Δ_i in the decompression proces, the concept of a so-called grey zone is introduced, which includes gradients Δ_i that should not lead to the occurrence of symptoms of decompression sickness DCS, provided that no additional factors burdening the diver are imposed on the decompression process. The upper boundary of the grey zone is represented by the maximum permissible values of the supersaturation gradients[68]. The value levels for the lower boundary of the grey zone are rarely described, and are often assumed to be within the range of $[75; 80]\%$ of the value for the upper threshold[69] Δ_i^{max}: $\exists_{\delta \in [0{,}75;\, 0{,}80]}\ \Delta_i = \delta \cdot \Delta_i^{max}$. Most commonly, zero conservatism $\forall_{\Delta_i = \Delta_i^{max}}\ \kappa = 0\%$ for leading tissue i and is assumed, at a given stage of the decompression process progression, for the upper boundary of the grey zone. Maximum conservatism $\kappa = 100\%$ is commonly referred, for leading tissue i, to the zero gradient $\Delta_i = 0$: $\forall_{\Delta_i = 0}\ \kappa = 100\%$. For the thus assumed conservatism limits, for $\kappa = 100\%$ decompression theoretically does not occur[70].

If decompression is planned at a significant level of conservatism κ, the impact of the materialisation of some additional stress factors can be expected to be compensated for [26,27]. If decompression is planned close to or within the grey zone, the emerging additional stresses[71] in a particular diving process may lead to the development of symptoms of decompression sickness DCS, despite a formally correct decompression profile based on the decompression tables used from correctly collected diving process parameters.

It is the responsibility of the dive operation planner and the person directly managing the dive to assess the level of conservatism κ applied in relation to the estimated residual risk[72] R_{DCS} of the occurrence of DCS symptoms. The analysis of risk R_{DCS} is conducted based on heuristics[73] comprising the expertise gained through apprenticeship.[74]

WORST CASE SCENARIO METHOD

The method of looking for worst-case scenarios is commonly used in estimations [26,27]. In diving technology, taking into account all the circumstances that increase the risk R_{DCS} can lead to a failure to find a good solution. For instance, using Table 3MW, a maximum of only two confounding factors are taken into account [22]. The materialisation of more confounding factors no longer entails the need to increase the level of conservatism κ when implementing the decompression process.

VARIABILITY

The decompression process is usually controlled by changes in the ambient pressure p $\dot{p} = \frac{\partial p}{\partial \tau}$ affecting the diver's body during exposure τ[75] and changes in the partial pressures of the components in the considered range $i\epsilon\{1..i\}$ of the breathing mix $\dot{p}_1..\dot{p}_i$. In most cases, any other factor affecting the gradients $\Delta_i = \pi_i - p_i$ between the gas pressures $\pi_1..\pi_i$ in theoretical tissues with numer in the considered range $j\epsilon\{1..j\}$ and their partial pressures are treated as compounding factors and not as factors controlling the decompression process.

A reduction in the exposure pressure $p \searrow$ is achieved by a controlled change in the depth H in water depth or pressure p in the habitat. This reduces the partial pressure of the components of the breathing mix p_i used by the diver in the breathing process, e.g. from the breathing apparatus or the atmosphere of the habitat. As the pressure $p \searrow$ decreases, the partial pressures $p_1..p_i$ of the components of the breathing mix to a level below its pressure $\pi_1..\pi_i$ in the tissues. The differences between the partial pressures p_i of the components of the breathing mix and the pressures π_i of this mix in the tissues create the necessary gradients $\Delta_i = \pi_i - p_i$ which drive the diffusion processes enabling the decompression process.

However, gradients $\Delta_i = \pi_i - p_i$ can also be induced by changing the composition $x_1..x_i$ of the breathing mix. Changing the composition $x_1..x_i$ of the breathing mix i will have the same effect of producing the necessary gradients $\Delta_1..\Delta_i$ for these components in theoretical tissues j with numbers in the analysed range $j\epsilon\epsilon\ \{1..j\}$, even at the same value of the total pressure p of the breathing mix. The method of conducting decompression without changing the pressure $p = idem$ is known as an isobaric decompression process.

As a result of the previously generated gradients $\Delta_1..\Delta_i$, isobaric decompression p=idem can also proceed without a change in the composition of the breathing medium $x_1..x_i$, e.g. at decompression stops[76]. It may also proceed as a result of a change in its composition $x_1..x_i$, e.g. when breathing oxygen by a person who has not previously dived – a gradient for nitrogen N_2 with a value of approx. $\Delta_{N_2} \cong 78\, kPa$ in each theoretical tissue j, causing a kind of "pursing" of N_2 from the body. Similarly, at the end of the dive, with air as a breathing medium, a certain chargé of N_2 remains in the body. That is, the nitrogen pressure π_{N_2} in the tissues will be higher than the partial pressure of nitrogen p_{N_2} in atmospheric air. The resulting gradient Δ_{N_2} will be the driving module of the proces that will lead to the reduction of the resulting gradient to zero $\Delta_{N_2} \rightarrow 0$ during surface isobaric decompression, without changing the composition of the breathing mix $x_1..x_i$.

For dives using artificial breathing mixes, both methods described for producing gradients Δ_i are most typically utilised. For example, when diving with breathing mixes on the basis of helium He, decompression breathing media sucha as various types of nitrogen-oxygen mixtures Nx or air can be used simultaneously in addition to lowering the pressure $p \searrow$, while oxygen O_2 can be used in the final phase to further accelerate the decompression process.

However, the values of the resulting gradients Δ_i are also influenced by other factors, the important ones being temperature, physical exertion, respiratory resistance, compression, immersion, etc. [26]. It is rarely the case that these other factors are used to control the gradients Δ_i produced, and thus the decompression process. It is usually assumed that they should be kept constant or within a certain range [26]. Most often, the decompression risk factors R_{DCS} are to some extent compensated by manipulating the level of conservatism κ.

RISK FACTORS

The Polish Navy traditionally considers some of the factors that increase the risk R_{DCS} of developing symptoms of decompression sickness DCS, when:

- the diver performs heavy work,
- the diver experienced cooling down/overheating,
- the dive is one in a cycle of dives,
- the diver is untrained or has a personal predisposition to develop decompression sickness DCS,
- the diver is obese or his weight exceeds 80 kg,
- the diver is over 40 years of age.

This list is not exhaustive and could be complemented with the following examples:

- specific hazards related to the diving equipment, auxiliary equipment, diving technology used,
- respiratory resistance,
- decompression to pressures below atmospheric or air transport following a dive,
- local compression caused by the diving suit and gear,
- forced position during operation or decompression,
- flooding of the suit,
- diet,
- use of nutritional supplements and medication,
- dehydration, etc.

The effect of the above factors on increasing the R_{DCS} of the occurrence of symptoms of decompression sickness DCS is not disputed, but but the interpretation of these factors is usually controversial. This is because it is difficult to define the exact impact of many of these factors on the risk R_{DCS}.

Risk R_{DCS} factorsand their effect on the decompression process will not be described here, as they have been discussed in an earlier paper [26,27].

CONCLUSION

When designing an optimal decompression process, the most common problem situation is related to the setting of a boundary between the hazard of developing of decompression sikness H_{DCS} and central oxygen toxicity H_{CNCyn}[77], taking into account the possibility of risk factors hindering the decompression process [26,27].

TERMINOLOGY

There are many requirements to be considered in the technology of underwater works, the most important of which are decompression requirements[78]. Efforts have been made to keep the descriptions of decompression types consistent with those found in the literature. The proposals for the description of decompression types quoted here should be treated as local terminology[79], which is to help specify the technology-centered system requirements, derived from the goals set for the diving process adopted for the selected underwater work technology, which have to be met so that the decompression *process* can be effectively carried out.

Relatively often, decompression requirements are associated only with the basic distributions of the decompression *process*. Sometimes attention is also paid to the aspect of diving in waters elevated above sea level. Extended decompression related to *conservatism* κ is mentioned more and more often, as this function has become a standard in newer designs of electronic decompression meters.

Requirements concerning the preconditions which accompany the possibility of using a specific decompression *system* are rarely specified, hence it is only a few descriptions of diving technology that contain such information. This seems strange, because the risk of *DCS* symptoms R_{DCS} in divers is relatively high, and further increasing the level of the risk R_{DCS} by improperly preparing divers to undergo the decompression *process* is rather an unreasonable approach. An analogy can be made here to the need for pre-season dry skiing, as a significant percentage of injuries relate to skiers who are not properly prepared for the season.

