Anthology: my articles in the "TECHNICAL DIVING MAGAZINE"

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plus Bonus Material:

- Frontiers in Psychology 09 / 2017:
  post-publication comment on:
  Dive Risk Factors, Gas Bubble Formation, and Decompression Illness in Recreational SCUBA Diving: Analysis of DAN Europe DSL Data Base
- International Journal of the Society for Underwater Technology, November 2012:
  Variations in the TTS: where do they come from?
  SUT, Vol. 31, No. 1, pp. 43 - 47, 2012

Fast & Super-fast Compartments

By Albrecht Salm

The following is an **essay** on fast and super-fast compartments. So this is not a strict scientific paper, neither in form nor in contents but a couple of preliminary thoughts on the topic, intended to raise awareness or for further discussion.

If you are new to *Tech Diving Mag*, new to TEC diving or even new to diving, you may enjoy some basic information on deterministic decompression models and algorithms in chapter 2, the „Background". The seasoned diver may skip this safely. Readers not intending to go into the mathematical details may then proceed as well directly to „Take-home Messages" in chapter 12.

Chapter 1: Rationale

During my first course on breath-hold diving some 20 years ago, I stumbled on the inability of standard decompression tables and algorithms to cope with breath-hold diving profiles. My then instructor on this topic, Andy Anlauf, who was at times an elite apnea diver, asked me if I could make a decompression table for the record profiles: for example in 2 min down to 130 m and then up to the surface. If you now look at a compartment, say with a halftime ($\tau_{½}$) of 12.5 min (compartment #3 in the standard ZH-L parlance), it will change its initial inertgas load from ca. 0.8 to only 1.1 bar after 1 min @ 90 m. The super-saturation of ca. 0.3 bar is not enough to yield any basic decompression; even on return to the surface it is still taking up inertgas and the super-saturation is raised to ca. 0.5 bar, still not sufficient for a substantial decompression time. The other compartments from # 8 on will not even take note on this pressure excursion.

Further on, there is a phenomenon called „Taravana": these are the many anecdotal reports on unexplained DCS cases during breath-hold dives, especially for commercial indigenious sea harvesters. As well Paulev (cf. chapter 11) observed cases of DCS type II during breath-hold submarine escape training; Schaefer (cf. Chapter 4) observed N_2 bubbles in blood samples from breath-hold divers, quickly disappearing after 10 sec.

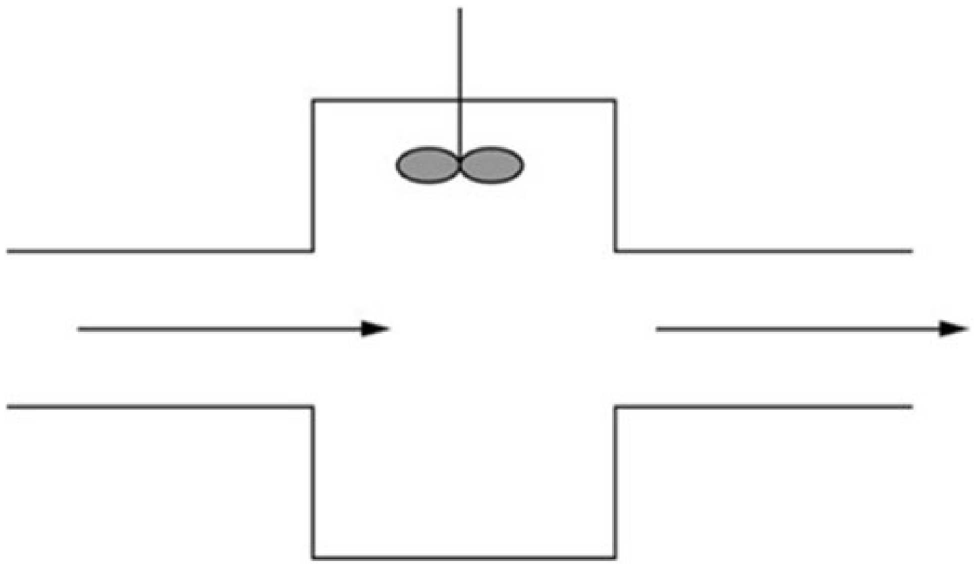
In the TEC community there is since long a sometimes overheated discussion around the effectiveness of short, 1 to 2 min, deep stops during decompression from mixed gas dives.

The time domain of all these phenomenon is in the sub-5 min region. Basically a phenomenological description needs thus an exponential halftime ($\tau_{½}$) in the order of a fraction of the maximal time-frame. Thus approximately 5 min divided by 6 halftimes would allow for a clean description to cope mathematically with the quick pressure changes: 6 halftimes being the rule-of-thumb for complete saturation or desaturation of any compartment (at constant pressure). We end up thus with $\tau_{½}$ of approx. 60 sec.

After a snappy introduction to decompression models and algorithms in the next chapter, there will be a short and limited literature overview which reveals if and how other selected researchers have been dealing with the spectrum of used halftimes.

