

DECOMPRESSION FOR DIVERS IN THE LABYRINTH OF SCIENCE, KNOWLEDGE AND EXPERIENCE. THE BEGINNING OF THE SERIES. PART I. DECOMPRESSION – SELECTED ISSUES.

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ABSTRACT

The first article in this series outlines the most important principles of decompression from a physical and medical perspective. It describes the current state of knowledge regarding decompression tables, their application and limitations, as well as the growing trend of replacing independent planning of safe decompression with the use of various dive computers.

Examples are also given of accidents resulting from various disruptions to the correct execution of compression and decompression.

Keywords: decompression, diving safety, underwater works, decompression tables, dive computers.

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INTRODUCTION

The authors of the following article present perspectives on the subject of diving that are very distant from one another in terms of time, fields of expertise and experience. The first author has over half a century of professional experience in military, commercial and recreational diving. The second is a recreational diver and an enthusiast of diving history and modern technology, with a particular fondness for closed-circuit rebreathers. The third author is approaching half a century of diving experience, having been involved in recreational diving, military and research diving, but above all in the medical safety of diving, as well as the study of diving-related illnesses and accidents.

As many authors and practitioners emphasise, familiarity with decompression tables is essential knowledge for divers supervising underwater operations, diving instructors and doctors specialising in diving medicine. In the past, basic knowledge of these tables was part of recreational diver training; however, 'dive computers' have replaced that knowledge, giving a false sense that someone else is thinking for the diver.

A higher level of understanding involves interpreting these tables to adapt them to the specific dive organisation, particularly when a dive deviates from the planned course—whether due to the diver's fault, technical issues, poor management, or the influence of the surrounding environment whilst carrying out underwater work or a task. Simply put, we should be able to use the tables in all conditions, including – or rather, particularly – in adverse circumstances.

Up-to-date diving knowledge requires specialisation across four interrelated disciplines: technique, dive organisation, and medicine and psychology, which relates not only to the diver's own condition but also, more broadly, to the interpersonal relationships within the organisation implementing the dives.

DECOMPRESSION IN DIVING WITHIN THE BROADER CONTEXT OF HUMAN UNDERWATER ACTIVITIES

The statement that decompression is a complex process is a well-worn cliché, but it must be emphasised that, despite advances in science in many fields that cover decompression, the process is not yet fully understood and there is no standard method for modelling it. During the training of divers and dive leaders, in both commercial and (formerly) recreational diving, the transfer of knowledge on this subject is often limited to the necessary subjective experiences and knowledge of the instructors.

Today, it is almost impossible to imagine a diver without a dive computer, although there are exceptions to this among knowledgeable older-generation divers. This is despite the fact that current formal documents governing commercial diving and, to a large extent, military diving rightly 'overlook' the direct use of such computers during dives. The market for personal computers is vast, and owning a personal computer is now standard practice across all areas of diving. Professional marketing and intensive advertising encourage the purchase of a specific model from a particular company, where the competitive factors are: the number of recorded parameters, the

method and clarity of information displayed on the screen, the variety of models and range of decompression algorithms, ergonomic design and ease of use, and the ability to record the dive log. The excess of information contained in a dive computer is intended to 'dazzle' the buyers and reassure them that they have the best and most fashionable equipment available on the market. This is complemented by fun extras such as games to make the decompression period more enjoyable [1].

The average diver, even one who is very interested in the subject of decompression, finds it quite difficult to assess the full practical value of a dive computer. It is hard to identify any shortcomings or limitations of such a device without understanding its full operating principles.

Information regarding the model used for decompression programming is partial, failing to take into account other aspects of the tables used, including the limitations of underwater physiology, the accuracy of decompression parameters, the influence of specific environmental parameters, and the characteristics of the diver using the decompression, or even information regarding their gender. What does information regarding the decompression models used in algorithms, e.g. ZHL12, ZH-L16, ZHL-8, ADT MB, ZHL-16C, or Gradient Factors settings, etc., actually tell the average diver? It sounds clever and sells well. Although this information is widely available and personal computer manuals cover many aspects of diving, for many divers understanding what is known as the philosophy of decompression continues to pose a problem.

This is a fundamental issue, as personal computers are becoming an essential part of a diver's equipment; yet in commercial diving, it is often the company carrying out the underwater work that decides which computer to choose for its team, provided, of course, that it uses computers at all. In recreational and 'technical' diving, the choice formally rests with the diver, with support from the organisation of which he or she is a member.

A fundamental and mandatory requirement in diving is that those who draft regulations, create national legislation or are responsible for international cooperation in all areas of diving – i.e. recreational, commercial, military, popular and scientific diving – and, in recent decades, also in 'technical' and extreme diving. Each of these forms of diving is formalised in its own specific way at different levels, with varying degrees of technical and medical support provided by the training organisation to bring these two undertakings together. Regulatory acts and the procedures arising from them affect the fundamental elements of diving, such as: safety, operating conditions, the equipment and diving techniques used, the qualifications of divers, administrative requirements (obtaining permits, supervision, etc.), and the direct and indirect financial costs incurred for diving.

A striking example of this in our country is the Act on Underwater Works [2] which links divers' qualifications to working depths and sets out mandatory diving techniques and organisational requirements. For instance, it specifies the minimum number of personnel required in a diving team for depth zones where air is used as a breathing mixture. The maximum working depths for a diver, depending on the diver's qualifications, are licences that are gradually obtained up to 20m, up to 50m, and for deep-water and saturation diving without defined permissible depths. What is the justification for such

a division? Is it determined solely by official national decompression tables for divers, and only those imposed by regulation? [2]. Each country applies different standards in this respect. For example, in Canada, when using air, there are two depth levels: up to 30 metres (diver with limited certification) and up to 50 metres. In many countries, diver classes are linked to the equipment the diver uses (self-contained diver, tethered diver, diver using breathing mixtures, saturation diver). The European Diving Technology Committee distinguishes similar classes: scuba diver certified to 25m, tethered diver certified to 50m and saturation diver. All diving qualifications worldwide take into account the technical capabilities for decompression, considering their national conditions, those applicable within the diving organisation responsible for training, and those within underwater service companies.

