●Original Article

Evaluation of decompression tables for enriched air diving

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エンリッチドエア（高酸素濃度空気）でダイビングを行う主たる理由は、減圧の改善にあります。これは停止不要時間が長くなること、減圧時間が短いこと、あるいは危険が少ないこととして表現され、このすべては呼吸混合気体中の窒素が少ないことによるものです。減圧とは、圧力の減少と定義されるだけではなく、ダイビングの場合では、コントロールした圧力の減少と定義されます。この計画的な圧力の減少のプロファイル（減圧すなわち浮上のこと）を減圧表と呼び、これは気泡の形成を防ぐか少なくするのに必要です。気泡の形成は減圧症につながるものです。減圧表を作成する最も一般的な方法は、ホールデンの方法を使うことで、これによって身体に吸収・排出される不活性ガスを仮想的に計算する手段が得られます。ガスは分圧として蓄積され、浮上はこの“ガス負荷”と経験的に決定された限界と比較してコントロールされるのです。減圧は停止不要、つまり停止することなくダイバーがコントロールされた速度でまっすぐ浮上するものか、ダイバーがいくつかのパターンに従って停止を実行しそれから予め決められた水深にゆっくりと浮上するもののどちらかになります。一日に二回以上のダイビングが行われる場合、次のダイビングは繰り返し潜水で、これには特別な手順が必要です。エンリッチドエアを使うダイビングでの減圧も、空気ダイビングのそれと同じ一般的な手順を使います。エンリッチドエア減圧表は、公表されているもの、専用に計算したもの、空気減圧表との比較で、“空気相当水深：equivalent air depth”すなわちEADテクニックという窒素分圧が同一のものを見るものがあります。エンリッチドエア“ナイトロックス”用の機能があるダイブコンピュータが効果的な方法で、ダイビング計画ソフトウェアなら、経験のあるダイバーが自分専用の減圧表を作ることができます。エンリッチドエア・ダイビング後の減圧は、空気でのものと比較してよりストレスが少ない、あるいはより危険が少ないという理由はいくつかあり、限られたデータによってですが、そのことが支持されています。

Abstract

The main reason for diving with oxygen-enriched air is to improve decompression. This may be expressed as longer no-stop times, shorter decompressions, or less risk, all because there is less nitrogen in the breathing mixture. Decompression is defiend not only as a reduction of pressure, but in the case of diving, a controlled reduction of pressure. This programmed pressure reduction profile, decompression or ascent, is called a decompression table and is necessary to prevent or reduce the formation of bubbles, which can lead to decompression sickness. One of the most common methods of designing tables uses the Halndane method, which provides a means of calculating the hypothetical uptake and elimination of inert gases by the body. Gases are accumulated as partial pressures, and ascent is controlled by comparing these “gas loadings” with emipirically-determined limits. Decompressions can either be no-stop, where the diver ascends directly at a controlled rate without stopping, or the diver can perform stops at predetermined depths to slow ascent according to several patterns. When more than one dive is performed in a day those following the first are repetitive, and these require special procedures. Decompression from dives with enriched air use the same general techniques as those for air diving. Enriched air tables may be published, custom-calculated, or prepared by comparison with an air table that has the same nitrogen partial pressure, a technique called

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*Hamilton Research Ltd., Tarrytown, NY 10591-4138 "equivalent air depth" or EAD. Dive computers equipped for enriched air "nitrox" are an efficient method, and dive planning software permits the experienced diver to calculate her own tables . There are several reasons why decompression from dives with enriched air should be less stressful or risky than from comparable air dives, and limited data supports this .

Introduction

It should be well known by now that the advantages of diving with enriched air nitrox are all related to decompression. One may see one of the advantages of "nitrox" touted that it "allows more bottom time." Then somewhere else it may be said that enriched air "allows a shorter decompression," as if these were different things . Still a third advantage often mentioned is that the decompressions are "safer." These are in fact different manifestations of the same thing. The only benefit of using enriched air is to reduce the level of nitrogen and hence to improve the decompression situation.

Let us examine these points and how they are achieved.

Decompression terminology

First, consider "the D word." While it deserves respect, the diver should not be intimidated by decompression. The word "decompression" has two different meanings in diving. The first is the dictionary definition. the second is the act of doing it in a controlled way.

The dictionary definition of "decompression" is the reduction of pressure or release from compression. In the context of a pressure vessel, this meaning is more or less obvious, reducing the pressure is decompressing the vessel. It might well be called depressurizing. In the context of a diver ascending, the ascent takes the diver to a place where the pressure is lower, and this too is decompressing. Decompression is nothing to fear, it is done on every dive.