Chapter 2: Background: What is a compartment, anyway???

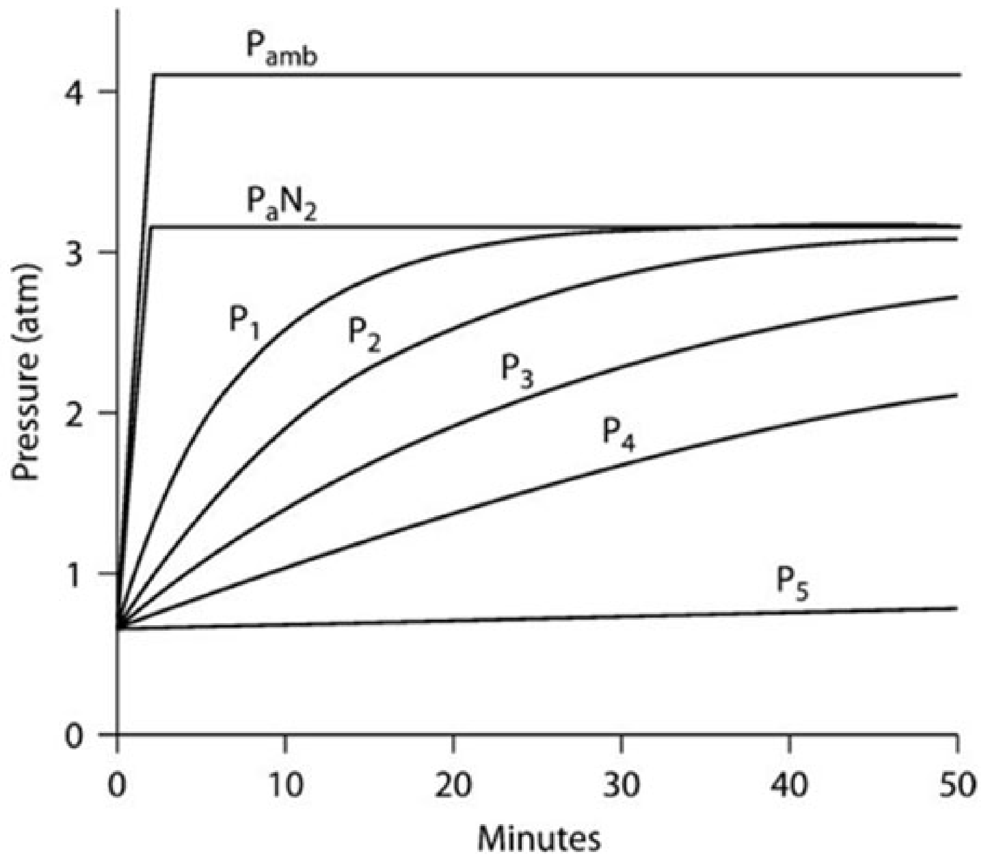
The following is a boldfaced copy from a book of Carl Edmonds, another chap of mine (Ref.: Edmonds, Carl. *Diving and Subaquatic Medicine, Fifth Edition*. CRC Press, 20150713. VitalBook file), the graphs used here have been drawed originally by Dr. David Doolette, working now for the Naval Experimental Diving Unit (NEDU) of the United States Navy (USN):



(with a friendly permission by Carl Edmonds and David Doolette)

The box depicted above is a model for the limited volume of some region in a mamalian body: one compartment is showed here. It is a model for a well-stirred tissue (thus the symbol with the little mixer) with a defined, perfusion-limited blood supply: the arrows from left, the arterial part to the right, the venous part.

Then we will look at a dive scenario with more compartments: we see the nitrogen uptake in five hypothetical perfusion-limited tissue compartments during a dive to 30 metres (4 ATA) using air. P_{amb} is the ambient pressure in atmospheres (atm). The inspired pressure of nitrogen and the alveolar pressure of nitrogen rise to ~3.1 atm (not depicted in the figure), and the arterial pressure of nitrogen (PaN_2) immediately equilibrates. The tissue pressures of nitrogen are slower to equilibrate, due to the final capacities of the blood, lung and circulation carrying the inert gases. Only tissues 1 and 2 approaching saturation within the duration of the exposure depicted. From the lines in the graph and with the rule-of-thumb cited above you can derive the halftimes of the compartments. For example P_1 reaches its 50% saturation after 5 min, so after 6 * 5 = 30 min it is supposed to be saturated; P_2 after 6 * 10 min.