It is useful and practical to understand the process involved in designing and validating decompression tables to be used in scientific research conducted in accordance with regulations and applicable legislation. [3] How can this objective be achieved when diving encompasses such a wide range of activities, where recognised decompression tables are an integral part of the documentation? As a first approximation, these can be divided into recreational, commercial, military, experimental and scientific diving. The classifications and purpose of the tables become even more complex when we take into account factors such as: depth, duration of stay underwater and under pressure, the gases the diver breathes, the breathing apparatus used, the safety techniques employed during the dive, and the formal requirements that must be met by the diving team. In addition to these factors characterising decompression tables, one must also consider the conditions of underwater physiology, the decompression model, and the research traditions and conditions of a given country.

With the development and understanding of decompression, the 'diving industry' and the 'scientific field' of diving emerged, within which distinct branches have been established, each with numerous 'sub-branches', such as recreational diving, where we distinguish between dives based on breathing mixes, e.g. using air, nitrox, trimix, and the type of breathing apparatus, such as open-circuit, closed-circuit or semi-closed-circuit systems. We can further classify dives according to their level of difficulty, for example, repetitive dives, ice diving, diving in conditions of limited visibility or high-altitude diving. Next are 'technical' dives (involving the use of multiple gases during the dive) and extreme dives, such as explorations of the interiors of wrecks, caves, flooded mines or dives at extreme depths. Various types can also be distinguished in military applications.

There are dozens of types of decompression tables used by divers worldwide, which are presented in tabular form and as software (dive planners), as well as those that are, so to speak, 'encoded' in the form of algorithms briefly described in tables or programmed into personal computers. The abundance of often dubious "knowledge" about tables circulating on the internet makes it difficult to understand them thoroughly. The ability to search for and sort data, as well as to verify its reliability, is not a common skill among modern divers, nor among the general public. Hence the almost habitual use of various online forums as sources of knowledge.

Meanwhile, anonymity and a sense of self-importance and profound competence, as well as the lack

of any form of moderation, mean that the information shared is often deadly dangerous for the potential user.

Even if we begin to consult this knowledge, we encounter barriers related either to the inability to verify the qualifications of the individual source of knowledge, or to the interpretation of that knowledge in a given country or on a given continent. On the internet, one can find materials from leading diving research centres, as well as diving standards, whether from governments or diving organisations, but the key issue is one's ability to access this data.

The proposed rules, procedures and diving practices designed to enhance diving safety depend on whether divers are willing to adhere to them and whether they will follow the requirements for decompression. These requirements are not consistent or uniform, as they reflect the knowledge, traditions and specific characteristics of a given research centre and country. Furthermore, they are linked to the development of research, the specific nature of breathing apparatus, and the conditions under which dives are conducted. Given the abundance and diversity of information available, which knowledge should be adopted whilst taking into account the specific conditions of a given country? This article will not provide such information, but we hope it will offer a different perspective on decompression – specifically, an approach to decompression issues based on the authors' experience. Perhaps this article will demonstrate to divers that, although 'decompression has its parameters', these are subject to change due to the constant advancement of medicine, information technology and underwater technology, as well as research facilities and tools [4]. The authors' intention is to share their perspective on the subject and the very nature of decompression. The information, which is flooding in at an exponential rate, places a heavy burden on those interested in professional or recreational diving (generally diving enthusiasts), as well as those professionally and scientifically involved in underwater medicine and ergonomics, diving technology, underwater work planning, and the design and construction of diving equipment. The authors aim to convey their experiences regarding decompression, which has been practised in Poland for half a century, to all those interested in the issues of diving and underwater works, not just on a daily basis.

DIVER DECOMPRESSION – SELECTED INFORMATION

Technological progress has brought personal dive computers into the world of diving over the last half-century, sparking something of a revolution in the sport. The evolution of these devices has led to an interesting phenomenon. Namely, a degree of polarisation has emerged amongst divers, particularly within the recreational diving community. On the one hand, it has, in theory, 'forced' users to undertake a thorough analysis of decompression theory and planning, making decompression a personal matter for the diver. Individual decompression planning, taking into account personal, equipment and environmental data and parameters, as well as monitoring the course of the dive, has become easier thanks to computers. The recording of computer data and the ability to transfer information on the decompression used to a database allow for statistical verification of a particular decompression model. All this,

however, requires additional mental effort, reading comprehension and a basic knowledge of physics, diving medicine and safety principles.

We will take a closer look at the second archetype of the diver later in this article, in the context of the development of personal computers.

The choice and implementation of a decompression model are also influenced by factors that might seem unrelated to diving, yet are common among professional divers, such as: remuneration for underwater work, colleagues' opinions, the experience of underwater operations managers and training staff, an individual approach to colleagues, the specific characteristics of the dive site, and many others. For example, a beard can be an obstacle when using an inhaler mask during oxygen decompression in a decompression chamber, as it causes the mask to leak. In such cases, the diver 'inhales' the chamber atmosphere during inhalation and releases oxygen into the atmosphere during exhalation. This problem also occurs in breathing equipment fitted with a half-mask instead of a mouthpiece. Two of the authors have beards and can attest to the existence of this problem from personal experience.