CONTINUOUS DECOMPRESSION

The continuous decompression involves a steady pace of reducing pressure $\dot{p}\searrow$ surrounding the diver, as a drive module Δ_i for the decompression process.

It would seem that the continuous decompression is a process better, though more difficult to implement, than the staged decompression interrupted by decompression stops. However, even simple experiments show that the staged decompression process is not only more effective, but also safer [28,29,30]. This can be explained by the observed phenomena of metastable equilibrium described in physics.

In nature, metastable equilibrium phenomena can be observed relatively often. It is fairly easy to obtain supercooling states during the crystallization process.

The phenomenon of supersaturation can be observed in many solutions, e.g. formation of supersaturation of concentration of many salts in aqueous solutions when they cool down slowly. Following the nucleation step, the fast crystal growth process takes place.

You can observe the phenomenon of supersaturation of carbonated drinks with carbon dioxide $⟦CO⟧_2$. They remain stable both when frozen and slowly warmed up. However, when they are rapidly heated, shaken or a porous substance is added to them, a more or less intense gas $⟦CO⟧_2$ liberation process occurs.

Tissues are susceptible to supersaturation with gases, hence in the state of metastable super-saturation of the inert gas in the tissues $\vdash \pi_i^* \dashv | \ \pi_i^* \gg \pi_i^{max}$, after an appropriate impulse is generated, there may occur a rapid separation of the gaseous form from the dissolved form. Dangerous supersaturation may occur in stabilized conditions, and the separation of the free gaseous phase may initiate a sudden increase in activity, a temperature impulse, etc. For this reason, cyclical exercising is recommended when the decompression process is slow.

In saturation, taking a warm shower gives good results. It is also important to keep the body well hydrated .

Redissolution of the separated gas phase requires a return to the conditions preceding the equilibrium state - recompression. It is impossible to predict exactly to which point in the decompression process the return must be made, because the slow gas phase gives macroscopic DCS symptoms with a significant delay.

Staged decompression may be used as a way to protect against the phenomenon of unwanted, excessive supersaturation.

DECOMPRESSION FROM SATURATION PLATEAU

Divers remain at a constant depth of the saturation plateau, most often, for up to 4 weeks, conducting trips at the working depth. When they remain on the saturation plateau, their tissues are completely saturated with inert gases π_i^{max} from the breathing atmosphere, hence the decompression process after saturation is its longest form, assuming the same levels of hazard of developing symptoms of decompression sickness H_{DCS}.

The decompression process after saturation dives is carried out in habitats, where it can be easily automated and carried out on the continuous basis[84]. This results in a significant increase in the comfort of work performed by the support personnel, but requires increased attention to prevent the previously described excessive oversaturation.

Automation of the decompression process is useful in diving complexes dedicated to medical procedures, as most treatment procedures require the use of slow continuous decompression [25].

STAGED DECOMPRESSION

As already mentioned, changes in supersaturation gradients Δ_i produce good results when the staged decompression is applied. Cyclic changes of supersaturation gradients Δ_i, within their allowable values in given conditions, not only optimize the decompression process, but also prevent the formation of metastable, dangerous supersaturations.

As mentioned before, a slow departure from the equilibrium state may cause the formation of the state of metastable super-saturation π_i^* of the inert gas in the tissues $\pi_i^* \gg \pi_i^{max}$. As a result of the impulse causing the precipitation from the metastable state, a rapid separation of the free gas phase may occur. Cyclic, relatively significant changes of gradients cause disturbances in the process of equilibrium gas exchange, preventing the formation of harmful super-saturation of tissues.

In free diving conditions continuous decompression is virtually impossible, and the changing activities done by the diver[85] gives additional protection against the formation of a state of harmful metastable equilibrium[86].

COMBINED DECOMPRESSION

Almost any decompression process can be regarded as a combination of the staged and continuous decompression, since at least the ascent to the first decompression station contains an element of continuous decompression. Also, travel between decompression stations and the last stage of the staged decompression takes place in the form of continuous direct decompression.

When each decompression process comes to an end, a certain supersaturation gradient Δ_i, is usually left and further decompression process continues as part of isobaric decompression while remaining on the surface or under other constant pressure, e.g. in a habitat.

Even in relatively simple decompression procedures, a combination of other, more basic decompression procedures can be found. However, there are cases when the complexity of the decompression process is much greater, as in the case of intermittent decompression or cases of acceleration of the decompression process.

OXYGEN DECOMPRESSION

The oxygen decompression can be [88] considered an important element of the combined decompression.

Oxygen O_2 can be removed from the body's tissues by metabolism, and the path of physical desaturation is of minor importance[89] [33].Breathing O_2 causes leaching of other gases from the tissues, and its metabolic consumption creates a partial pressure defect Δπ available for other gases, commonly known as the "oxygen window" [34-36]. Thus, breathing O_2 accelerates[91] the decompression *process* by a factor of 2.5 in theory, but a factor of 2.0 is adopted in practice [23].

ISOBARIC DECOMPRESSION

By modifying the composition of the breathing medium $x_1 .. x_i$, it is possible to modify the gradients Δ_i that are the drive module of the decompression. Hence, decompression processes can take place under constant pressure $p = idem$, with a change in the composition $\dot{x}_1 .. \dot{x}_i$ or even elimination of some components from the breathing agent [38]. For example, the previously mentioned isobaric decompression *processes* accompany breathing oxygen on the surface. The isobaric decompression *process* does not always have to occur with a change in the breathing agent. This change can be triggered by the remaining imbalance of gradients Δ_i, as for example in the case of surface decompression under normal atmospheric conditions after air diving. Changes in gradients Δ_i can also cause a change in temperature, physical effort, etc. [27].

The isobaric decompression is associated with the risk of materialization of decompression sickness symptoms R_{DCS} caused by counter-diffusion with an inadequate change in the type of breathing mixture [39-42].

ACCELERATED DECOMPRESSION

As mentioned earlier, the most common way to accelerate[92] the decompression *process* is to use oxygen O_2 in its final phase [23]. The use of this method is limited to relatively small depths due to the toxic effects of oxygen O_2 under increased pressure [7]. The solution applicable at depths above the applicability of oxygen O_2 is to replace the breathing agent with its analog[i] having increased oxygen content. This allows decompression with the use of upper allowable partial pressure values of oxygen p_{O_2} in the breathing medium because of the risk R_{OSynn} and its toxic effect on the diver.

The toxic effect of O_2 is caused by the formation of reactive oxygen metabolites, which are potentially dangerous and produce symptoms of various forms of oxygen poisoning.

The toxic effect of O_2 is caused by the formation of reactive oxygen metabolites, which are potentially dangerous and produce symptoms of various forms of oxygen poisoning [7,23]. Therefore, changes in the hazard of occurrence of various oxygen toxicity symptoms[94] $\underline{H}_{OSyn} = f(\tau)$ as a function of time τ should be recorded and paid attention to, and if necessary, the history of the previous dive should be also taken into account. The hazard $\underline{H}_{OSyn}$ is colloquially referred to as the "oxygen clock", which actually activates the moment the O_2 partial pressure has been exceeded at a level $p_{O_2} \geq 100\ kPa$ for the symptoms of central nervous system toxicity $H_{CNSyn} \nearrow$, and for symptoms of pulmonary toxicity after the O_2 partial pressure has been exceeded at a level $p_{O_2} \geq 38\ kPa$ [95] [7].

It is not only analogous versions of the same type of breathing agent with increased O_2 content that are used as breathing decompression mixtures, but also its type is changed, for example from using Heliox Hx or Trimix *Tx* to Nitrox *Nx* . As a result of such a change, the basic component of the previously used breathing mixture usually disappears and a new one may appear in its place, for example, when *He* is replaced by nitrogen N_2 during the transition from breathing *Tx* or Hx to breathing *Nx*. As a result, the partial pressure *He* in the breathing mixture drops to zero $p_{He} \searrow 0$ whereas the partial pressure N_2 increases $p_{N_2} \nearrow$. Hence, the absolute values of the gradients increase: $|\Delta_{He}| \nearrow \wedge |\Delta_{N_2}| \nearrow$ and even at a constant pressure *p=idem*, an intensive decompression *process* for *He* and a compression process for N_2 may occur.