However, although divers occasionally use the word as just defined, they usually use the word "decompression" to mean the release or reduction of pressure in a controlled or planned way to avoid bubble formation and decompression sickness (DCS). The latter is an outcome of decompression when the pressure release is not done properly. So it is in the best interest of the submerged diver to "decompress" in order to reach surface pressure. "Decompression" in this sense means the diver is required to follow a specific time, depth, and breathing gas profile. This profile, which may be called a decompression table or decompression schedule, is designed to allow a diver to ascend to the surface without incident or symptoms. It may involve stops, or may only require a specific ascent rate without stops.

The process of ascending to the surface is decompression in both senses. Ascending without stops is still decompressing. The important point is that every ascent is a decompression; a diver actually "decompresses" from every dive; every dive of any consequence involves a certain decompression obligation .

Which brings up the term "no-decompression," which when applied to a dive implies that the dive does not involve decompression, but in fact it is merely a dive that does not require decompression stops. A better term is "no-stop." A "safety stop" rs often recommended. This usually refers to a 3-5 min stop in the range 3 to 6 msw, just before reaching surface. Such a stop may not be required as a decompression stop, but is a good idea, and some organizations require it under certain circumstances.

Managing decompression: Computingn tables

Because the benefits of diving with enriched air relate solely to decompression, it is worthwhile to know a little about the need for controlled ascent and how it is quantified. This section reviews the basics.

Gas uptake

When a person's body is exposed to increased pressure, greater than the familiar one atmosphere at sea level, additional inert gas dissolves in body tissues. Inert gas is gas that is neither metabolized by the body nor is a product of body metabolism; inert gases are not changed in the body. When a gas is dissolved it is not in gaseous form. The inert gas of interest in air and enriched air diving is nitrogen (N_2). Other inert gases used or considered for use in diving are helium, neon, hydrogen, and argon.

During an exposure to increased pressure inert gas is picked up by the blood in the lungs and distributed to all parts of the body, at different rates and not necessarily evenly. When pressure is reduced slowly the opposite takes place; gas is picked up from the tissues—still dissolved—and moves to the lungs where it resumes the gaseous state and is exhaled in a gradual uneventful process. However, if the pressure reduction takes place too fast the gas does not stay dissolved but is released into the tissue or blood as bubbles. Bubble formation inhibits the transport of gas out of the body in several ways, and bubbles can damage the blood and linings of the blood vessels.

The science and practice of decompression is dedicated to predicting under what conditions bubbles may form, and what it takes to prevent bubble formation or excessive bubble formation.

The Haldane method

The most common method used for predicting if a dive profile (of pressure and gas as functions of time) will cause DCS dates back to around the turn of the century, when physiologist J.S.Haldane developed a method for keeping track of gas in the body and showed how to prepare decompression profiles or "tables." At the outset it is important to make clear that this "model" proposed by Haldane and later modified by others is hypothetical. It is not what really happens in the body, nor was it intended to be, but it does afford a method of moving from yesterday's dive experience to tomorrow's new tables. This was the first such model; many others have followed, and many are offshoots of the Haldane method. A well developed computational method similar to Haldane's was published by the late Swiss cardiologist, Prof. A.A.Bühlmann, and it has been widely used by others (1984; 1995).

A significant characteristic of the method just mentioned, and of the other useful ones, is that the only criterion for the preparation of useful decompression tables is empirical experience. As models improve, prediction capability will continue to get better, but the judgment as to whether a model is right is how well it actually works, not how sophisticated the math is.

Review of Haldane

The Haldane method considers that the body is made up of a number of parallel and independent compartments, each of which takes up and releases inert gas at different rates; the computations keep track of where the gases are expected to be. Although compartments are sometimes called "tissues" they are not anatomical entities; each consists of whatever parts of the body handle gas at a specific rate.

The rate of uptake and elimination of a gas is proportional to the difference between the amount in the compartment and the inspired gas in the lung, and it is normally considered to work the same way in both directions (it is "symmetrical"). The greater the difference between the gas in the lung and in a given compartment, the faster gas moves into or out of that compartment. Quantitatively this process is called "exponential" after the mathematical method used to calculate the rates.

The rates associated with the individual compartments are described in terms of "halftimes," which is the time it takes the gas in a given compartment to proceed halfway toward being equal to the source. From six to as many as 32 compartments have been used. with half times ranging from two to over 1200 min. A short half time results in a faster rate of gas transport. Gas "quantities" in this context are handled as partial pressures. One may speak of the "gas loading" in a compartment as the partial pressure of that gas in that compartment. Remember that these are hypothetical values.