Decompression is not merely a matter of adhering to strict rules and procedures, as some clients of underwater work and recreational divers believe. Modern decompression systems (decompression theories) take different approaches to assessing the onset of decompression sickness. Although divers in the early stages of the development of diving and caisson work used proper decompression, they often suffered from illnesses given colourful names such as: the bends, chokes, staggers or diver's palsy. These were symptoms familiar to us today, associated with working under increased air pressure. The condition associated with post-decompression difficulties is known as decompression sickness, though its historical name (derived from work carried out in caissons) is caisson disease. [5]

Put simply, decompression refers to any reduction in ambient pressure. We are all subject to the phenomenon of decompression from time to time; during a drop in atmospheric pressure, when flying in an aeroplane, whilst climbing, etc. Variations in pressure distribution, such as those within our country, can mean that when travelling across Poland, we undergo imperceptible decompression or compression. Changes in pressure also accompany changes in the weather.

The decompression process for divers is, in its most basic definition: the final phase of a dive and a method for 'releasing the human body from increased atmospheric pressure and ensuring its safe return to normal environmental conditions'. We assume a priori that this is a safe return, posing no threat to life or health (paying less attention to the psychological or mental implications) and without side effects or so-called delayed effects of diving. A situation may arise where, after a dive, a diver does not feel comfortable, shows signs of fatigue, experiences mild muscle aches and, under a certain kind of psychological pressure, begins to wonder: 'Did I choose and carry out the decompression correctly? Did I strictly adhere to the time and depth requirements for the stops? Was the preparation of the breathing mixtures correct? Or perhaps did I engage in 'unacceptable' activities underwater or in the decompression chamber, and this marks the beginning of a so-called decompression incident?'

In the above situation, the dive leader or instructor, observing the diver's doubts, begins to succumb

to them themselves. These concerns are particularly heightened during experimental dives involving decompression studies or new designs for breathing apparatus and diving equipment. Other factors that may give rise to doubts include the diver having performed heavy physical work, activities carried out in a current, or in cold conditions. In such cases, the diver's discipline and supervision of the dive prove to be of paramount importance. Examples from our experience, both personal and those investigated through inquiries, can be particularly interesting and provide a clear illustration of the phenomenon of losing one's composure. Errors in the execution of decompression cannot be imagined or even anticipated. However, keeping a cool head, possessing the necessary knowledge, having the right team composition and selecting the appropriate equipment (including medical equipment) allow us to state with a probability bordering on certainty whether a decompression accident has occurred or not.

Below we cite some striking cases drawn from our experience.

The first case concerns decompression following a deep dive, which took place in a hyperbaric chamber under conditions of complete comfort. The divers underwent the procedure whilst lying on their bunks – which was prohibited – with oxygen masks fitted. Monitoring the decompression via the TV feed revealed that one of the divers had fallen asleep, and his oxygen mask was loosely fitted to his face. The supervisor had to respond decisively, as the dive leader and the crew had failed to react to this. As always, the divers and the crew claimed it was only a momentary lapse.

The second incident occurred during deep-water operations at a depth of 80 metres. The percentage of helium and nitrogen in the trimix mixture was miscalculated. Two dives had already taken place before the error was noticed. At the time of discovery, decompression following the second dive was underway. In both cases, no signs of a decompression incident were found. 'Good diving practice' was applied by extending the decompression time, and composure was maintained. In such cases, the decompression parameters prove effective. In hindsight, however, it was recognised that this was pushing the limits of acceptable oversaturation. Of course, this does not exempt anyone from keeping a close eye on divers, not only after the dive. It was a critical moment where a thorough understanding of the principles of the decompression model in question was essential.

Both of the above cases occurred in the 1990s during the operational implementation of deep diving for commercial purposes.

An exceptionally tragic accident involving the Polish Armed Forces occurred in the 1970s. In ORTOLAN-type decompression chambers, in accordance with metrological recommendations, pressure gauges calibrated in atmospheres (at) and metres of water (m H₂O) were replaced with gauges calibrated in megapascals (MPa). Inexperienced personnel failed to notice the change in scale and continued to monitor the readings using the conversion of 1 atm to 10 m H₂O, thereby applying this conversion to 1 MPa. During a training session involving three divers, in which a depth of 10m was planned, a depth of over 100m was reached. This triggered the safety valve, foreshadowing the impending tragedy. After activation, the valve closed at approximately 70–75m. The result: routine and, worst of all, a lack of knowledge regarding

decompression, the construction and operating principles of the ORTOLAN chamber on the part of the chamber operator led to a series of reprehensible errors. Helplessness in attempts to correct the error, (The technical capabilities of the ORTOLAN base allowed for two divers to be accommodated in a 2m³ chamber for a maximum depth of 60m, using ventilation to remove carbon dioxide, which required high-capacity air compressors and did not allow for oxygen decompression) prevented a successful resolution of this incident. Three divers were undergoing decompression in the chamber, which impaired ventilation capacity and necessitated frequent air replenishment. Proper therapeutic recompression was not initiated until a considerable amount of time had elapsed. The incident ended tragically. One of the divers died during decompression, the second over a month later. The third came out of the situation

without any health consequences. This serious case is not the only one to confirm the theory that the human body's tolerance to pressure is an individual trait, and that decompression tables do not account for all factors.

To conclude this account of the accident, it is worth emphasising that these two needless deaths are among the very few fatal accidents in the Polish Armed Forces—fewer than one could count on the fingers of one hand—that occurred between the Second World War and the first decade of the 21st century. This figure pales in comparison to the dozens, and probably hundreds, of deaths among amateur divers. Unfortunately, obtaining data on this subject meets with resistance from all the institutions and organisations that are being questioned on the matter.



Fig. 1 ORTOLAN-L chamber – photographs from the 1970s.

However, certain individual characteristics of a diver can already be determined using software on many modern personal computers, for example on a graded scale. As early as the 1970s, decompression tables designed for the APW 3 and APW-6 semi-closed circuit apparatus using nitrox (a mixture of air and oxygen) were in use in Poland, taking into account the diver's anthropometric characteristics.