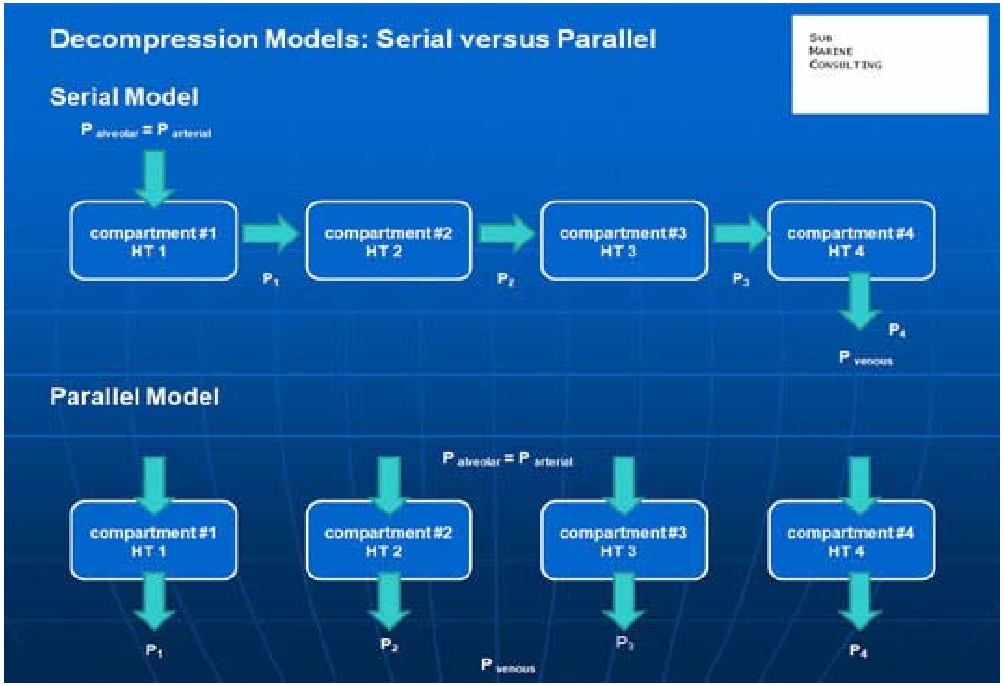


(with a friendly permission by David Doolette)

The lines of saturation follow an exponential curve, typical for many natural phenomena, the math behind a simple linear differential equation is already described elsewhere, for example here: https://www.divetable.info/theory.htm.

In this model we have P_1 to P_5 in a parallel circuit (cf. graph below, the lower part), other models with a serial circuit are possible as well. The most prominent decompression models like the ones from Haldane, Workman (USN tables), Schreiner and Bühlmann (ZH-L) are using the parallel perfused setup. The serial circuit showed below (upper part of the graph) is used by Kidd, Stubbs, Nishi et al for the DCIEM tables and Canadian military and commercial procedures. We see 4 compartments designated # 1 to # 4, with halftimes $\tau_{½}$: HT 1 to HT 4. In the serial setup there need not to be different values.

Serial versus parallel coupling of compartments



All these models are called „deterministic“: they try to predict a safe decompression, that is safe stop depths and stop times, based on the pressure/time profile and the inert gas content of the breathed gases.

A completely other game is a „statistical“ decompression model: there the outcome of thousands of dives is analysed after surfacing. The outcomes (DCS: YES or NO) being fitted to a model and then a decompression table with a defined probability of getting DCS is derived.

Physiologic definition of the compartment halftime

As was described earlier, the halftimes ($\tau_{½}$) are related to the change in the moved blood volume, i.e. the volume per time (ml per min) per ml of compartment volume; thus the physiologic definition looks like that:

$$\tau_{½} = 0{,}693 * \alpha_{ti} / (\alpha_{bl} * dQ/dt) \qquad (0)$$

where:

α_{ti}: solubility of the inert gas per compartment (tissue = ti), $ml_{(S)gas} * ml_{ti}^{-1} * (100\ kPa)^{-1}$

α_{bl}: solubility of the inert gasin blood (blood = bl), $ml_{(S)gas} * ml_{blood}^{-1} * (100\ kPa)^{-1}$

dQ/dt:perfusion rate, $ml_{blood} * ml_{ti}^{-1} * min^{-1}$

The ratio of the solubilities blood / tissue ($\alpha_{bl} / \alpha_{ti}$) has a well-known name: the „partition coefficient“; it could be looked up in tables (cf. the remarks on PBPK in chapter 8). If you do not have the partition coefficient of your compartment in question and you do not have a clue about its perfusion rate, you collapse everything into a single value. This approach leads directly to the pragmatic Schreiner matrix (cf. chapter 5).

A compartment as a „low pass“!

The exponential functions to describe the on/off gasing of the compartments are nearly the same for an electronic circuit, consisting of a capacitor and a resistor. It is used for example to rectify the current from AC to DC: the high frequency parts of the AC are filtered, allowing only the lower frequencies to pass the electronic circuit; thus the name „low pass".

Now, if you have a part of your dive profile with a „high frequency" behavior, i.e. noticeable changes of the diving depth versus short times as in yo-yo diving, the decompression algorithm is „blind" for it: the dive computer may log the depth changes over time but the slower compartments will never notice it. (Ref.: Hahn MH (1989): *Reponses of decompression computers, tables and models to „yo-yo" diving*, Undersea Biomed Res 16 (Suppl.:): 26.)