The whole strategy should be based on choosing such an exposure *time τ=t* for the changed breathing mixture that the whole maneuver is as effective and safe as possible. Changing the type of breathing mixture supplied to the diver together with the increased, within safe limits, partial pressure of oxygen p_{O_2}, most often ensures that the efficiency requirement is satisfied and it may also increase the safety. However, when the dominant component in the breathing mixture is changed, the possibility of occurrence of conditions dangerous for the counter-diffusion *process*, where the stream of gas entering the tissues will exceed the stream of gas leaving the tissues [36] should also be taken into account. This may lead to an increase in gas pressure in tissues π_i above the permissible values Δ_i^{max} of supersaturation $\Delta_i > \Delta_i^{max}$ and, as a result, cause the separation of the free gas phase [41].

Although it seems that the level of hazard of neurological form of oxygen toxicity H_{CNSyn} and counter-diffusion H_{cDCS} can be increased to the level still considered safe for a given type of diving, it should be remembered that their values are significantly influenced by casuistic parameters[96] [27]. Psychological parameters of potentially great importance, such as attitude[97], excitability[98], ability to act under stress[99], experience[100], etc., can be difficult to assess. Hence, the already mentioned notion of “gray zone” has been introduced. It includes safe exposures, but only when additional burdens/difficulties do not occur. Exploration and pushing boundaries by individuals within the “gray zone” must inseparably accompany extreme dives conducted in order to break records of hyperbaric exposures.

The acceleration of decompression *process* described so far concerned a strategy employed to increase the efficiency of this *process* while maintaining the same or a slightly increased level of hazard of decompression symptoms $H_{DCS} \cong idem$. This form of acceleration entailed the increase in hazard of especially neurological oxygen toxicity symptoms $H_{CNSyn} \nearrow$ to acceptable levels for the type of diving adopted. Accelerated decompression is also used when the typical limits of the hazard of decompression sickness symptoms H_{DCS} are exceeded. Rescue situations may require accelerated decompression with a controlled increase in $H_{DCS} \nearrow$.

In rescue situations, extra ordinary[101] rules of conduct can be applied. The best-known rules of conduct, not related to diving, include the selection process for a typical mass casualty accident, where the most important indication for taking action by rescue services is no longer the condition of the victim, but the prediction of effectiveness of the assistance provided [43].

An example of accelerated decompression in emergency are the procedures described by NOAA[102], which, among other things, constitute protection for the *Aquarius Reef Base system*[103] [44]. The Aquarius Reef Base is the habitat located in the typhoon zone. Relatively shallowly anchored, it is susceptible to the impact of strong waves. With well-developed modeling of typhoon evolution, it can be used for early warning of an impending threat. However, the time needed for a typical evacuation by applying standard saturation decompression is long enough to expose aquanauts to serious consequences. Therefore, the accelerated decompression is used with simultaneous transport to a hyperbaric treatment center in the event of decompression sickness symptoms. Although this procedure increases the hazard $H_{DCS} \nearrow$ as compared to the standard hazard, it exposes the aquanauts to a lesser hazard than that associated with the exposure to a hurricane.

In rescue operations of crews from disabled submarines, an additional complication may be pressure increase inside the distressed submarine *DISSUB*[104]. The most advanced rescue method is the use of deep submergence rescue vehicles *DSR*V[105]. The rescued submariners can go through the accelerated decompression on board such a vehicle [10,45,46]. Regardless of whether victims can be transported under pressure TUP to decompression chambers, the implementation of accelerated decompression on board a DSRV during its ascent *intensifies* the rescue *process*.

EMERGENCY DECOMPRESSION

The accelerated decompression is one of the forms of emergency decompression used in extraordinary circumstances.

The emergency decompression is a plan of action for an emergency situation, e.g. for failure in supplying the appropriate breathing mixture. An example may planning the decompression process to be conducted with the breathing mixture used during the diving process when oxygen is unavailable during the conduct of oxygen decompression.

The emergency decompression may also involve switching to a breathing mixture other than that used in the diving process. For example, it is assumed that it is possible to switch to air decompression as an emergency during Hx, Tx or Nx dives [13,25]. Usually, breathing air is available in large quantities at each diving station. Therefore when the surface or bell-oriented supply of Hx, Tx or Nx fails, it is relatively easy to switch to emergency air supply.

A complicated method of self-rescue of the crew from a DISSUB when there has been no increase in pressure on board $p = idem$ is extremely fast compression in the escape chamber[ii] and taking a risk of direct decompression to the surface of the water [47].

EXTENDED DECOMPRESSION

The extended decompression can sometimes fall int the category of emergency decompression, although in many cases it is a more general case classified here rather as alternative decompression.

The extended decompression should be planned for a situation when the diver has got stuck under water, for example has entangled in floating nets or ropes, has gotten caught on elements of the underwater structure, etc., regardless of whether this happened during the dive or decompression phase. Sometimes, compensation for the resultant schedule delay consists in switching to another profile compliant with the main decompression procedures. For greater delays, which may happen a diver gets locked in a compartment in a wreck, gets buried in sand while drilling in the bottom, etc., emergency tables should be used, e.g. sub-saturation tables.

An important reason for using the extended decompression is the occurrence of hindering conditions [27]. They can be diagnosed as early as in the preparation phase for diving, or they can arise during the diving phase preceding the decompression *process* or during the decompression *process*.

In the planning phase of the diving *process*, it is possible to diagnose such hindering factors as: relatively poor diver training, current predisposition, fatigue, obesity, advanced age of the diver, successive dives, surface and submerged current, waves, elevation of the diving area or the need for immediate air transport, difficult diving conditions[iii], etc. Many of these factors are compensated by adopting an increased level of *conservatism* κ, and hence by the use of extended decompression. As for some of them, such as successive dives, oxygen accelerated surface decompression may be used, whereas in the case of diving in the area elevated above the sea level, special decompression schedules or compensation methods should be applied [31].

Difficult conditions present during the dive, such as freezing, overheating, excessive workload, etc., are usually compensated by increasing the level of *conservatism* κ during the dive, and thus using the extended decompression [27].

ALTERNATIVE DECOMPRESSION

The alternative decompression includes procedures other than the main procedure used for conducting the decompression *process*.

As early as at the planning stage, the main procedure for carrying out the decompression *process* should be supplemented with alternative ways to carry it out, taking into account foreseeable changes in the assumptions related to the baseline plan of the main decompression *process*. One of the types of the alternative decompression is the emergency decompression, such as, for example, the previously described emergency air decompression applicable for Trimix *Tx* or Heliox *Hx* dives.

The previously discussed accelerated decompression is an example of alternative decompression. It can be considered a way of shortening the decompression process in the event of an unexpected risk *R*.

The case of changing the baseline plan for organizing the decompression process may refer to a change in the time spent under water in relation to the time planned in the diving *process*, e.g. its shortening or extending.

Extending the diving time may refer to many events, sometimes of little importance, e.g. a temporary loss of control over the diving time or extending it consciously. Most often, extending the decompression *process* is associated with the occurrence of hindering conditions and the transition to the extended decompression plan [27]. During direct decompression dives, it is good practice to plan an alternative scenario which includes implementing the decompression dive plan, e.g. in the event of an unplanned extension of dive.

Making the decompression process shorter than planned may be a purposeful act or a mistake. With the acceleration ranges allowed by the procedures, as in the case of shortening the time to reach the first decompression stop, the compensatory decompression, provided for by the procedures, cab be used. In the event of a gross mistake, such as bypassing a de-compression station, the diver rather consistently moves towards the surface in accordance with the rational accelerated decompression, where the compensatory decompression is applied or hyperbaric treatment procedures are implemented immediately.

Sea state-dependent decompression is a rarely described type of alternative decompression. Interrupted decompression can be classified as the alternative decompression although it is often regarded as the main procedure.

SEA STATE-DEPENDENT DECOMPRESSION

Decompression plans taking into consideration sea states assume the possibility of a significant increase in waving in the diving area during the decompression process. An important element of the execution of the decompression process plan is the uninterrupted operation of the longest decompression stops close to the very surface of the sea. However, the impact of the waving extends deep into the water body and is estimated to be significant at depths of three to seven times the wave height. It follows from this that in such conditions remaining at shallow decompression stations may be problematic, because to the rhythm of waving the diver will once fall to the depth of the previous decompression station, and then ascend almost to the surface of the sea.

Decompression plans for sea states include alternative decompression, carried out only to a certain depth, e.g. the penultimate decompression station, e.g. $6\,mH_2O$, and then continuous direct decompression to the surface. The alternative decompression plan should not significantly increase the hazard of decompression sickness symptoms H_{DCS} in relation to the hazard adopted in the main decompression plan – but, as a result it is usually a little longer, being part of the extended decompression.