In addition to monitoring errors, the problem of diver attitudes and responsibility arises for those participating in experiments. These are divers who have been specially examined and prepared for research and testing, such as for the purpose of developing decompression tables. As a rule, experimental divers are well paid. The health of such a diver on the day of the dive is assessed by a doctor prior to diving, based on the diver's declaration as well as a range of tests, from basic to highly advanced. Despite such stringent standards, unexpected situations still occur.

During tests of the new tables for saturation diving using nitrox, more than a year after the completion of the experimental nitrox pressure exposure tests, one of the test divers suffered an episode of decompression sickness. It is worth noting that this individual was an

experienced saturation diver. The dive depth was approximately 20 metres, and the time spent at depth was merely a dozen or so minutes. The dive profile, as well as the preparation and execution of the dive, ruled out the possibility of a decompression incident. Following the onset of classic DCS symptoms and therapeutic recompression, the diver underwent a series of tests. A thorough medical investigation revealed that the diver had a PFO – a congenital defect in the form of a hole between the atria of the heart. Does this incident ultimately prove that the nitrox tables developed for saturated diving are very safe, and that they can even tolerate cardiovascular abnormalities? Certainly not, as many factors influence the occurrence of an incident, such as the method of equalising pressure in the ears and sinuses. The only thing this incident certainly demonstrated was the insufficient specificity and accuracy of the methods currently used routinely for PFO diagnosis [6]. However, the specialists who developed the tables interpreted this case as an example of the use of very safe tables. Further assessments indicated that these tables are safer than those for short-duration dives. Today this is obvious, and saturation diving (saturated and subsaturated, therapeutic tables) is treated as therapeutic

recompression for very severe and difficult-to-treat cases of decompression sickness.

Another example providing valuable insights: During a table verification experiment using a nitrox mixture and an APW-6m regulator, the diver remained in the hyperbaric chamber at a depth of 30 metres. The experiment supervisor applied a 200W workload to the test divers instead of the planned 100W. This 'improvement' resulted in two mild decompression incidents. The test was not conducted in water, which reduced the influence of other factors interfering with the decompression process. Many authors state in their publications that the final verification of decompression tables for short-duration dives should take place under real-world conditions, even though most experimental chambers have a pool and the facility to place a diver with equipment in it. [6]

In practice, this means that the diver declares that he or she is fit to dive and that the equipment prepared for the underwater task is in good working order. These are the rules applied in commercial diving and certain military operations, where responsibility for the dive—including its conduct—lies with the persons identified in the relevant regulations. In recreational diving, diving takes place on the basis of personal responsibility and that of the dive organiser.

In decompression theory, the fundamental concept found in almost all models – from the oldest model, i.e. Haldan's and its modifications, to the currently popular models – is that of tissue oversaturation with an inert gas. What, then, is tissue oversaturation, the phenomenon that has been haunting divers for over a century?

When faced with the need to choose from among many tables, a fundamental question arises: which tables are the 'best' and the 'safest'? What criteria should be adopted for selecting decompression tables?

DECOMPRESSION IN THE DIVING PROCESS

As a diver ascends, the ambient pressure decreases, thereby creating a pressure difference between the pressure of the so-called inert gases dissolved in the tissues and the pressure of those same gases in the breathing gas mixture, which results in changes in blood pressure. The difference in the concentrations of dissolved gases causes the direction of diffusion to reverse from the previous direction (from the lungs to the blood and from the blood to the tissues) to the opposite direction. The transport of gas from the tissues to the blood, and then to the lungs, takes time (the desaturation process). During decompression, the rate of this process is slower than the rate of decrease in ambient pressure during ascent. Under such conditions, it is almost inevitable that during ascent there will come a point when the pressure of the dissolved inert gas in most of the diver's body tissues will exceed certain permissible pressures for the given ambient pressure. The differences between these pressures are referred to as supersaturation, and this is a typical phenomenon.

Once a certain level (gradient) of supersaturation is exceeded, the pressure differences between gas molecules mean they can no longer remain in a dissolved state, and bubbles begin to form. For example, one decompression model employs the theory of so-called 'gas nuclei', which has been experimentally confirmed. This process is initiated by 'gas nuclei', which manifest as microbubbles that are entirely normal structures under

decompression stress. If the pressure difference increases, these microbubbles grow and, by merging, take the form of 'large' bubbles of inert gas, provided that a specific value characteristic of the tissue in question is maintained or increased. To prevent the formation of gas bubbles that disrupt the body's functioning, controlled pressure changes are applied within the selected, permissible supersaturation limits specified in the relevant decompression table.

In our country, since the 1990s, it has become established practice in recreational and, to some extent, commercial diving that doctors specialising in underwater medicine—whether on a full-time or part-time basis—are responsible for introducing and supervising divers' decompression procedures. In most countries around the world, decompression is modelled, described and prepared by physicists and mathematicians. Doctors collaborate with them, verifying decompression at all stages of table development and introducing physiological limitations. They also prepare the methodology and organisation, as well as the procedures for the recompression of divers for the treatment of specific diving-related illnesses.

When conducting experimental and research dives (in Poland, at military institutions), representatives of underwater medicine are frequently asked 'uncomfortable' questions such as: To what degree of accuracy should dive parameters be maintained? To what degree of accuracy should depth, time, temperature, or the composition and purity of the breathing gas mixture be measured? What ascent rate should be set? How should one behave in an emergency? Subsequent questions were even more uncomfortable: How will we proceed in the event of these parameters being exceeded or deviations from the dive plan? To put it more simply: what is the interpretation of the use of tables in all phases of the dive, not just during decompression and the so-called post-dive period ('buble time')?