Chapter 3: Experiment with goats: Haldane

(Ref.: Boycott AE, Damant GCC, Haldane JS. *The prevention of compressed air illness*. J Hyg (London). Jun 1908; 8(3): 342–443.)

The set of halftimes for his 5 compartments was generated by just doubling the 5 min halftime 3 times, with the longest halftime being 75 min due to a hypothetical saturation of nitrogen uptake at around 5 to 7,5 h (pages 349 and 350) for the goats he used for his experiments: 5, 10, 20, 40 and 75 min. Then there could be as well a compartment with a halftime of 2.5 or 1.25 min. On page 348 he gave a hint to a faster saturation process within max. 10 min which would yield a halftime of: 10 min / 6 → ca. 1.6 min.

We could easily exploit this with his rule for safe ascent, the famous „2:1" rule to generate a „new" haldanian-type decompression table, but with **deep stops!** These stops being noticeably deeper than in the original tables, in the 1 min region and not altering the shallow stops by much [an easy procedure on how to do that and an appreciation of the work of Haldane and his colleagues you will find in this magazine, cf. *Tech Diving Mag*, Issue 25 (December 2016), on pages 13 – 20].

Chapter 4: Submarine escape: Schaefer

In his 1955 contribution to the first Underwater Physiology Symposion, he presented his paper titled: *The role of carbon dioxide in the physiology of human diving*, Schaefer describes on page 135 that during breath-hold dives in the 90 feet submarine escape training tank there have been bubbles observed in alveolar and venous blood samples which have been attributed to N_2 and not to CO_2. The blood samples were drawn from the divers immediately on surfacing after a breath-hold dive. The foam due to these bubbles may have been disappearing 10 sec after surfacing or 40 sec after start of ascent, the duration of these dives being ca. 1 to max. 2 min. An allowable super-saturation ratio of 3:1 seems to be exceeded.

This in turn would imply a de-saturation with a halftime of approx. 10 + 40 / 6 (ca. 10 sec) and a saturation process with a halftime from 1/6 min up to 2/6 min.

Chapter 5: The pragmatic Schreiner matrix

In this contribution to the fourth Symposion in 1971, Schreiner and Kelley presented their paper titled: *A pragmatic view of decompression*.

As we can see in the following page, the pragmatic 4 by 4 matrix of the 16 compartments, compartment # 0 is never used. That is: we (*) could easily extract a super-fast compartment with a halftime of 2.5 or 1.25 min by exploiting his scheme on page 210 with dQ/dt * R = 0.2772 min^{-1} resp. 0.5544 (fat fraction X = 0.0)

Specific rate of tissue perfusion ($\dot{Q}/R$)	Tissue fat fraction (X)			
min^{-1}	0	0.3	0.7	1.0
0.3	0	1	2	3
0.1	4	5	6	7
0.03	8	9	10	11
0.0085	12	13	14	15

FIG. 2. Derivation of inert gas exchange compartments by the arbitrary pairing of four specific rates of tissue perfusion and four levels of tissue fat fraction. The resulting compartments are numbered 0 to 15 as shown.

min^{-1})* in solving Eq. (13), one obtains a total of 16 different values of k representing 16 inert gas exchange *units* or *compartments*. These entities are not necessarily identifiable anatomical substructures of the body but rather represent assemblages of those regions within the human body that happen to be characterized by one and the same specific time constant of inert gas transport. These 16 inert gas exchange *compartments* (numbered 0 to 15 for ease of reference) are shown schematically in Fig. 2. It is immediately clear that any other arbitrary array of $\dot{Q}/R$ and x may be employed to derive gas exchange *compartments* as long as representative and minimal rates of the specific rate of tissue perfusion and extreme values of fat fraction are included.

Chapter 6: United States Navy method: Workman

(Ref.: Workman, Robert D. *Calculation of Decompression Tables for Nitrogen-Oxygen and Helium-Oxygen Dives*, Research Report 6-65, U.S. Navy Experimental Diving Unit, Washington, D.C. (26 May 1965))

Here we have compartment halftimes for N_2 from 5 to 240 min (p. 5) and the corresponding allowed inert gas super-saturations, called M-Values. The M-value follows a simple linear relationship, based on empirical dive data (Eq. 1):

$$M = M_0 + \Delta M * d \qquad (1)$$

where M_0 is the maximum inert gas partial pressure in the compartment for surfacing and ΔM is the change with the diving depth (in feet). By fitting separately the ΔM (Delta M) and M_0 over the halftimes we (*) could as well extract faster compartments and the corresponding allowed super-saturations.

Fit for M_0

Our generator function yields with a correlation coefficient of nearly 1, for example for the halftimes 1.25, 2 and 2.5 min these values for M_0 are 156, 134 and 126 fsw respectively.

Fit for ΔM

The above generator polynom gives here, as well with a very high correlation coefficient for the same choosen halftimes of 1.25, 2 and 2.5 min these ΔM values are 37.5, 8.4 and 4.5 respectively.

