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Technical Paper

Decompression calculations for trimix dives with PC software: variations in the time-to-surface: where do they come from?

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Abstract

Dive computers for mixed gas diving and PC software for decompression calculations are often considered as ‘black boxes’ to the diver: they perform part of their function – the calculation of a decompression schedule – but leave the user in a somewhat nebulous state about the relative safety of this schedule. This is because, in reality, the technology, underlying algorithms and utilised constants are not clearly documented, especially if the so-called gradient factors come into play. Gradient factors are sometimes praised as safety knobs for the decompression schedules, or as a unique selling proposition for these black boxes. This paper discusses the impact of gradient factors on the calculation of decompression times, as well as how the different implementations of dive profile data can influence these calculations.

With one inert gas in the breathing mixture, the analytical expression for the decompression time is t_d. However, if there is more than one inert gas present, the decompression time must be calculated numerically. Therefore 480 square dive-profiles were analysed in the technical/recreational diving range using one freeware, two commercially available software packages and one private software with numerical methods. There are significant differences in the calculation of the decompression times with trimix gases, depending on the helium percentage. In the present analysis, these differences do not come from variations in the decompression algorithms but rather from different implementations of these numerical methods. Presently, a definitive answer cannot be given about the origin of these variations but the user should be aware that these exist.

Keywords: decompression, diving theory, mixed gas, models, simulation, technical diving, trimix

1. Introduction

Time to surface (TTS) is normally the sum of the stop times over all decompression stops, plus the ascent time. The algorithm accounting for inert gas loading during an exposure to overpressure is implemented using software for a dive computer or desktop-based decompression software. A gradient factor is normally used to manipulate the tolerated inert gas partial pressures in the various theoretical body tissues. Therefore, a decompression method with prolonged stops can be forced using pure mathematics but is not directly related to any physiological issues. Perfusion decompression models exist where a theoretical blood perfusion element defines the boundary conditions. These deal mainly with the dissolved gas phase: inert gas bubbles are not considered within these models but are described in other literature (see Boycott et al., 1908; Workman, 1965; Müller and Ruf, 1966, 1971; Schreiner and Kelley, 1971; Bühlmann, 1983, 1993; Bühlmann et al., 2002; Hahn, 1995). Other terms used for this paper are REC for recreational diving (i.e. SCUBA-diving with air and normally within no-decompression limits), and TEC for technical diving with a lot of equipment and usually using mixed gases. The mixed gas used usually contains helium (in a trimix: oxygen, nitrogen, helium) and decompression stops where oxygen enriched air (EAN, Nitrox) and/or pure oxygen can be used.

Classical, perfusion-limited decompression algorithms were first described by Boycott et al. (1908) but tend now to be termed Haldane models after one of the co-authors, JS Haldane. The Haldane models describe the absorption of one inert gas per compartment through a mono-exponential function; the classic Haldane equation is:

$$P_t(t) = P_{alv0} + [P_{t0} - P_{alv0}]\ e^{-kt} \qquad (1)$$

Where $P_t(t)$ is the artial pressure of the gas in the tissue, P_{t0} is the initial partial pressure of the gas in the tissue at $t = 0$, P_{alv0} is the constant partial pressure of the gas in the breathing mix in the alveoli, k is a constant depending on the type of tissue, and t is time.

One mainstream source for these perfusion algorithms is in Hills (1977), which gives Equation 1 and discusses the relationship between the tissue half-times and the perfusion rate. The decompression time (t_d) for unary mixes (i.e. only one inert

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gas, e.g. enriched air, nitrox, EAN or heliox) can be calculated directly with the Haldane equation. The analytic expression for the decompression time ($t = t_d$) is:

$$t = -\tau/\ln 2 * \ln[(P_t(t) - P_{alv0})/(P_{t0} - P_{alv0})] \quad (2)$$

This is the analytic solution for Equation 1 and is only possible with one inert gas – in this case N_2. With more than one inert gas, the calculation of t_d has to be done numerically, via an approximation procedure, that is by trial-and-error.