This also applies to the use of tables—or, more accurately, decompression algorithms implemented as computer software. The current technical and IT capabilities of most personal computers mean that divers no longer need to consider the scenarios mentioned above, as the software automatically applies corrections should there be any deviation from the assumed model, thereby adjusting the ascent process. It should be noted that modern computers adapt decompression to the course of the dive, and in more complex cases, even to the equipment available to the diver and, to a very limited extent, to their anthropometric parameters. However, this does not eliminate the problem of the user's mental capabilities; will they set it correctly, will they follow the indicated changes, and will they consult source documents when interpreting them, or will they look for them on an online discussion forum? Here is another case, fortunately not fatal, of how amateur divers 'cope' in such situations.

In 2010, a diving tour operator (Diving Centre) organised a so-called 'safari' in the Mediterranean. The programme generally involved 3–4 dives a day, often to a depth of 30 metres and lasting around an hour. It is no surprise that the participants' dive computers 'froze up'. 'Fortunately', the organisers and local guides were happy to lend out new ones, which allowed the diving to continue. The result of this organisational practice (which is extremely common nowadays) was a case of severe decompression sickness linked to physical exertion. One can only add that 'thanks' to the attitude and level of training of the organisers, the attitude of other participants

in the event, and shortcomings in the boat's equipment, the victim was taken to a hyperbaric chamber 13 hours after the accident and suffered serious, permanent damage to his health, particularly to his lower limbs.

In commercial and military applications, the regulations governing the construction of broadly defined breathing apparatus, diving stations and diving equipment

used in a given diving method have little bearing on the decompression process for divers, and deviations from the prescribed decompression profile constitute an emergency situation. [3]



Fig. 2 Divers undergoing oxygen decompression in the Af-2 diving system chamber.

The question arises as to whether we adapt our diving technique to the chosen decompression tables, or vice versa? In our practice, the former approach is the most commonly used and applied. This is because changing the diving technique is more difficult, if not impossible.

For the client commissioning underwater work involving divers, decompression is an unproductive element, increasing costs by limiting the diver's working time and forcing the maintenance of additional equipment, some of which is not used during the actual work dive. For recreational and 'technical' divers, decompression limits the time spent at depth and forces a tedious, often long and uncomfortable stay underwater in order to return safely to the surface.

The last four decades have seen work on optimising decompression, with the aim of safely shortening the process (acceleration). These optimisations are 'constrained' by physiological standards (the effects of partial pressures of oxygen and inert gases, taking into account exposure time) and the need to ensure the diver's comfort (e.g. thermal, respiratory and ergonomic).

This approach is evidenced by the development of dozens of personal and tablet computer models dedicated to decompression tables and utilising algorithms that can be modified, i.e. the so-called decompression planner function. [7]

IN THE MAZE OF INFORMATION ON DIVER DECOMPRESSION

At present, several million people worldwide engage in diving in various fields. Some of them have had experience with decompression, whether during military service, whilst working as commercial divers, or whilst participating in a wide range of recreational activities, as decompression is one of the fundamental aspects of diving. There is a wealth of literature, including online resources,

on diving and decompression. The knowledge and theory of decompression, as well as its practical application, dates back over 130 years and continues to evolve, keeping pace with technological advances and our understanding of underwater physiology. Unfortunately, these aspects are also reflected in and confirmed by unfortunate cases of decompression incidents.

It seems to us that the excess of information and the overly technical presentation of problems in the fields of mathematics, physics and physiology make decompression a subject of knowledge reserved only for the select few and the 'enlightened', who have passed it on or are passing it on to the wider diving community, usually without delving into its spirit and structure. The knowledge acquired comes mainly from articles and books translated into the native language, which depends on the translator's knowledge, talent and experience. This situation is similar to the translation of poetry, where the translator will either convey the beauty of the work being translated or put people off it. Meanwhile, Poland also has its own rich body of scientific work on decompression research; however, the use of foreign sources is regarded as proof of 'cosmopolitanism', much like the absurd insertion of English words into Polish diving terminology to describe objects or activities that have, and always have had, Polish names.

Some authors discourage reading by presenting information in a complicated manner, or without explaining where it has been, is, or might be applied. A certain tendency can be observed in the approach of some scientists, not only those dealing with decompression from a physical and physiological perspective. The more an article is saturated with complex formulas, like the ancient books of alchemists, the more it bears the hallmarks of 'scientific' research. Sometimes this tendency even takes on the guise of an imaginary 'elitism', which unfortunately discourages many readers from exploring the issue for themselves, whilst allowing the

scientist to feel like the sole enlightened figure, or even a national or international centre of expertise. A symptom of this is presenting the subject in such a way as to avoid suggesting an effective, straightforward solution to the problem described. And yet everyone expects solutions that will clearly reassure the diver or dive leader of the correctness of their actions, especially when the question arises of how to behave in a situation where the surrounding reality deviates from the accepted standard of dive decompression and the planned schedule. They expect solutions that will indicate what the margin of error is, whether a correction is needed, and how to carry out decompression most effectively based on backup and contingency dive plans. This is where the computer beats the 'conservative' methods of presenting decompression in tabular form. The problem is that not every computer can handle it, but above all, not every situation can be entered into the computer.

However, at this point, it is important not to confuse the decompression tables themselves with the conservative approach used to characterise their application in decompression.

Based on their own experience, the authors believe that no dive strictly adheres to the requirements of decompression tables or a computer-controlled algorithm. This is due to the measurement errors of the devices used to measure parameters, not to mention the vertical, horizontal or intermediate position adopted by the diver underwater, and the determination of the point of the body at which the depth is taken for selection and/or the determination of decompression by the computer. For example, the current official commercial tables in our country, in the form of charts, require decompression to be measured with an accuracy of ± 0.5 m H₂O. In a horizontal position, the pressure difference between a diver's feet and head is 1.6–1.8 m H₂O. 'Good practice' stipulates that pressure should be measured at the depth of the lung's mean expiration point (the so-called pneumonic point), but the diver's depth pressure measurement points differ in position from the aforementioned point. In SCR and CR systems, lung pressure is determined by the pressure in the bag. Any uncertainties and variations in pressure selection, which affect the determination of the decompression procedure, should be 'accounted for by decompression tables'. The variable oxygen content in the breathing circuit, depending on the diver's exertion, and consequently the variable partial pressure (only in closed-circuit regulators with electronic maintenance of a constant oxygen partial pressure (the so-called setpoint), which is maintained within a range of ± 0.2 ata [6]) and carbon dioxide in the breathing bags, coupled with the high breathing resistance of semi-closed or closed-circuit systems using gas mixtures, necessitate that these processes be taken into account when developing tables. In Polish decompression tables, this problem has been solved by creating tables for the lowest calculated oxygen level, for heavy-duty conditions and oxygen partial pressure, taking into account the diver's weight.