Chapter 7: Swiss altitude diving: Bühlmann

(Ref.: *Tauchmedizin*, Albert A. Bühlmann, Ernst B. Völlm (Mitarbeiter), P. Nussberger; 5. edition in 2002, Springer, ISBN 3-540-42979-4)

Here we have already a simple relationship between the halftime $\tau_{½}$ of a compartment and the allowed super-saturation for N_2. If we combine the two empirical relationships for the coeffcients a & b from p. 129 (Eq. 2) with the linear equation for the tolerated ambient pressure (p. 117) (Eq. 3) into one:

(2)
$a = 2{,}0 \text{ bar} * (\tau_{½} N_2 [\text{min}])^{-1/3}$
$b = 1{,}005 - 1 * (\tau_{½} N_2 [\text{min}])^{-1/2}$

$P_{compartment} = (P_{ambient,tolerated} / b) + a$ (3)

This yields the following generator function (Eq. 4) by setting the tolerated ambient pressure to 1 bar (for a direct ascent to the surface for breath-hold diving or submarine escape training):

$P_{compartment} = (1 \text{ bar} / (1{,}005 - \tau^{-1/2})) + (2 \text{ bar} * \tau^{-1/3})$ (4)

Thus we could extract here as well faster compartments and the corresponding compartment overpressures. Here around a halftime of $\tau_{½} = 1.005$ min is a divergence in (Eq. 4) and thus this is the smallest allowed value.

Our choosen halftimes of 1.25, 2 and 2.5 min are yielding the compartment overpressures of ca. 11, 4.95 and 4.1 bar respectively. These we could compare directly with the M_0-values from the Workman set above, i.e. for d = 0 fsw in (Eq. 1): 4.8, 4 and 3.9 bar respectively.

Chapter 8: PBPK: Mapleson, Nishi, Flook et al.

One of the first PBPK (**P**hysiologically **B**ased **P**harmaco-**K**inetic) models solved via a simulation with an electric analog circuit was the one from Mapleson, intended to simulate the uptake of inhaled narcotic gases like halothane in the human body:

Mapleson , W.W. *An electrical analogue for uptake and exchange of inert gases and other agents*. J. Appl. Physiol. 18: 197 – 204, 1963.

Others, like: Morales, M.F. and R.E. Smith, 1944, 1945 and1948 in: Bulletin of Mathematical Biophysics, have not been successfully solved at that time due to a lack of fast-enough hardware.

Since then the PBPKs are used to simulate as well drugs and other environmental influences on the human body: by the same token we could designate the Haldane model as one of the first PBPKs.

Mapleson‘s parameters have been used for operational diving by: Flook, V., R. Nishi, A. Khan. *Modelling and Validation of Treatment Tables for Severe Decompression Accidents*. In: Operational Medical Issues in Hypo-and Hyperbaric Conditions [les Questions medicales a caractere operationel liees aux conditions hypobares ou hyperbares] ADA395680, DCIEM, Oct. 2000.

Here we find as well super-fast compartments, i.e. # 1 and 2 in the following table:

Characteristics of each compartment. Time constant in minutes.

Compartment	Tissues	Time constant
1	Adrenals, kidneys, thyroid	0.86
2	Heart, brain grey matter	1.87
3	Liver plus portal system, other small glands and organs	3.07
4	Brain white matter	5.31
5	Red marrow	12.25
6	Muscle and skin	50.62
7	Nonfat subcutaneous	69.14
8	Fatty marrow and fat nitrogen helium	211.3 78.3

Reference values for resting blood flow to organs of man: R Williams* and R W Leggett; Metabolism and Dosimetry Research Group, Health and Safety Research Division, Oak Ridge; National Laboratory, Oak Ridge, Tennessee 37831-6383, USA, 21 February 1989. On page 188 we have a compilation of the relevant perfusion values:

Table 1. Blood flow rates (ml per kg tissue per min) to tissues of resting man, as given in some reviews and physiology texts.

Tissue	Mapleson 1963[a]	Bell *et al* 1968[b]	Cowles *et al* 1971[c]	Brobeck 1979[d]	Ganong 1979[e]	Guyton 1982[f]
Adipose tissue	20	–	24	–	–	–
Adrenals	5000	–	5100	–	–	1800
Bone	0	120	0	–	–	50
Brain	510	650	530	540	540	500
Lung tissue	–	–	–	570	–	180
Heart tissue	800	1000	810	700	840	610
Intestines	–	700	390	540	–	700
Kidneys	4100	1500	4000	4300	4200	3600
Liver (total)	410	1500	840	540	580	750
Red marrow	90	–	400	–	–	–
Skeletal muscle	20-50	20	21	27	27	26
Skin	20-50	30	57	–	130	120
Spleen	–	400	390	–	–	700
Thyroid	4000	5600	5000	–	–	2500

The perfusion rates vary not only with a factor of 250 from ca. 20 (bones) to 5000, but as well over time course and authors. This variance should be reflected as well in the spectrum of used halftimes for a decompression algorithm. As well there are data for just 14 compartments, meaning that using a lot more, as some of dive computers do, would probably not give any further clues. The only argument of using more being philosophically, that „Nature does not make leaps“ (Gottfried Wilhelm Leibniz: La nature ne fait jamais de sauts).