INTERRUPTED DECOMPRESSION

The interrupted decompression is sometimes referred to as surface decompression[109], however, here the surface decompression is equated with the isobaric decompression occurring most often at the sea level p_0 during compensatory rest after the dive.

In the interrupted decompression it is possible to interrupt the decompression process at the depths, conduct quick ascent, quick re-compression in the habitat on the surface and continue the decompression *process* until a safe transit to the atmospheric pressure present at the surface[110]. This way of using the decompression process procedures makes it possible to shorten the time spent in the depths[111] so that the decompression *processes* can be completed in a relatively safer and more comfortable environment.

The beginning of thinking about the interrupted decompression was connected with the absence of decompression sickness symptoms recorded in the course of uncontrolled surfacing of a diver during the Nitrox *Nx* saturation diving process, provided that a quick return[112] was made to the appropriate depth [48]. NOAA's *Nx* saturation diving procedures allow an astray diver to ascend to the surface for a moment to determine the direction of the habitat[113] ([44,49].

The interrupted decompression may be regarded as the main, alternative or emergency decompression, depending on the approach adopted,

MAIN DECOMPRESSION

The main procedure to be used in the decompression *process* is planned based on the adopted assumptions related to the diving process,

The procedure used in the main decompression *process* should always be supplemented with plans for alternative decompression *processes*, including the mandatory procedures to be used in the following decompression processes: emergency, compensatory and in the *system* of emergency treatment re-compression.

SUCCESSIVE DECOMPRESSION

A decompression system should have established methods for conducting successive dives[114], in which the influence of the previous dive on the planned diving *process* may be significant[115], especially for the time needed to establish equilibrium in rest conditions[116]. Underwater work technologies may not allow for successive dives, but should assume the need to use repeatable/repetitive[117] dives in order to save human lives, or use of successive alternative/emergency decompression in case of emergency.

Restoring the gas balance can sometimes be accelerated by the use of special surface accelerated decompression. It is rather impossible to accelerate the time of compensatory rest after physical effort, hypothermia or overheating after diving, but the diver's body should unaided achieve the conditions of homeostasis. Attempts to heat or cool down after hyperbaric exposure usually end in disturbing the surface decompression *process* and may lead to a separation of the free gas phase in the tissues[118], which may lead to decompression sickness symptoms. Even if the decompression sickness symptoms do not occur, such actions may adversely affect gas exchange *processes* during the next dive[119].

When analyzing the plan of the main decompression *process*, various hindering parameters, both diagnosed and relatively likely, should be taken into account, in particular the influence of the parameters of previous dives[120]. The reference to the so-called Reverse Dive Profiles is not without significance [50].

There is a free gas phase in the body, which is formed e.g. as a result of cavitation in the heart, which can create growth of germs for the free gas phase during the decompression process. From the middle of the last century, the prevailing view was that successive dives should follow a certain sequence of depths in order to reduce the risk of free gas phase formation. The first dive in the series should be the deepest, with a short exposure [13]. This dive will cause the free gaseous phase normally existing in the body to compress to a smaller and therefore safer size. Subsequent successive dives should be conducted progressively towards smaller and smaller depths depending on the depth of the first crush dive [51]. In the Polish Navy from the beginning, this concept seemed questionable for many reasons. They will not be analyzed here, as they would take too much time. At the beginning of this century, attempts were made to refute this view [50]. Preliminary national studies on successive decompression showed that for similar values of diving depth, the sequence of dives does not matter [6].

Currently, opinions are still divided as to the possibility of using inverted profiles of sequential dives, hence it seems that the decompression system should specify whether such a possibility has been tested in the decompression system validation *process*.

HYPOBARIC DECOMPRESSION

Anyone who moves to a higher elevation, for example when climbing in the mountains experiences hypobaric decompression. Such small changes in pressure affecting humans are almost imperceptibly compensated by the human body[121] [52]. Some people experience decompression effects during ascent and then "clogging" of the middle ear during re-compression, manifested by pressure on the eardrum.

The *process* of diving in high mountain lakes is related to the transition of decompression to a pressure p, lowered $p < p_0$ in relation to the atmospheric pressure p_0. In such cases, most often, special decompression procedures are developed. Elevated water bodies can cause a significant increase in the hazard of pressure sickness H_{DCS} , e.g. when diving in high mountain lakes and using the standard profile for decompression to normal pressure p_0, present at sea level. The decompression profile in areas elevated $p > p_0$ above the sea level p_0 should be validated for decompression conditions to the pressure of the area of rest after the diving p.

Air transport after diving which is accompanied by a decrease in the value of pressure $p < p_0$, as is the case when flying on commercial planes or transport helicopters, can cause such serious imbalances in gas pressures in tissues after diving π_i. Changes in cabin pressure during an airplane or helicopter flight[122] may affect the conditions of the decompression process due to the decrease in pressure $p < p_0$ at the cruising altitude[123].

This may result in the evolution of a free gas phase leading to decompression sickness symptoms. The procedures used to assess the decompression distribution should specify the altitude and and time at which the surface isobaric decompression will be occurring. Hence, the time of rest after which air transport at the required altitude will be safe can be calculated.

To protect military aircraft pilots against hypoxia oxygen inhalers are used, and to protect them against overloads they use special reactive suits. However, they do not have sufficient technical support to counteract explosive-related decompression caused by cabin unsealing, e.g. when the cabin has been shot through and the explosive decompression has occurred[124]. Failures of life support systems, including oxygen inhalers, can also cause dramatic consequences [53].

SURFACE DECOMPRESSION

As mentioned above, the surface decompression is sometimes referred to as interrupted decompression, but here the surface decompression is the isobaric decompression, used to restore homeostasis in the diver's body in the atmosphere of the habitat. The habitat can be the atmosphere at the sea level, in the area of a high-mountain lake, in a cave, diving bell, compartment of an underwater diving vehicle/underwater house, etc.

The pace to reach homeostasis can sometimes be accelerated, e.g. by using oxygen-enriched or pure oxygen mixtures for breathing. Theoretically, acceleration based on the counter-diffusion phenomenon is also conceivable, although in practice such an action is so dangerous that it is not practiced.

Homeostasis can be achieved in hyperbaric conditions present on the saturation plateau, from where the diver can dive to greater or lesser depths in relation to the saturation plateau. In most cases, diving from the saturation plateau is planned for possible ranges of the direct decompression. In addition to saving a number of necessary decompression processes when diving outside the saturation zone, saturation dives offer the opportunity to increase the divers' workload. Dives outside the saturation zone cannot lead to a decrease in blood pH, because the efficiency of oxygen transport by hemoglobin decreases drastically in an acidic environment [7]. Lactic acid is a metabolic product formed during anaerobic changes[125] associated with increased effort. For safety reasons[126], in saturation conditions, only dives from the saturation plateau are performed, allowing for the use of direct decompression[127]. Hence, a temporary decrease in blood pH, and the resultant loss of ability to effectively transport oxygen by hemoglobin, does not significantly increase the hazard of decompression sickness symptoms H_{DCS}. When preparing for the main decompression

from the saturation plateau, divers can take a sufficiently long time of rest[128] to be able to compensate, with absolute certainty, for all the factors hindering the decompression *process*[129].

ADAPTIVE DECOMPRESSION

The problems related to the surface decompression *process* described so far have focused on the situation of returning to homeostasis after the diving *process*. However, it is also important to achieve homeostasis before diving, because virtually every decompression system assumes full homeostasis before diving. The adaptive decompression is the isobaric decompression, used to achieve homeostasis in the diver's body in the habitat atmosphere, to which the diver will return after the diving *process*. As is the case with the surface decompression, the adaptive decompression can be a habitat at sea level[131], in an elevated area[132], in a cave atmosphere of[133], diving bell, diving compartment of an underwater vehicle/underwater house, etc.

Like in the surface decompression, the recovery pace for the adaptive decompression can sometimes be accelerated, e.g. by using oxygen-enriched breathing mixtures or oxygen.

In the case of the adaptive decompression, it is necessary to take into account the achievement of homeostasis after effort, hence the decompression system should take into account the time the diver is relived of effort and the time needed to rest after physical effort before a dive. Probably, there are some recorded death cases related to excessive effort before starting the diving process. [32,54].