For over a century, scientists around the world have been developing, and continue to develop, methods for safe decompression that are also tailored to diving conditions. This issue is one of the most extensively studied in diving technology. The results, which are difficult to understand, stem from multi-level approaches: techniques for assessment, validation and verification, as well as the assessment of the probability of decompression sickness occurring for the tables currently in use and those under development.

THE INCIDENCE OF DECOMPRESSION SICKNESS IN RELATION TO THE USE OF A GIVEN DECOMPRESSION TABLE

One way to improve diving safety is to reduce the acceptable risk levels associated with decompression incidents. It should be emphasised that the 'statistical analysis of decompression tables' to justify the safety indices of the tables is based on strictly defined diving conditions and does not account for the individual characteristics of the diver or the course of the dive, i.e. for a specific diver profile.

Risk is calculated by estimating empirical data, i.e. from actual dives. The risk assessment of decompression tables is now an administratively imposed standard for the acceptable safety level of divers. This is linked to the planning of dives and underwater work. One of the parameters for decompression tables that divers often overlook in everyday practice is the probability of decompression sickness, which is calculated using statistical methods.

Statistics is a mathematical science, highly subjective in its approach to statistical inference, the reliability of which is based on data. The data must be precisely defined and systematised. The value of statistical studies assessing the safety of decompression is all the greater the more accurate the statistical description and the sampling from the given population. In diving, it is difficult to specify exactly which variations can be attributed to random fluctuations. For example, when analysing decompression tables, samples differ in terms of depth, duration of pressure exposure, conditions of the dive and, most importantly, the diver's data. The reliability of the results obtained is higher the larger the sample for statistical evaluation. If the empirical distribution does not match the theoretical distribution, the cause is sought in the sampling method. Statisticians themselves caution that common sense is necessary when interpreting the results of their statistical inferences. [8] Statistics provide only the information necessary for decision-making, but cannot constitute proof of the correctness of a decision. Most often, the probability/uncertainty of a decompression incident occurring is expressed as a percentage. But what should be done if no case of decompression sickness occurs during a diver decompression study experiment? And for this case, statistics have an answer, resulting from the choice of statistical inference method. The application of a given distribution is a highly subjective approach, allowing conclusions to be drawn that are not always consistent with reality.

Statistical inference is more reliable when it is based on a large dataset and when the law of large numbers can be applied. Over the last thirty years, much research and many practical issues have concerned the safety of recreational diving. This was due to the widespread use of personal dive computers, which have only begun to make their way into commercial and military diving in the 21st century. In this respect, recreational diving is in a very privileged position, providing at least several thousand data points per week using a given decompression model. They provide, or rather have the potential to provide, such data, since there are no publicly available repositories accessible to researchers where data read from amateur divers' computers would be collected – along with even basic data on diving conditions and anthropometric data. Existing databases are not publicly

accessible, nor are the details of the research methodology; consequently, these studies are not randomised and there is no possibility of conducting cohort studies, (one of the basic types of research used to determine whether a factor, e.g. lifestyle, diet or exposure, influences the risk of occurrence, in this case decompression sickness), which is required when transferring research results to humans, as in clinical trials. Even more questionable are the data on the occurrence of DCS incidents; severe forms are generally diagnosed and treated, whereas mild forms (the bends, cutaneous form) are in many, and probably most, cases not diagnosed, because current training for basic recreational diving qualifications either makes no mention at all of diving diseases (so as not to put off the payer) or the information is so limited that it does not even allow for the suspicion of a diving illness: the bends = a dislocated shoulder when carrying equipment, cutaneous form = an allergic reaction, lymphatic form = swelling of the limbs after a long flight.

In Polish research on tables for saturation diving, the studies by the American scientists Weathersby, Honer

and Flynn were used to assess the risk of decompression sickness, with rates of 1% and 10%, depending on the incidence of decompression sickness in small samples [Table 1]. This method of decompression assessment was applied to Polish continuous decompression tables, without 8-hour breaks, for saturation dives in 6 exposures, in which 15 test divers participated.

The tables were based on trimix as the breathing gas mixture, at a plateau depth of 30–70 m, with an oxygen partial pressure of 50 kPa, during decompression and with a nitrogen content of 16–44% in the chamber atmosphere.[9]

Tab.1

Assessment of the risk of a decompression incident.

Number of dives	Number of cases	Risk level 0.10 Confidence interval 0.99	Risk level 0.10 Confidence interval 0.90
1	2	3	4
5	0	0.95	0.59
	1	0.04	0.33
	2 and more	0.01	0.08
			0.35
	1	0.09	0.39
	2 and more	0.01	0.26
20	0	0.82	0.12
	1	0.16	0.27
	2 and more	0.02	0.61
50	0	0.61	0.01
	1	0.31	0.03
	2 and more	0.08	0.96

The table developers believe that modern decompression tables, which assume a risk of decompression incidents of less than 1%, are practically acceptable. In statistics, this is referred to as a confidence interval, which, at 1%, corresponds to 99% positive results. This stems from the statistical methods used for the so-called 'paper' decompression tables. In the past, these data were based on studies and tests with a limited number of 'samples' for a given population of divers, which included 'dry' dives, i.e. tests in a decompression chamber. This approach was adopted because dives in water were not recorded electronically, and data collection was very difficult and time-consuming. Furthermore, the samples available for data analysis were not precise. The high costs of research verifying the tables meant that not all times spent at a given depth could be tested; therefore, they were only examined selectively to validate the model. In Haldan's models, the leading tissues were those with a half-life of 40 minutes. The relatively small number of

dives and research based solely on test divers reduced the reliability of the statistical indicators.