Perfusion models for air, nitrox, EAN and heliox as breathing gases are based on extensive records of well-documented dives, whereas those for trimix diving are not. For one inert gas perfusion models are mathematically straightforward and have enjoyed popular implementations in many dive computers and PC programs (Bühlmann, 1983, 1993; Bühlmann et al., 2002). Technical divers want to dive deeper and longer, and many of their dives are outside the trusted envelope. Nonetheless, studies on this envelope have been already published at length (e.g. Brubakk and Neuman, 2003) and, in summary, consider:

- lonly inert gas loading;
- lmono-exponential relationships for one compartment – such compartments are all in a parallel circuit, while the linear connections (e.g. spleen to liver, or bowel to liver) are not considered; and
- lmono-calculation of inert gas saturation and de-saturation in a symmetrical manner, i.e. with the identical coefficient in the exponential terms of the Haldane equation (equation 1).

However, some of the potential drawbacks when modifying these models for use for decompression modelling of trimix diving are:

- that user-dependent physiology and adaption are not reflected at all in the algorithms;
- inconsistent consideration of metabolic gases such as oxygen, carbon dioxide and water;
- the influence of ‘uneventful’ decompression exists where only the gas in solution may be considered and not the free gas phase (bubbles);
- that no allowance is made for short-term pressure changes and their relative influence against the fastest half-times;
- the effects of workload, temperature and excessive oxygen partial pressures; and
- consideration of the second inert gas and repetitive dives.

Another critical point is that the mapping of the compartment half-times from nitrogen to helium is normally done according to Graham’s law using the square root of the proportion of the molecular weights (i.e. ca. 2.65); this factor is uniform to all compartments. This has been met with criticism from serious researchers in the field (D’Aoust et al., 1979; Lightfoot et al., 1978; Rodchenkov and Skudin, 1992). Especially in newer experiments, the perfusion rates are viewed quite differently (Doolette, 2005). The pivotal 2.65 seems to be valid only for saturation exposures (Berghage et al., 1979) which are not pertinent to technical diving.

With a so-called trimix there are two inert gases: N_2 (nitrogen) and He (helium) along with oxygen. This generates two exponential functions with different exponents for the same compartment, one for N_2 and one for He. The inert gas saturation (or the de-saturation) for these two has to be calculated separately, but the criteria for safe ascent are the same regarding length of time. This is where problems arise with the numerical calculation but for commercial applications in oilfield settings, the numerical approximation of a TTS is standard procedure. The present study presents a methodology for examining the performance of decompression models employed in the management of trimix diving.

2. Methods

There are at least three simple methods to evaluate decompression times (t_d):

1. Trial and error method: for small increments in time, e.g. 1sec or 0.1min, all relevant terms are calculated and checked to see if the ascent criteria are met. This is called a classical numerical solution.
2. Quasi-analytical method: an error is tacitly accepted by using Equation 2. Thus the two different tolerated overpressures are considered as independent constants for each phase of the decompression.
3. Approximation method: all the exponential terms are approximated via a polynomial expression, i.e. Taylor Expansion (Bronstein and Semendjajew, 1979).

For commercially available off-the-shelf (COTS) desktop decompression software, method 1 should be used because the computing power of topical PC hardware does not impose any waiting time for the users, unlike standard mix gas diving computers. The relatively high costs incurred during the development for waterproof hardware combined with low sale volumes means that the industry tends to use standard chips rather than full-custom microchips (ASIC) in diving computers. However, in comparison, standard chips are somewhat slower and have high energy consumption.

Method 1, in comparison to method 2, consumes more computing power, time and memory, and includes more variables. All of these factors can generate limitations for use in equipment that is being designed for use under water and so there is a tendency to employ method 2 where costs are at premium and the results from the calculations are needed rapidly. Unfortunately, the actual methods used in commercial products are rarely known because the manufacturers of dive computer hardware tend to cite commercial confidentiality in reply to any enquiries.