It is important to achieve homeostasis in hyperbaric conditions present on the saturation plateau after the compression *process*. If the compression *process* has been slow enough, divers could immediately proceed to plateau dives and undertake underwater work activity. However, when reaching the saturation plateau has required strenuous effort, divers should be given time to adapt to the saturation plateau [25].

COMPENSATORY DECOMPRESSION

When discussing the successive and surface decompression, it was pointed out that the period between dives related to the time assigned to the isobaric surface decompression to achieve homeostasis can be shortened by using the surface, isobaric accelerated decompression, e.g. by administering oxygen for breathing. This procedure is colloquially referred to as "oxygen flushing". This procedure can also be regarded as an element of the combined compensatory decompression in a situation where there is a significant increase in the hazard of decompression sickness symptoms H_DCS [37,55]. Such a procedure was described when discussing cases of usin g alternative decompression, related to the omission of a decompression station or other acceleration of the decompression process. The surface "oxygen flushing" can compensate for the acceleration of the completed decompression process in relation to the assumed main decompression. Also, the implementation of hyperbaric oxygen flushing can be regarded as compensatory decompression.

During the decompression process after a saturation dive, or after a trip from the saturation plateau, there should exist appropriate procedures to compensate for the unplanned increase in the hazard H_DCS, as is the case with the procedures developed for therapeutic recompression[134] in the event of DCS symptoms at various stages of saturation diving [25].

THERAPEUTIC RE-COMPRESSION

Here, it has been assumed that the implementation of procedures for treating the symptoms of decompression sickness DCS involves re-compression and subsequent therapeutic decompression [58,59].

An absence of the re-compression phase characterizes compensatory decom-pression, which, even if it concerns counteracting the materialized symptoms DCS , does not have to be a therapeutic procedure in the legal sense of the word.

SPECIAL DECOMPRESSION

The special decompression refers to unusual decompression procedures that differ from the standard procedures of the main decompression. An example of such a rather unusual special decompression may be the procedure of instantaneous direct decompression, used in some types of saturation dives, discussed earlier in the part dedicated to the interrupted decompression.

During rescue operations, non-standard actions must be taken many times. Hence, some rescue decompression procedures can be regarded as special decompression processes, such as discussed earlier the free-surfacing self-rescue procedure devised for a DISSUB crews.

Similar situations as in the case of conducting a rescue operation can happen in combat situations when it is necessary to use the special combat decompression, which is usually characterized by a significant increase in all kinds hazard _H.

Special types of decompression procedures must be used during extreme dives, for example, when attempts are made to beat various types of records. Such cases involve the use of inherent features of the diver, special adaptation training and reaching the individual physiological limitations, or even exceeding the limitations considered safe in the decompression process.

An important type of special decompression is the analogous decompression.

EQUIVALENT DECOMPRESSION

It is possible to use some decompression procedures in conditions different from those originally assumed by the developers of the decompression systems.

It was mentioned earlier that air tables not originally devised for use in elevated areas can be used when appropriate corrections are made [31,60].

The most common application of the special decompression is the use of air decompression procedures for Nitrox Nx dives, they have been converted according to the equivalent air depth EAD[139] [61].

During Heliox Hx saturation dives, the Hx decompression tables can be used for dives outside the saturation zone to conduct the emergency decompression when the compression process to the saturation plateau is interrupted due to an accident and decompression of divers is required [62].

Nx saturation procedures developed by NOAA allow converting decompression from the US Navy standard air decompression tables for bounce[140] dives to emergency staged decompression to the Nx saturation plateau when the diver exceeds the limit of exposures allowable for direct decompression [49].

RESCUE DECOMPRESSION

As mentioned earlier, in the part discussing the accelerated decompression, in a rescue situation special procedures are used. They involve implementing the decompression processes with an increased hazard of decompression sickness symptoms H_{DCS}, of central oxygen toxicity H_{CNSyn}, etc. [40,45].

However, a rescue situation may force the implementation of non-validated methods of conduct, which from a theoretical point of view can be applied, and without their implementation, the situation may reach a much more dangerous phase. For example, there are no dedicated elements of rescue systems that can be used to effectively decompress people have got stuck and have become saturated in the air cushion of a sunken vessel [38].

So far, the chances of surviving underwater in the conditions of saturation in a wreck have been assessed skeptically, with the exception of the crews of sunken submarines who are trained to survive in such conditions [10].However, the case of *Harrison Okene*, who survived over 62 hours in the sunken tug *M/S Jascon*-4, which sank in the Atlantic on May 26, 2013 at a depth of 30 mH_2O about *30 km* off the coast of Nigeria, requires a different approach to this issue [63]. To conduct decompression for *Harrison Okene*, probably a decision was made to implement the standard US Navy Heliox *Hx* decompression [25]. Theoretically, such a decision was associated with an increased hazard of DCS related to the counter-diffusion *process*.

In the Polish Navy, there was a problem of decompression of deep-water divers who got stuck in a diving bell that got caught in the nets attached to the German ship *M/S Goya*, which had been sunk during World War II. The divers exceeded the exposure limits worked out for the standard Trimix *Tx* decompression process. The rescue decompression procedure that could be implemented was the use of the T4 MW emergency decompression table [22]. This table was dedicated to a situation when a typical diver has got stuck during a dive with air as the breathing medium, to the level of sub-saturation saturation. As in the case of *Harrison Okene* rescue, there was a potential hazard of counter-diffusion related DCS symptoms. However, despite almost twice the diving depth, the hazard was assessed as much lower than in the case of the rescue operation on the *M/S Jascon*-4 wreck.

In the case of both rescue operations, the implementation of non-validated rescue decompressions paid off, as human lives were saved without any damage to health.

COMBAT DECOMPRESSION

As in a rescue operation, a combat situation sometimes requires a quick decision to apply a special decompression. Therefore, appropriate action procedures applicable is such situations should be devised in advance . In developing such procedures economic effectiveness must be taken into consideration. An example of such an approach was the idea of developing an algorithm for calculating the decompression process for the US Navy, taking into account the hazard H_{DCS} in terms of probability success[141] of a military operation, whose part was a diving operation [64].

SUMMARY

The descriptions of the types of decompression presented here are not an attempt to standardize the relevant ter-minology, but they are intended as local subject specific terminology, i.e. an ordered set of terms used in diving.

The phenetic[142] taxonomy[143] of the types of decompression described here is shown in Fig. 2. It is intended to facilitate formulating requirements for diving technologies being reviewed or newly developed, with particular emphasis on the decompression process.