Using the simplest binomial Poisson distribution, the number of samples required to achieve a standard error of 2% was 469. For tables of saturation dives and deep dives, this number was and remains unattainable in the process of testing and implementing the tables.

The authors believe that it is currently possible to launch a database of commercial dives. This requires divers to be mandatorily equipped with a personal computer, either solely for reporting purposes and, where necessary, for proceedings (data from the computer constitutes objective evidence in such cases), or for the computer to be legally recognised as a formal basis for commercial and other underwater work. Insurance companies and firms providing underwater services should also take an interest in the existence of such a database.

Nor should we forget the possibility to reintroduce this form of reporting within the Polish Armed

Forces, which, apart from the Special Forces, should not constitute a significant burden.

The revolution associated with the widespread use of personal computers in diving, particularly in recreational diving where we work with relatively reliable data from short dives, enables us to collect a large volume of data for the evaluation of a given decompression model. Data collection for dives is currently being undertaken by organisations such as: Divers Alert Network (DAN), Los Alamos National Laboratory (LANL), and DAN USA as part of projects such as Project Dive Exploration (PDE), whilst DAN Europe is running a parallel initiative called the Diving Safety Laboratory (DSL). DAN analyses recreational dives using air and nitrox. The LANL Database collects data on 'technical' dives using gas mixtures, open-circuit regulators and rebreathers (semi-closed and closed-circuit systems). [10]

The collection of data from personal computers at DAN USA, DAN Europe and LANL—including dive logs and decompression analyses for various decompression models—has enabled the compilation of statistics. It was found that the rates of decompression incidents and oxygen toxicity in recreational diving are low and remain stable. Unfortunately, it is necessary to view these results in the light of the comments made earlier regarding the limitations of incident data collection, as well as the fact that DAN is a private, commercial organisation involved, inter alia, in insurance activities; consequently, the reliability of these findings is limited.

It was also pointed out that 'technical' diving is 10 to 20 times more risky than entry-level recreational diving. In our opinion, the data from computer manufacturers is anecdotal, and amounts to 143/6,000,000, i.e. 0.0024%, which, from a statistical point of view, defines a safety confidence interval of $99.99 \pm 0.005\%$. For DAN and LANL data, the incidence of decompression incidents is low, at 80 people per 187,451 and 28 per 3,459 respectively, which translates to 0.043% and 0.8% [based on 17,25]. It is estimated that in 2021, the fatality rate in road traffic accidents was 15 people per 100,000 inhabitants [according to WHO estimates from 2021], i.e. an incidence rate of 0.015%, which falls within the risk range for the application of decompression tables. The reliability of this comparison is reinforced by the fact that the WHO bases its figures on 100,000 inhabitants of a given area rather than road users. After deducting, for example, children and the elderly who do not move around independently, as well as prisoners (a very significant percentage of the population in the USA), the research results converge even more closely.

AMIDST THE HAZE OF 'DECOMPRESSION MODELS'

A contemporary trend is the gradual replacement of 'paper' – i.e. printed – decompression tables with computer algorithms. The advantage of personal

computers is undoubtedly that they perform decompression calculations in real time, measuring depths in fractions of a second. They calculate (averaged – based on anthropometric data and other factors!) the degree of saturation and desaturation of the body with inert gases, as well as the degree of oxygen toxicity (CNS watch), track changes in ascent and descent, and control the diver's dynamics and the overall course of the dive, including decompression. There are also expert-level devices based on a specific, user-configurable decompression model. Most computers are based on modified dissolved gas models, the so-called Neo-Haldane models, with selected theoretical tissues and varying quantities thereof, sometimes including partial saturation, as well as the newer bubble growth model. These models have limitations and correlations arising from underwater physiology and the impact of real dive data.

The differences between these decompression models lie in their mathematical description. Dissolved gas models focus on controlling and eliminating hypothetical dissolved gases by bringing the diver as close to the surface as possible. They are based on an exponential saturation and desaturation curve, or, as in the case of US Navy tables, on a linear desaturation process. Gas bubble growth models mathematically describe the hypothetical growth of bubbles and the associated dissolved gas, which implies starting decompression at deeper stops by 'positioning' the diver deeper prior to surfacing. The first decompression method assumes shallow decompression stops, whilst the second requires deep decompression stops, as is commonly referred to in current jargon.

As B. Wienke, one of the pioneers of decompression modelling, noted "the above models are rather primitive; they only refer to the very approximate dynamics of dissolved gas accumulation and bubble growth in tissues and blood. Of course, their use and implementation are limited to computers, but they are useful when correlated with available data. To quote a phrase from the wider community, all models are wrong, but some are useful." Models that are correlated with diving data—i.e. tests, databases or long-term safe operating protocols—are useful. Useful and popular models include the USN, ZHL, VPM and RGBM algorithms, which will be used for comparative risk assessment in the future.[11]

Personal computers are manufactured worldwide by over a dozen companies, in numerous designs, utilising both neo-Haldane algorithms and gas exchange models, gas bubble growth models, and so-called 'substitute tissue' models, all of which are incorporated into more than a few dozen mathematical models. Computers for recreational diving are based on the gas exchange model (GM), whilst dive computers for 'technical' divers use the gas bubble growth model (BM). These models are very similar in terms of nominal exposure limits and short durations (non-stop diving).