To assist in answering this question for the technical diver, the following experimental method was developed: 480 square-wave dive profiles were generated to be representative of those regularly observed in the TEC/REC domains, with depth ranging between 30–80m (6 profiles at 10m increments) and with a range of bottom times (20–60min; 5 profiles in 10min increments). The profiles used helium fractions of 5–80% (16 profiles in 5% increments), with only one normoxic mix (i.e. no travel gases and no EAN decompression mixes). The profiles were evaluated with four software products and compared to:

- two commercially available COTS decompression software products that have a very broad user basis in the TEC community;
- one freeware/shareware version of DIVE (www.divetable.info/dwnld_e.htm, version 2_900); and
- the commercial version 3_0 of DIVE.

All of these four products claim to have implemented the Bühlmann method for calculating decompression (Bühlmann, 1983, 1993; Bühlmann et al., 2002) called ZHL-*n* (where 'ZH' represents Bühlmann's hometown of Zurich; 'L' is the linear equations of the criteria for safe ascent; and *n* is the number of compartments/half-times). In addition to the standard ZHL method, it was possible to set the above-mentioned gradient factors. During the analyses gradient factors were set to 1.0 for all of the products.

The version 3_0 of DIVE implemented method 1 exactly, while the freeware version 2_900 was flawed with a problematic implementation of method 2. For the two COTS products, the available technical documentation was incomplete and no statements were available from the programmers to detail what methods were being used.

The first step, tested these four products against each other with 40 different air and Nitrox/EAN32 profiles. The test checked the actual convergence of the numerical method 1 with the COTS products. Table 1 shows one paradigm with the TTS values for a square dive to 40m, with the bottom times ranging from 20min to 60min.

A sensitivity analysis was performed for the numerical solution in order to ensure that minor variations in the starting parameters did not lead to mathematical artefacts. The four products were compared against the 'gold standard', which is the Zuerich 1986 (ZH-86) table for air dives (Bühlmann et al., 2002). This presented deviations of ±2min per decompression stage; sometimes the staging began 3m deeper in comparison to the table. This is mainly because of the different sets of coefficients used: the ZH-86 table uses the ZHL-16 B set, whereas decompression software or dive computers normally use the ZHL-16 C set (Bühlmann et al., 2002). In addition, the printed tables treat truncations in a completely different way to dive computers. There are many US Navy trials that confirm that decompression information generated from published diving tables rarely matches computer-generated output (Joiner et al., 2007).

To force comparability, all the calculations in the present study were based solely on the set ZHL-16 C and there was no manipulation via gradient factors (GF) – that is, GF high/GF low = 1.00 or 100% of the original published a- and b-coefficients. There were also slight adaptations of the dive profiles via ascent and descent rates, to make sure that the bottom times and the inert gas doses matched.

3. Results and discussion

Evidently there are significant differences in the calculation of decompression times depending on the helium-fraction and the amount of decompression obligation as determined by the inert gas dose (see Fig 1). These differences are not caused by variations in the decompression algorithm, but instead through different methods of calculation.

Table 1: TTS for EAN32 dive versus the four products (TTS, i.e. sum of all decompression stop times + time for ascent)

40 m, Nitrox/EAN 32 bottom times [min]:	20′	30′	40′	50′	60′
TTS DIVE 2_900	8	16	28	42	55
TTS DIVE 3_0: numerical solution	7	17	28	40	57
TTS COTS product 3	5	15	28	41	53
TTS COTS product 4	7	16	28	41	54

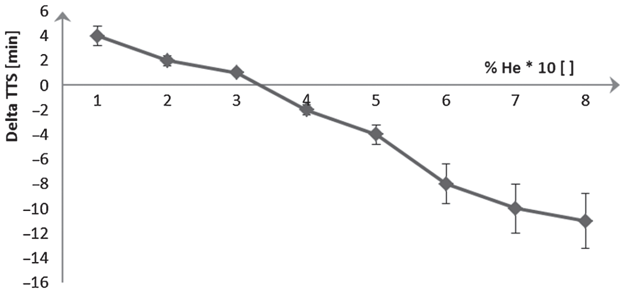

Fig 1: Delta TTS versus percentage of He in the breathing mix dive to 40m with a bottom time of 40min

Fig 1 shows the deviation of the TTS based on the percentage of helium in the breathing mix, using the example of a dive to 40m with a bottom time of 40min.