Chapter 9: Mixing two models: Egi & Gürmen

There is a nice method in this paper: Egi SM, Gürmen NM: *Computation of decompression tables using continous compartment half-lives*. Undersea Hyper Med 2000; 27(3): 143 – 153.

The authors were considering the Workman and as well the Bühlmann framework. But instead of fitting each set of M-values to the appropriate halftimes within the corresponding framework they fitted all M-values to all halftimes in a hybrid manner and such combining the Workman and Bühlmann values. The result is a smoothed M versus halftime function with high correlation coefficients. The plot of ln(M) versus ln(halftime) yields a straight line (Fig. 7 on page 149):

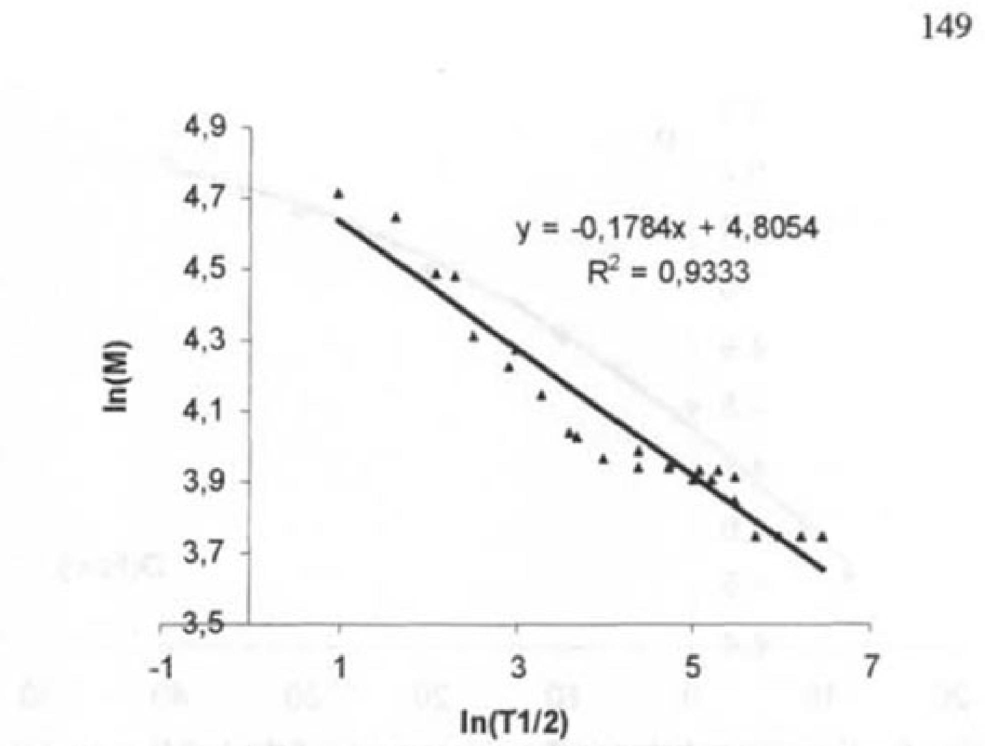


FIG. 7—Correlation between ln(M) and ln($T_{½}$) for the hybrid data set (Workman and Bühlmann) at sea level.. Table 4 lists the slope of the line and y-intercepts of different data set combinations.

If we exploit this function with x = 0.25 (i.e.: halftime = 1.28 min) the results are M_0 = 117 fsw; with x = 0.1 (halftime = 1.1 min) yields M_0 = 126 fsw.

Chapter 10: Breath-hold and DCS Type II: Goldman et al.

(Ref.: *Decompression sickness in breath-hold diving, and its probable connection to the growth and dissolution of small arterial gas emboli*; Saul Goldman, J.M.Solano-Altamirano, Mathematical Biosciences 262 (2015): 1–9.)

In this paper we find a super-fast compartment (brain) with the halftime of 72 sec.

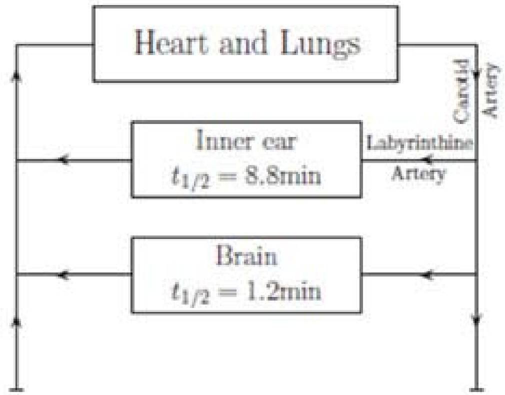


Fig. 3. Independent parallel compartmental model of the head showing the brain and inner ear, each represented as independent mono-exponential compartments, with their respective half-lives ($t_{1/2}$).