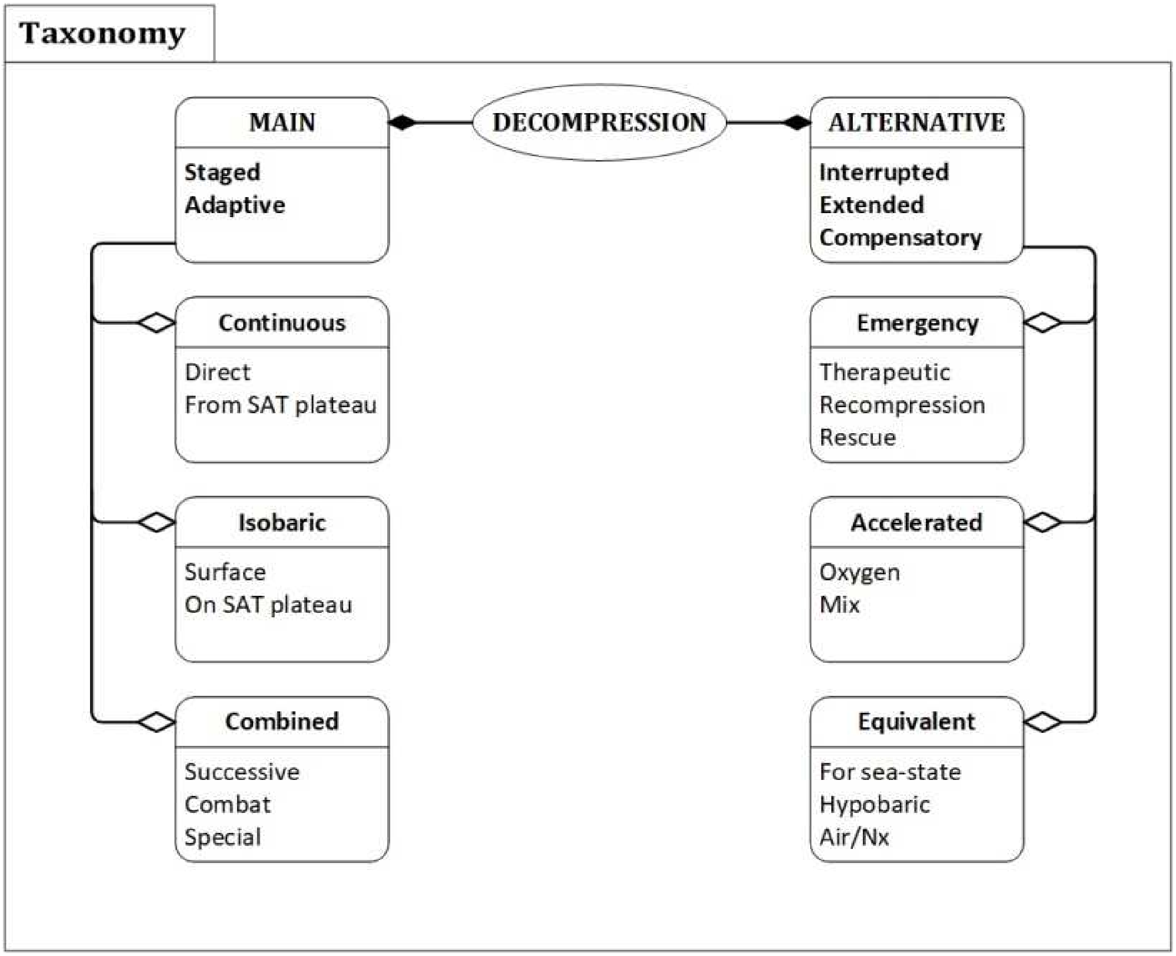

Fig. 2 Common types of decompression together with common subdivisions.

REQUIREMENTS

In respect of the decompression system, the diving technology should include information on the possibilities/conditions for its application in practice, in particular specifying:

- the types of the breathing mix, equipment and accessories foreseen to secure the diving process and subsequent decompression,
- for which group of divers it is dedicated/validated,
- standard diver parameters and environmental conditions,
- information on how to prepare for the decompression process through strength, fitness, adaptive training, etc,
- possibility of applying decompression for consecutive dives,
- options for diving in elevated areas, and options for air transport,
- reference to recommended emergency and recovery procedures,
- possibilities to use alternative or combined decompression.

TECHNIQUE

The determination of the breathing mixes, equipment and diving equipment is crucial for the diving technology and the decompression process. For instance, if the decompression system is oriented towards transport under pressure *TUP* in a sealed diving bell to the diving complex, and the decompression process involves changing the breathing mix several times, it is difficult to provide such a progression and comfort for the decompression process underwater.

An example of the orientation of decompression procedures towards diving gear and equipment can be found in the new US Navy system for bounce dives [25]. The decompression tables are divided into ranges of applicability by the technical equipment used during the diving process.

STANDARD

Making it clear for which group the diving technology, and in particular the decompression system, is dedicated/validated can be important, especially when there are anticipated concerns/differences in the intended system environment under conditions of diving technology application. For example, in a military service environment, there is usually a system of selection, physical checks, medical checks, maintenance of military and diving fitness, etc., which, unlike admission to recreational diving, where sometimes only a statement of intent is sufficient, are not met. Military systems are usually assessed on the basis of validation and observation of the propagation of the occurrence of DCS cases among people who are relatively young and maintained in good diving fitness. It can be argued that a decompression system developed for the military may not be adequate for use in a civilian environment, for example for individuals of advanced age. Historically, US Navy tables were widely used for commercial and recreational diving, although they were judged as lacking in conservatism, but the observation of a relatively high percentage of light DCS symptom incidents was not found to be a misjudgement of the extent of their application, or a failure to place sufficient importance on maintaining adequate diving fitness. This has contributed to the development of new decompression models such as *RGBM, VPM, TGBM* etc. The same was true of the Bühlmann algorithm developed for the Swiss army, which underwent several modifications to increase conservatism. For example, Max Hahn applied the Bühlmann algorithm with his amendments for the Swiss Underwater Sport Association, and Bob Cole for the Sub-Aqua Association[144] [51].

Defining the 'standard diver' for whom the diving technology has been validated helps to identify conditions that impede the diver-dependent decompression process. For example, if a decompression system has been validated for a man with a petite physique, in some cases it may be inadequate for a man with an athletic physique.

What is important to note about military technology is that it was predominantly developed for men. Nowadays, equality is being pursued, which raises the fundamental question of whether these systems are appropriate for women. Preliminary studies conducted internationally and by the Polish Navy show no significant differences [9,23,65]. A study done in the USA by Susan Bangasser in 1978, shows that there were 3.3 times as many suspected and as many treated cases of DCS among a group of women compared to a group of men [16,51,66], but it dealt with hypobaric issues and the mechanism of induction of DCS symptoms is slightly different in this case [23].

Information regarding environmental conditions is used to accurately identify environmentally dependent hindering conditions for the decompression process in conjunction with the diver and the equipment and gear used. For instance, it may address the impact of overcooling, although when an active thermal protection system is used, these recommendations are no longer as relevant, and become important when the active thermal protection system fails. Sometimes the conditions are closely related to the diver, as in dives without access to the surface of a body of wate[145]. The associated mental stress can lead to an increased sensitivity to central oxygen toxicityR_{DCS} [67].

In the case of distributed information systems influencing the decompression process, attention should be paid to whether revised requirements in various documents have a significant impact on the related underwater work technology. For example, in the past the Polish Navy applied diver height range limits related to the type of classic diving suits used. Only two sizes of wetsuit were provided for classic divers. Too short a suit could result in a potentially dangerous situation where, when the crotch strap broke, the helmet "escaped" to such a high level that the diver was unable to reach the relief valve, while too tall a diver could not be tightly bolted into the suit. Nowadays, suits can be selected individually for divers, so the requirements for a height range for diving candidates can be removed. The safe use of semi-closed-circuit breathing apparatus is often influenced by personal oxygen consumption in conjunction with lung ventilation [8,10]. In sports medicine, the aim is to ensure such a level of training of the athlete that he or she maximises the oxygen intake with the breathing mix $\dot{v}/\dot{V}_E$. Depending on how the limits of these parameters have been set during the design and validation process of a decompression system dedicated to a specific equipment, it may pose a potential hazard H_{DCS} of the occurrence of DCS symptoms for divers with increased or reduced oxygen consumption $\dot{v}$ relative to lung ventilation flux $\dot{V}_E$ [8].

PREPARATION

Information on preparation as part of adaptive training should include prerequisites for the use of diving technology with the decompression processes described. This usually involves a step-by-step adaptation process to undergo the decompression process. An example of this approach will be presented in the second part of the article. Many neo-Haldane decompression systems are based on models developed by Bühlmann, but often their implementation is not accompanied by sufficient attention to the author's recommendations on their utilisation [13].

SUCCESSIVENESS

The information on successive decompression may only concern the statement that successive dives are not permitted and that the rest time between dives is the relevant recommended period. Successive decompression should also be understood as procedures to adapt to diving in elevated regions etc., as the hypobaric decompression process at the surface of the body of water precedes and directly affects the first dive in the depths of the body of water. Similarly, air transport after a dive should be viewed as an additional decompression process.

It should be borne in mind that after the dive, while on the surface, a surface isobaric decompression process is still taking place, which has a direct impact on the safe possibility to undertake successive dives[147] and post-dive effort output. The decompression regime should take into account the pause time to reduce supersaturation during the isobaric decompression process occurring at the surface during post-dive rest[148] and the possible range of effort output immediately before and after the dive. Therefore, the decompression regime should include reliable limits for the recommended rest time after a dive in the isobaric decompression phase, and repeat dives should take into account the remaining supersaturation state after the previous dive and the fatigue state of the diver resulting from previous dives.

EMERGENCY PROCEDURES

References to recommended emergency and treatment procedures are rather self-explanatory when planning the decompression process. Having such information in the system not only facilitates the selection of these procedures, but prevents them from being overlooked during the dive execution planning process. The procedure for the execution of the basic decompression process should always be complemented by plans for the execution of alternative decompression processes, and compulsorily including procedures for the execution of emergency and compensatory decompression processes, as well as a therapeutic decompression system. Reference to recommended emergency procedures in the decompression system may also point to their wider use. For example, Table 4 used for dives with the use of air in the Polish Navy, but was also recommended as an emergency table when using Trimis Tx.