After gas uptake, when an ascent is begun and pressure is reduced, some of the compartments may not release gas fast enough to match the ascent rate, and as a result bubbles can form.

Computing decompression tables

Experience has shown that certain profiles —and presumably the hypothetical gas loadings produced by such profiles—do not normally produce DCS. With enough experience—data—it is possible to assign limits to ascent. With these tools, table developers calculate suitably slow ascent rates for a variety of exposure profiles; the results of these calculations are distributed as decompression tables.

The limits just mentioned are in terms of the gas loading that can be tolerated in each compartment at each depth during ascent. Ascent limits are normally considered in 10 fsw or 3 msw increments, and are known as "M-values" (where M stands for "maximum"), the maximum permitted gas loading at that depth in that compartment. To calculate a decompression table, the developer needs a set of M-values, usually determined from experience. The calculated gas loadings in each compartment are compared with the M-values, and ascent is adjusted to keep the loadings below the limits. The diver's ascent is halted with "stops" at specified depths to wait until the hypothetical gas loadings have "decayed" by losing inert gas partial pressure to below the limits for that depth; the diver then ascends to the next stop and the process is repeated. Level stops are not essential; it is possible to ascend in a linear manner as long as the rate is acceptable.

Haldane's method goes back nearly a century, but by using it with continuously updated experience, it can be used to produce reliable decompression tables. It is not quite correct to consider this a "theory" of how the human body works. Rather, it is a computational tool that allows prediction of tomorrow's dive from yesterday's experience. Bühlmann's method uses the same gas uptake but calculates the ascent limits in a different way; it, too, incorporates experience.

Still another popular and successful computational method, Kidd-Stubbs, uses compartments but considers that they are in series, such that the second compartment fills from the first, and so on. This is the computational algorithm used to calculate the DCIEM tables.

Dive patterns in enriched air diving

As is implied in the definitions, in the realm of air diving there are two more or less distinct categories of diving as used by recreational and scientific divers. By far the most prevalent category is to do all or essentially all dives with no decompression stops, using no-stop or no-decompression techniques. The other category is to do dives that normally call for decompression stops. The latter category can be further divided into several specific decompression techniques.

Most recreational divers in North America and Japan are taught to perform all dives as no-stop dives, using decompression stops only as contingencies require. The same applies in general to scientific divers. NOAA divers are allowed to do decompression dives with special permission.

In Europe most divers, especially those trained by the British Sub-Aqua Club, are taught decompression techniques.

Repetitive dives

Another important dive pattern is that of repetitive diving. This can apply to all of the different dive patterns. Repetitive diving is not widely practiced in either the commercial or military diving communities. but is quite common in recreational and scientific diving.

In the physiological sense, a repetitive dive is one carried out soon enough after a previous dive that its decompression is influenced by the previous dive or dives; effects may accumulate over several dives.

Unless the first dive was relatively short and the interval between them (called the "surface interval") is relatively long, there is likely to be a "gas loading" remaining from the earlier dive. This means that some inert gas is still dissolved in the diver's tissues.

Another thing that may result from an earlier dive is bubble formation. Bubbles may form and may be eliminated during a decompression, but some may remain; these can grow if subjected to an additional compression and decompression. On the other hand, preexisting micronuclei (necessary to form bubbles) can be destroyed by the first dive, leaving fewer available for the second dive; this can be beneficial. The relative effects of these factors is not well understood.

Research indicates a higher incidence of DCS from repetitive dives than from single non-repetitive dives. This depends to a large extent on how repetitive dives are defined and how they are done.

Although uncertainties remain about the physiology of repetitive diving, to some extent it has been defined explicitly. The U.S. Navy defines a repetitive dive as one that begins within 12 hours of a previous dive. This means that the tables assume that a diver is clear of inert gas (for practical purposes) after 12 hr. If the second dive starts within 10 min it is considered an extension of the previous dive. There may be residual effects lasting beyond a 12-hr surface interval, so some organizations consider that the influence of the first dive may last longer, for example to I 6 or 24 hr.

The developers of the USN tables devised a somewhat arbitrary but quite effective method of managing repetitive dives. They assumed that the effect of a previous dive on a following dive can be expressed in terms of gas loading, and calculated this for each schedule using the 120-min halftime compartment as the reference. They developed a method of using "groups" to allow the diver to calculate the effect on a subsequent dive, taking into account time spent at the surface between dives.