(Source: l.c., page 5)

Chapter 11: A Fit to the Paulev data

To be completely honest with my sources, I recieved the Paulev papers from Karl Huggins, with whom I started to discuss this topic around the turn of the millenium. Karl created his version of a USN deco table („HUGI table“) as well he was fundamental for the ORCA EDGE dive computer in the 80s (The ORCA EDGE being one of the first diver carried computers not only interpolating stored table values but instead using a full-blown decompression model). Paulev, as described in the „Rationale“, observed on himself a case of neurological DCS during submarine escape training (ref. 1) which has been treated successfully in a deco chamber. Subsequently he made measurements of exhaled gases during breath-hold diving (refs. 2 and 3):

Ref 1: PAULEV, P. *Decompression sickness following repeated breath-hold dives*. J. Appl. Physiol. 20(5) : 1028-1031. 1965.

Ref 2: PAULEV, POUL-ERIK, AND NOE NAERAA. *Hypoxia and carbon dioxide retention following breath-hold diving*. J. Appl. Physiol. 22(3) : 436-440. 1967.

Ref 3: PAULEV, POUL-ERIK. *Nitrogen tissue tensions following repeated breath-hold dives*. J. Appl. Physiol. 22(4): 714-718. 1967.

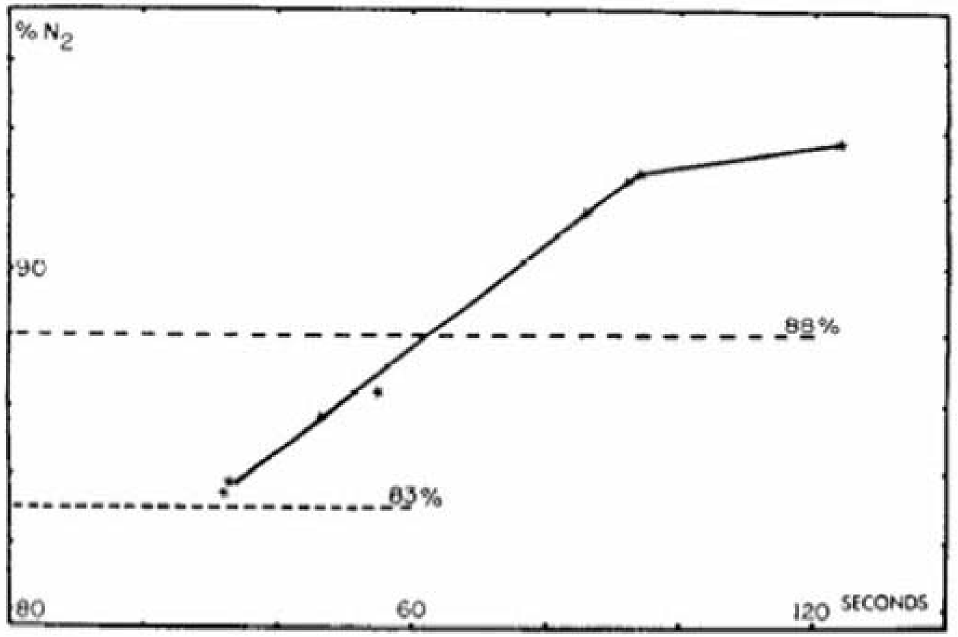


FIG. 1. N_2 percentages from alveolar samples obtained at the bottom of a 18.5 m deep submarine escape-training tank (7). The abscissa is the period from the start of the dive to the time of sampling. The mean durations for descent and ascent in such dives are in seconds [±SE (n = 14)]: 22.6 ± 0.3 and 13.3 ± 0.6, respectively.

From this published curve (Fig. 1 on page 715 in paper 3.; as well the Fig. 3 on page 438 in the paper 2), we (*) extracted graphically the raw data in order to simulate the N_2 uptake of one super-fast compartment. A fit to a mono-exponential saturation function like:

Y = 1- a *EXP(- b *X) (5)

Where Y = N_2 Saturation, alveolar [%] and X = dive time [seconds] yields the following:

a= 0.24
b= 0.01

with a relatively high correlation coefficient around 0.97; the mathematical details are too specific for an essay like this. But anyway there is:

Error propagation
We end at an error of approx. +/- 12 % of the fitted values due to uncertainities of the published graphical data, which is not available in digital form.

Halftime of the super-fast compartment
Thus the halftime is, by definition, $\tau_{½}$=**ln 2 / b = ca. 70 sec +/- 12 to 15 %**, with a stunning coincidence with Saul‘s value (chapter 10). This one would give, in return to the a and b coefficients of Eq. (2), a maximal inert gas partial pressure (4) in this „fast compartment“ of 8 up to ca. 20 bar within the Bühlmann framework. One could question the sheer size of this value derived from the model directly, but presently there are not enough data at hand. On the other hand, there are no arguments for not keeping the maximal tolerated overpressure from the fastest compartment as well for the super-fast compartments. Thus we could designate the ca. 3.5 bar overpressure from the traditional 2.5 to 5 min compartment to the faster ones.