SUMMARY

Ideally, the decompression system should be tailored to suit each need. However, most often[149] for financial reasons, the decompression system is not adjustable to fit all existing needs. Sometimes it can be supplemented by non-validated methods, such as using the air-equivalent depth EAD for dives utilising Nx.

It is good practice to perform a decompression system capability analysis in the context of assessing the level of risk and all needs to fulfil the objectives of the diving process. The method of conducting such an analysis will be performed against the background of the air decompression system used in the Polish Navy [22].

FINAL REMARKS

In adapting diving technology, attention should be given to combined and emergency decompression profiles[150], hygiene and proper preparation. Whereas in military diving, emphasis should be placed on a system for enforcing the arrangements associated with the diving technology developed

OBJECTIVE

It seems that, apart from utilitarian dives[151] the diving process can be carried out without a specific objective. However, it can be noted that in such a case it is also possible to specify the non-utilitarian purpose being pursued, e.g.: recreational, exploratory, training, sporting, competitive, ambitional, etc.

CONTEXT

Structural elements of the safety system for the diving process are selected depending on its objective. The selection of the structural elements of the system should take into account the internal and external context for the defined system, which influences the adaptation of the appropriate diving technology.

TACTICS

The internal and external context for the defined system makes up the tactical context, which is the main parameter influencing the adaptation of diving technology. The tactical context is understood here as the theory and practice of using the structural elements of the system to effectively carry out the intended process in the system, leading to the achievement of a defined goal.

RISK

The system adopted to achieve the objective of the diving process is selected, modified and supplemented according to the principles of system analysis in the course of risk analysis. The risk analysis process is conducted based on the knowledge of the available technologies for the execution of underwater works, their technical requirements, legal requirements, possibilities of modification and combination, etc. [27].

Depending on the level of acceptable risk R, the adopted minimal system to achieve the diving process objective is supplemented with redundant elements, guaranteeing an increase in the probability of achieving the diving process objective or a decrease in the level of residual risk R in the system. The risk analysis process is most often conducted based on calculations for the systems: with and without a specific element. The difference in the values of the residual risk for these systems and the probabilities of achieving the goal by the processes taking place in them provides an indicator for defining the structure of the desired system and the structure of alternative systems [3].

The decision regarding the final choice from among the proposed systems to achieve the planned process objective is made on the basis of an analysis of the availability of the structural elements of the proposed systems and an economic analysis.[152]

LAW

A number of legal aspects are particularly relevant to diving technology during the process of adopting and modifying it to meet the objective of the diving process. For example, the use of compensatory decompression can be interpreted as: a standard approach, a potentially dangerous situation or a situation of implementing a therapeutic procedure, depending on the legal provisions used in the investigation of diving accidents. The legal qualification associated with the investigation can lead to severe sanctions.

Attention should always be paid to the legal effects of the procedures implemented to ensure that they do not result in decision-making paralysis[153] or loss of relevant information when utilising the decompression system.[154]

MONITORING

An important structural element is the system's self-monitoring procedures, which most often reveal their relevance when the established system is used repeatedly for a single purpose carried out using the same process.

A number of examples may be found where a properly designed system, as a result of the cumulative effect of various residual risks R, against which the precautions established in the system were relaxed, resulted in system failure. It must therefore always be taken into account that, during the continuous operation of the established system, a degradation process occurs causing a continuous increase in the level of hazard H of materialisation of residual risk R. This process is commonly referred to as 'system ageing.' It is vital to establish in the system's structure elements capable of revitalising it in order to halt the 'ageing' processes.

SUMMARY

The article presents the definition of a decompression system based on a process approach for the performance of a system analysis.

On the basis of the analysis of diving accidents and potentially dangerous situations during the execution of diving processes, it can be concluded that a frequent premise for the materialisation of residual risk R was the inappropriate choice of the system structure, which was to guarantee the secure and safe realisation of the objective of the executed diving process.

CONCLUSION

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[1] Underwater Working Group NATO Standardization Office

[2] Decompression Sickness DCS

[3] Central Nervous Syndrom CNSyn

[4] based only statistical modelling

[5] here, implementation of the model under conditions of unsatisfactory estimation of the level of uncertainty of the decision to be taken

[6] lying outside the system but influencing the processes within it

[7] ability to maintain relatively constant internal system parameters

[8] for example, by establishing the boundaries

[9] if, for structural reasons, there is a need for redundant elements, for example relating to safety, this approach also falls within the term "reasonably minimal set of elements" as used here

[10] joint effect stronger than the sum of separate actions

[11] the objective of basic science is to know these processes

[12] for example, it is not really clear what the process of natural nuclear decay is actually designed to achieve

[13] „…he who experiences various signs and consequences of a lack of reflection or absurd reflection, i.e. of understanding, whether his own or someone else's, must eventually arrive at the general hypothesis that stupidity exists …" [68]

[14] existence of different systems in the same type of system structure

[15] existence of similar systems capable of supporting different processes

[16] similarity of systems and their processes

[17] a relatively isolated system, minimally complex, working in analogy with the original to study information and control flows in the modelled systems

[18] an economic model is a conceptual construct comprising an arrangement of assumptions adopted in economics to capture the most salient features and relationships in a given economic process

[19] a feasibility study most often only includes a financial model as part of an economic model which, in addition to the financial study, also includes a valuation of social effects

[20] such an approach is justified when the observed variation is largely random - the process is under so-called statistical control

[21] for functional models, all the algebraic factors of the model have a strict physical interpretation

[22] for example, due to time constraints, financial constraints, etc.

[23] for semi-empirical models some of the factors of the algebraic equation lack a clear physical interpretation, while for empirical models none of the factors have such an interpretation

[24] a process of phenomenological cognition that uses only our sensory organs

[25] precise and accurate

[26] a probabilistic description that makes it possible to value the risks of decisions when making inferences in a problematic situation

[27] meaning that it cannot be evaluated only in terms of financial profitability, but also in terms of social consequences

[28] making the model a permanent part of the knowledge system as a reliable tool for predicting the process behaviour of defined systems

[29] research consists of the basic research, which is carried out in order to obtain models regardless of the possibility of their application, and industrial research, which is carried out when there is the possibility of their application, although it may not be economically viable to implement them at a given moment

[30] indeterminate integral

[31] prevailing at diving depths

[32] pulmonary toxicity

[33] usually normobaria

[34] where i is the index of the corresponding gas

[35] is not always the atmospheric pressure, as the decompression process can be oriented e.g. to the saturation plateau

[36] Oxygen Poisoning Syndrome [7]

[37] Oxygen Poisoning Syndrome [7]

[38] the dot above the symbol indicates the derivative after time

[39] change in other environmental factors $\boldsymbol{\eta_{\bullet}}$ is not used in practice

[40] inseparable

[41] rather than only changes in the pressure $\dot{p}$ and composition of the breathing mix $\dot{x}_1..\dot{x}_i$

[42] residual risk that can no longer be minimised under given conditions

[43] presented condition assessment based on studies and analyses

[44] Good Diving Practice

[45] activities designed to test adequacy at a given level of accuracy and precision

[46] extrapolation

[47] interpolation

[48] most often these are collected in the form of a case study, and the conclusions of the case study are introduced as pilot recommendations for use or possible patents making up good diving practice GDP

[49] wiedza jeszcze niewalidowana metodami i metodykami uznanymi za naukowe

[50] master disciple/apprentice

[51] apprentice's master

[52] the gaseous composition of the reference atmosphere is given as a simplification of their normal content, although it also changes slightly with altitude due to differences in the specific weight of oxygen and nitrogen, which may result in [52] slight stratification53 a corridor cut off by the water may have a pressure much higher than would result only from its level below the sea surface

[53] a corridor cut off by water may have a pressure much higher than its level below the sea surface alone would suggest

[54] gradient vector $\underline{\nabla}$ includes gradients for all considered gases i: $\underline{\nabla}(\Delta_1..\Delta_i)$

[55] the concept of conservatism is defined later in this chapter

[56] Varying Permeability Model [69]

[57] Reduced Gradient Bubble Model [70]

[58] Tissue Bubble Dynamics Model [71]

[59] statistical model [64]

[60] where appropriate, also further history of the exposure

[61] the decompressiometer cannot normally take into account the residual risk

[62] most often a comment is included about using the decompression system at one's own risk

[63] to avoid a pejorative meaning of this statement, these skills can be compared to those of diamond cutters, master chefs, etc.