The *x* axis in Fig 1 is the percentage of helium in the breathing mix from 10% to 80%, while the *y* axis is the Delta TTS. This is a difference of the numerical solution to an arithmetic mean out from the three TTS according to: $\sum (t_{d,1} + t_{d,2} + t_{d,3})/3$, where $t_{d,i}$ is the calculated t_d of the products $i = 1 - 3$ (DIVE 2_900, COTS product 3, COTS product 4).

The *x* axis is defined as the zero baseline of the TTS of the numerical solution. An ‘error’ in minutes is the deviation (Delta TTS) of this mean value against the TTS of the numerical solution. The calculation of this arithmetic mean was superimposed by the strong closeness of the t_d from the three products. The absolute errors (see the vertical error margins) rise with the increase of the inert gas dose and with the increase of the percentage of He in the mix. The curve progression is more or less universal for all of the 480 square profiles. In relatively simplified and qualitative terms, the following can be determined:

- In the region of the helium fractions 0.05 up to ca. 0.25, the TTS is overrated withpositive error (i.e. the TTS is too great, and the decompression is too conservative).
- In the region of helium fractions which is relevant to most technical divers, that is ca. 0.30 – ca. 0.40, the error vanishes – Delta TTS = 0.
- In the region of increasing helium fraction, the error is negative (i.e. the TTS is too small, and the decompression is too liberal).

The results of the two COTS products and DIVE 2_900 were very close to each othersomewhat and so a similar calculation method is assumed. However, this ‘similar’ method means that the error of DIVE 2_900 could be repeated in the implementations of the two COTS products. In other words, the relative identity of the absolute values and the prefix leave room for speculation that the two COTS products are using method 2, although there are also some other factors that could be responsible for these deviations. The following are a few possible factors, although this list is not exhaustive:

- undocumented gradient factors;
- a respiratory coefficient unequal to 1;
- another weighting of other inert gases;
- another weighting of the water density;
- empirically adapted a/b coefficients, especially for and as a consequence of the helium fraction;
- small deviations from the original helium ZHL spectrum of half-times (i.e. a mismatch of a and b coefficients with the half-time);
- utilisation of the so-called ‘1b’ compartment, instead or additive to compartment ‘1’;
- ascent rates varying with depth;
- de-saturation varying with depth and ascent rate; and
- different approach to truncations.

Restrictions in software operations caused by hardware limitations were quite common in the early days of dive computers. For example, there was a product in Europe which could only interpolate linearly between stored table values instead of calculating full-scale saturation/desaturation relationships. Even today, there are applications which rely on a modified ZHL instead of the promised and advertised bubble model.

4. Conclusions

There are a raft of constraints to be considered when attempting to expand the largely theoretical approach detailed in the present study into a wider determination of how models are being implemented in some dive computers. It is difficult to develop any solid conclusions and there may be additional legal considerations. This limits the ability to achieve some transparency in how some of the models are being implemented. The lack of open documentation of the ‘defaults’ and constants leads to numerous questions: for example, is there really a ZHL inside a computer when the label reads ‘ZHL’?

The clear message resulting from these tests is the following: a decompression time in a digital display, be it on a dive computer or a PC, is subject to interpretation. This not so much because of errors in the measurements (e.g. pressure, time, temperature) and other statistical contemplations, but rather caused by the method of programming and the choice of a solution for a mathematical algorithm (i.e. the software technology and implementation). The range for these interpretations is not only in volumetric terms, but also is dependent on the inert gas dose and the helium fraction, in the one- or two-digit percent range.

Therefore, the answer to the question in the title (where do variations in the time-to-surface come from?) is not straightforward. First, the wisdom of using perfusion algorithms could be questioned, but perfusion models work much better than the bubble models (see below); to quote Hamilton (1978): 'Haldane works if you use it properly'. Second, with the aforementioned gradient factors, the users could fix the Delta TTS variations shown in Fig 1. However, the question remains: do gradient factors then provide a safer decompression schedule or are they better employed for user-based software manipulation, as illustrated in the example of method 2?

This will need to be the subject of future research, as new technology and products are being introduced constantly.

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