The safety stop

Some "no-stop" procedures call for the diver to make a safety stop of 3 to 5 min in the range of 3 to 6 msw (10 to 20 fsw), nominally 5 msw. This has been shown experimentally to reduce the level of ultrasonically detected bubbles, and should therefore reduce the likelihood of decompression sickness.

Enriched air decompression methods

There are some specific methods of performing decompression from an enriched air dive.

Air tables

The simplest and most straightforward method of decompressing from enriched air is to use an air table. This does not take advantage of the longer no-stop times or faster decompression, but may be at lower risk, and such tables are readily available. Any standard air table can be used, but special procedures may be necessary for repetitive diving.

Prepared tables

There are now a number of decompression tables prepared specifically for enriched air nitrox diving. Most prominent of these are those of the U.S . National Oceanic and Atmospheric Administration, NOAA. These, which are limited to a mixture of 32% oxygen, 68% nitrogen, were introduced in the second edition of the NOAA Diving Manual, so they have been in use for some years and have a good track record. The display of the tables is in the same format as the USN tables. The tables were calculated using what has become known as the "equivalent air depth" concept, discussed below.

In 1979 the diving program of the National Oceanic and Atmospheric Administration, NOAA, introduced diving procedures and decompression tables for a standard oxygen-enriched mixture of 32% oxygen, 68% nitrogen, which NOAA named NOAA Nitrox I or NNI. The NOAA decompression tables were calculated using what has become known as the "equivalent air depth" concept, which is simply to decompress from an enriched air dive using the air table that has the same nitrogen partial pressure (PN_2). As the air basis for their enriched air tables NOAA used the U.S.Navy standard air tables.

JAMSTEC now has its own set of enriched air tables for 32 and 36% oxygen, which are part of a comprehensive set of "special air" tables. These have been subjected to limited laboratory testing. They are being developed for the community of Japanese diving scientists (Hamilton, Yamaguchi, et al, 1997).

Most of the recreational diving training organizations have tables for 32% and 36% oxygen enriched air mixtures for divers taking their courses Tables for other mixes are not generally available. Some of these are calculated with the EAD method from existing air tables, others are calculated directly. NAUI has adapted the NOAA tables, and presents them in a condensed and more convenient format (which NOAA will use in the next edition of its manual). The NAUI tables also include a 36% Oxygen mix, done in the same manner. The British Sub-Aqua Club has its own enriched air tables, and these are presented in an innovative and concise format designed by Dr. Tom Hennessy.

Air tables with "equivalent air depth" adjustments

The equivalent air depth (EAD) is the depth defined by the partial pressure of nitrogen that will be breathed, rather than the actual depth of the dive . For a nitrox mixture with less nitrogen than air, the equivalent depth is shallower than if air were being breathed. Although a diver is physically at a specific depth, physiologically the body is absorbing nitrogen equivalent to a shallower depth, since it is the partial pressure of the breathing gas that matters. The diver can decompress according to the air table for the shallower depth.

Once the EAD has been determined, the diver can use the "equivalent air depth" with any air diving table and find the resulting no-stop and decompression stop dive times, and the repetitive criteria. In practice, the EAD or the equivalent no-stop time is selected from a chart, but these can be calculated as well, using the above process or by using a look-up chart or applying a formula.

Custom tables

The equivalent air depth method does not take full advantage of the decompression possibilities of enriched air. To optimize decompression requires tables calculated specifically for OEA.

Accordingly, the diver might seek out a professional "table maker," a person well-versed in decompression computation who is able to prepare custom tables designed for the specific situation.

Dive computers

There may be situations where a table for a specific mix and depth are needed for a special diving project. In these cases, the diver has a few choices. The first and most effective option is to use a dive computer equipped for enriched air calculations. A dive computer performs the same sort of calculations as are done for tables, but does them in real time. Instead of displaying a series of stops at 10 fsw increments as a table does, the computer shows the "ceiling, the depth to which the diver can ascend without violating the computer's ascent limits.

There are two options for using dive computers with enriched air. The best is to use a computer designed for enriched air, and use it with the proper mixes. Contemporary dive computers allow the percentage of oxygen to be set. Some computers even allow for multiple nitrox mixes to be used during advanced types of dive. Enriched air computers monitor the diver's exposure to oxygen, based on the mixture in use, and warn when limits are approached or exceeded. A dive computer is not a substitute for proper training .