[64] we refer to professional cosmonauts and not people who are mere tourists in space

[65] nowadays, it is becoming increasingly common that having a service manual requires a franchise agreement with the manufacturer

[66] contradictions

[67] this recommendation also applies if the depth of exposure is equivalent to that found in the table

[68] these are the results of tests carried out under controlled laboratory conditions

[69] maximum allowable pressure gradient

[70] in order to avoid this situation some people adopt conservatism $\kappa = 0\%$ for gradient $\Delta_i = 0{,}30 \cdot \Delta_i^{max}$ referred to the leading tissue i at a given decompression stage, and $\kappa = 100\%$ for gradient $\Delta_i = 0{,}75 \cdot \Delta_i^{max}$ [72]

[71] residual risk materialisation

[72] actually on the basis of a multidimensional risk $\underline{R}$ taking into account not only the risk of decompression sickness R_{DCS} ut all the risks of oxygen toxicity symptoms R_{OSyn} and other risk factors [26,27].

[73] heuristics here means an approximate model for which there is no guarantee that it is optimal, often even correct over the entire range of variation in the model domain, which is used e.g. when the use of an adequate model is too expensive for technical reasons or it is unknown

[74] in general in Poland, the prerequisite for admission to journeyman apprenticeships is vocational training, and for admission to the master's examination at least secondary technical training in the profession and, after obtaining the title of technician, at least six years' work experience in the profession to which the examination relates.

[75] without changes in total pressure, the diver would not be able to leave the hyperbaric environment

[76] the decompression process also takes place after the formal end of changes in pressure/breathing mix composition during the rest period after the dive

[77] other symptoms of oxygen toxicity must also be taken into account during saturation dives, treatment of decompression sickness symptoms, etc. [7]

[78] reduce the impact of ambient pressure on the diver

[79] Nomenclature is an ordered collection of terms used in a particular field

[80] capillary separation - laboratory practice uses freshly broken porcelain shards added to solutions that do not react with the porcelain to balance the boiling process when they are heated

[81] Not only because of the protection against the increase of gas accumulation in tissues

[82] way is to gradually increase the depth until the depth of relief

[83] super-saturation

[84] The decompression process after carbonation can also be carried out using step decompression

[85] within a certain acceptable range, of course

[86] pay attention to the possibility of reduced blood circulation due to local compression or insufficient hydration

[87] probably, this is the effect of incorrectly shortening the decompression term without decompression stations

[88] both stepped and continuous

[89] with very rapid oxygen decompression, DCS symptoms can be induced [33,73]

[90] accelerates

[91] if only because of the difficulty of achieving 100% O_2 concentration in the inhaled respiratory factor

[92] accelerations

[93] a chemical compound similar to another compound; here, a similar breathing mixture differing in increased oxygen content

[94] which are cumulative risks

[95] The Lorrain Smith effect was first observed with normo-baric p_0 oxygen breathing for τ>24 h [49,74,75].

[96] Here in the sense of describing cases with a relatively infrequent course, relatively infrequently occurring

[97] there are known cases of extraordinary resistance of the body to harmful exposures due to mental attitude, for example, described during the Chernobyl nuclear power plant accident

[98] there are known cases of extraordinary strength and endurance of people able to mobilize in the face of adversity

[99] deferred anxiety actions are often observed, when a person is able to act extremely pragmatically under extreme conditions, although the typical traumatic reaction of de-escalation follows later on

[100] the experience of a traumatic situation can make one immune to similar situations, for example, in the form of indifference turning into habit, as among some people the experiences of war

[101] extraordinary, exceptional

[102] National Oceanic and Atmospheric Administration

[103] Underwater habitat near Key Largo

[104] Distress Submarine

[105] Deep Submergence Rescue Vehicle

[106] Transport Under Pressure

[107] using special rescue suits, such as Mk-10/12

[108] for example, the phases of not having access to the free surface as when diving to the inside of a wreck, flooded pit, tunnel, cave, etc.

[109] because most often its final phase takes place on the surface at the dive base

[110] for theoretical consideration is also possible decompression implemented in a separate chamber of the underwater base.

[111] and thus reducing the diver's risk associated with being in the depths, which can contribute to the intensification of underwater work carried out by a wider team of divers

[112] this time is taken within τϵ[5;7]min depending on the adopted tables ([76] - Appendix A

[113] it is indicated by the position of the buoy, which is moored near the habitat

[114] repetitive/repeatable

[115] for example, due to the accumulation of fatigue

[116] both during the return to normal conditions, the region elevated above sea level, occurring in habitat, etc.

[117] the world does not describe the difference between repetition dives and repetition dives, the Polish regulations distinguish between repetition dives in a time not shorter than τ≤2 h and a time above τ>2 h, but when the time between dives is so shortτ<τ_max that the effect of the inert gas deposit remaining in the body must still be taken into account; from a theoretical point of view, this time depends on the longest saturation half-life τ_(1⁄2) for the accepted set of theoretical tissues and most often for the US Navy it is τ_$\tau_{max} = 12\,h$ h and for many other $\tau_{max} \in\in [12, 36]\,h$ [60].

[118] when conducting research on the effectiveness of the decompression process, DCS symptoms are provoked through ink,

[119] residue of free gas phase bubbles after previous dive may be seed to facilitate free gas phase buildup

[120] is not just about the impact of the remaining inert gas load, but also the impact of fatigue in the broadest sense after the previous dive(s)

[121] generally up to 1,500 meters above sea level, unless one's body overreacts to the impact of weather conditions - meteopathy

[122] in cruise aircraft are allowed to reduce cabin pressure for strength reasons - aircraft in this way can be designed for smaller pressure changes, hence their structure can be lighter

[123] according to generally accepted guidelines, inside passenger aircraft cabins, the pressure must be maintained at a level no lower than that corresponding to being at an altitude of 2438 meters above sea level (0.75 atm) [77]

[124] sometimes, pilots are trained/tested for this, for example, on the web you can find such a test for a USAF pilot: https://www.youtube.com/watch?v=OmeJlewaU7s

[125] with oxygen deficiency

[126] at depth and with a residence time that allows for direct decompression

[127] in the event of a diagnosed potentially dangerous situation, it gives you the opportunity to immediately return to the diving bell

[128] it is usually up to two days

[129] return to conditions of typical homeostasis before the decompression process is undertaken by decompression

[130] For example, after air travel or returning from high mountainous regions

[131] for example, a high mountain lake

[132] where there may be significantly elevated pressure relative to atmospheric pressure

[133] for example, according to Table TT 5 USN, implemented without any other indication than an increase in the risk of H_DCS the possibility of pressure disease symptoms of DCS

[134] in particular, these may be the same procedures, but implemented for different indications, but in the case of compensatory decompression, there will be no concept of 'depth of relief'

[135] Hyperbaric Therapy

[136] Hyperbaric Oxygen Therapy

[137] for example, action against infections with anaerobes, poisoning by volatile or gaseous substances, when oxygenation needs to be implemented, etc.

[138] applications of direct decompression

[139] Equivalet Air Depth

[140] Dives outside the saturation and sub-saturation zone

[141] achievement of the goal of the process of implementation of the military operation

[142] here, a preliminary analysis of the processes, consisting of the separation of homogeneous subpopulations subject to separate further analysis

[143] a method that clusters processes into relatively homogeneous classes, based on the relationship of similarity between the classified systems and the processes running in it

[144] formally the Sub-Aqua Association prefers direct decompression profiles and the decompression tables developed by Cole are procedures for special emergency/alternative decompression

[145] for example, inside a wreck, flooded cave, mine workings, etc.

[146] had no impact on the diving technology used

[147] repeated

[148] the isobaric decompression process is not the only limiting factor for undertaking the next dive

[149] for example, in the situation of deciding to limit decompression tables to direct decompression, as in saturation plateau dives

[150] for example, omitting shallow decompression stations, when diving in marine conditions, as the effect of wave action in the body of water has such a significant impact on the diver remaining in the depths near the surface that it becomes questionable whether he or she can remain in shallow decompression stations, which in many decompression systems are essential for decompression safety

[151] aimed at a practical, material benefit

[152] one should not equate financial analysis with economic analysis, which in addition to financial analysis includes the valuation of social effects

[153] if any implementation of alternative decompression is penalised, the decision to implement them will be deferred for fear of sanctions to the detriment of safety

[154] if every implementation of alternative decompression is penalised, it is possible that these will not be reported for fear of sanctions, thus distorting the statistics on the risk posed by the decompression system