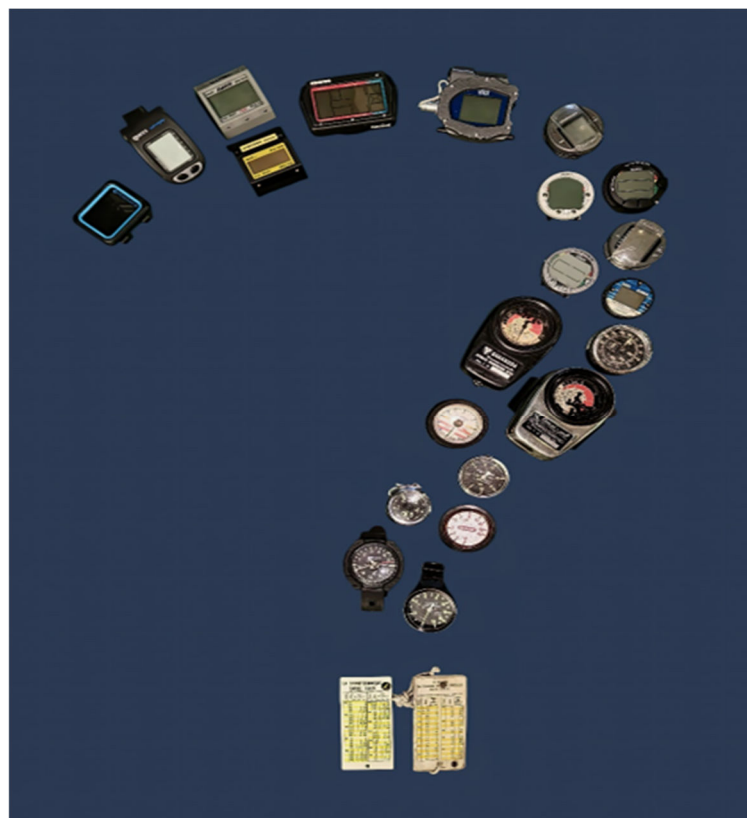


Fig. 3 An overview of the tools used throughout history for decompression diving.

GAS BUBBLES AND THEIR EFFECT ON THE DECOMPRESSION PROCESS

The invention of Doppler ultrasound technology in the 1960s confirmed the formation of bubbles during all decompression procedures and almost all dives using non-oxygen-supplied breathing apparatus. These studies became a means of assessing the quality of decompression, and, as practice during the research demonstrated, a means of determining the execution of decompression with great precision. In many cases, the measurements necessitated adjustments to the decompression stops. In our country, studies on the formation of bubbles using the Doppler method were carried out in 1984 during the GEONUR II programme, which involved long-duration air dives to a depth of 18 metres. Unfortunately, the study did not yield the expected results due to a lack of experience in this type of research and the improper use of the Doppler apparatus. We did not return to the Doppler method in Poland until 16 years later, thanks to collaboration with the Canadian research centre DCIEM. The 5-point scale for bubble count developed by Kissman and Masurel states that decompression sickness should occur at stage 4, however, cases of decompression sickness were observed as early as stage 2, while in some cases no symptoms of decompression sickness were observed at stage 4. [12] Currently, Doppler techniques using sound waves reflected from the bubbles or their imaging on an ultrasound screen are routine tools for assessing the normal course and effects of decompression.

If, for any reason, bubbles have formed, the subsequent removal of inert gases from the tissues is slower than Haldane's model suggests. This explains why, over the years, a large number of empirical experiments have been carried out to apply calculated decompression

procedures and adjust decompression stops. [11]

Decompression methods continue to be modernised with a view to preventing the formation of bubbles that interfere with gas exchange. A 'safe' gradient factors (the difference between the pressure of inert gases in the blood and the pressure in the tissues) is being developed. The gradient factors should be reduced to a level that limits the diffusion of inert gas into microbubbles, thereby preventing their growth and the progression of decompression stress into fully symptomatic decompression sickness.

In practice, this means an earlier starting point for decompression stops. This approach required the use of deeper stops, which shortened the duration of stops at shallow depths and, as a result, implied a reduction in decompression time compared to the Haldane model [13]. The 'good old diving practice' used to this day says that when we have to apply extended decompression (i.e. extend the time according to the chosen decompression method, e.g. due to the divers' heavy workload, age, exertion, working in a current, etc.), we have two schools to choose from. Either we adopt the next time of stay for the diver's working depth, or for a given time we adopt the next depth. Which solution is safer from the perspective of the bubble model? Unfortunately, the correct answer requires clarification as to which tables, what time and at what depth. These problems do not arise when using a personal computer for decompression planning, where the diver is responsible for selecting and setting the decompression profile, and the computer adjusts this profile based on current measurements of diving parameters. And here, once again, it is worth remembering that, unfortunately, not all of the parameters mentioned (and others that will be discussed later in this review) can be entered into a computer, partly because they often have non-numerical values. For the time being, this situation

applies only to recreational and 'technical' dives, and to a limited extent to military dives. Our observations suggest that in commercial diving, personal computers are finding their way into widespread use due to formal restrictions; the introduction of only a single set of tables of dubious applicability to numerous types of dives by national regulation. [14] Many professional divers use personal computers for decompression, explaining that these computers bear the CE mark indicating that the product complies with European Union regulations, which means they meet safety, health and environmental protection requirements. Of course, this is merely an excuse and has little to do with actual safety; however, in the event of an incident, it is easier to justify the use of a computer than to explain why one has rejected the tables imposed by

regulation, which are unsuited to the reality of a given dive. On the other hand, for obvious reasons, personal computers have not found their way into saturation diving. For four decades, computers have been used in our national saturation diving systems to record and control decompression parameters.

In this series of articles, the authors will present the challenges of creating decompression tables and the impact of a given model on the decompression process, along with the resulting technical and organisational limitations. Furthermore, they will present selected tables used in our country, research into these tables, their adaptation, and the steps taken to implement them.

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