As a second dive computer option is to dive with an enriched air mixture using a dive computer designed for air. Here the main gain is as for air tables, a reduced risk of DCS. In using an air computer with oxygen enriched air it should be possible to use the computer to its full no-stop limits (but not beyond!) without the need for as much added conservatism as when using air. The user has to keep track of the oxygen exposure and maximum operating depth of the mix in use, because an air computer will not do that.

"Do-it-yourself" tables

In recent years there has been a remarkable development in the field of decompression technology, the development and marketing of commercial computer programs for generating decompression tables. For decades it had been felt that only decompression specialists, and in the case of the Navy, diving medical officers, were qualified to produce decompression tables. That consideration has not really changed in the eyes of commercial divers, diving companies, and their lawyers, as well as the Navy, but the development of enriched air and technical diving has presented a need for tables that were just "not in the book."

Several entrepreneurs have prepared and distributed computer programs that can be used to generate tables. With one of these a diver can generate ("cut") tables specific to the actual dive project.

This has been possible in large measure because of publications by Prof. Bühlmann (1984; 1995) that give tested and accepted algorithms for computing tables. All the readily available programs are based at least fundamentally on Prof. Bühlmann's algorithms. The different programs manage the algorithm in different ways, especially with regard to introducing extra conservatism into the computations. Even so, when used properly they all produce acceptable enriched air tables. Many of these programs allow oxygen exposure to be tracked and warn the user when limits are exceeded. It is up to the user to know the meaning of the oxygen calculations and the limits used.

The caveat remains, however, that producing proper decompression tables in a safe manner requires a substantial knowledge of decompression practice. The user should have a firm idea of what to expect, and should be able to recognize if things are not right. These programs can generate satisfactory tables in the right hands, but we do not advocate their casual use by novice divers or those with limited experience in decompression.

Evaluating enriched air tables

Now that we have touched on the decompression process and the methods used for generating enriched air decompression tables, it remains to comment on their efficacy.

Direct evaluations

The most obvious assessment of decompression tables is their outcome, the incidence of decompression sickness resulting from their use. Unfortunately, studies making this assessment have not been done on large numbers of dives. Large numbers are needed to assess differences because the incidence is so low. Data collection is in progress by the Diver's Alert Network to collect a large number of carefully monitored and recorded dive records with reliable outcome information, but until the data are available it is not possible to make a realistic assessment based on field data (Vann. et al. 1999).

Some studies addressing the equivalent air depth concept, that of basing the decompression on only the partial pressure of the inert gas, were reviewed by Vann (1989). The conclusions were that in most cases the data support the EAD concept, even in a project dedicated to showing that it was not valid.

Inferred assessment

When interest in enriched air diving began to develop a few years ago, the statement was made that even though you may get a decompression benefit by using equivalent nitrogen partial pressures, the resulting tables were "no better than the original table" on which the equivalent calculations were based. Actually it is probably better than that, for several reasons. First, one uses enriched air during the travel portion of the dive as well as the bottom time, and that is not really taken into account with EAD. Next, the "grouping" of the tables requires moving up to the next table for uneven values of depth or time, and each of these steps adds conservatism, since everything is taken to the worst case situation in each group. And the USN tables for short dives in the range to 35 msw (115 fsw) where OEA is useful are quite reliable.

There is yet another factor. When a table is calculated with enriched air, it will be shorter than the equivalent table with air, and it is fairly well known that a shorter table invokes less decompression risk if the constraint limits are the same. That is, the shorter a person is exposed to "supersaturation" or the stresses of decompression the better off the person will be. The enriched air dive has a shorter decompression; it is entirely reasonable to expect divers who receive the shorter, higher-oxygen decompression to feel better afterwards. The rationale given here applies best to dives requiring stops.

The concept of "safety"

As mentioned, the main reason for using oxygen-enriched air is to gain a decompression advantage. This is based on the valid principle that only the inert or nitrogen component of a gas mixture is involved in the requirement for decompression. This one advantage is often stated several ways and presented as if it were several reasons. With OEA the allowable no-stop time is increased, less decompression time is needed, and a given dive using OEA as the breathing gas but with a decompression table based on air will be more reliable or have a lower predicted decompression sickness incidence. All these are essentially the same thing.

Calculations not with standing, it seems ludicrous to promote that nitrox is "safer" when the difference in incidence could not be detected except by a controlled test program involving hundreds or even thousands of dives. Further, the possibility of being injured by decompression sickness from a properly conducted dive is truly trivial compared to the many other things that can go wrong in diving.

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