Chapter 12: Take-home messages

A compartment is not a single physiological site in the body, instead, it is a group of various tissues, sharing some common properties, like the perfusion rate, which is basically the invers of the halftime used in the exponential curves.

If you use more compartments, say in your dive computer or a decompression model, you do not get closer to the truth, instead you just get closer to the data points at hand.

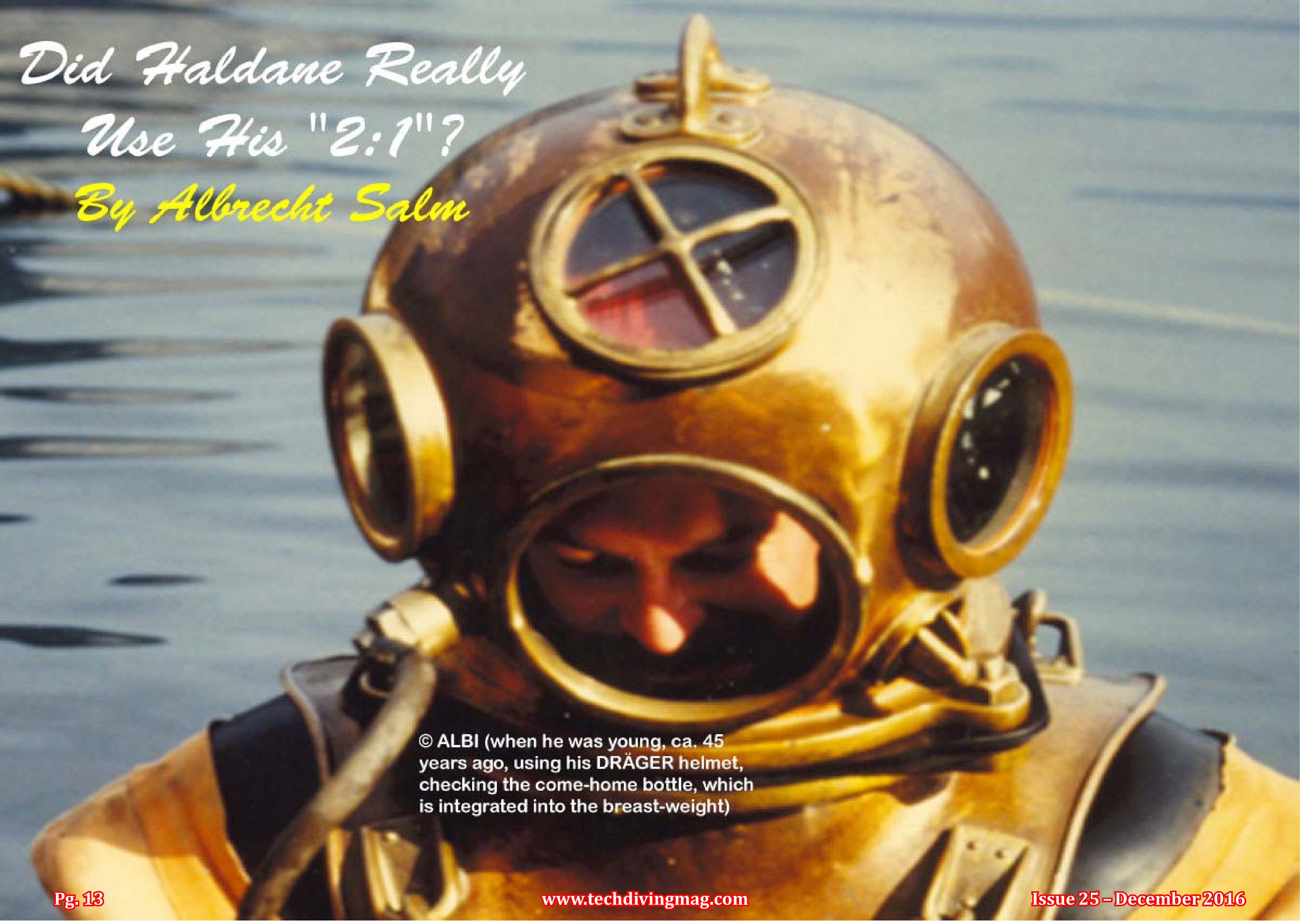
For fast processes, like yo-yo diving or breath-hold profiles, the usually used halftimes are by far too slow, i.e.: the dive computer (resp. the decompression model) acts like a „low pass".

To simulate processes like that, you need faster and/or super-fast compartments, namely in the sub-min region, like a halftime $\tau_{1/2}$ from 30 sec to 1.5 min.

(*): SubMarineConsulting: www.SMC-de.com

Did Haldane Really Use His "2:1"?

By Albrecht Salm



© ALBI (when he was young, ca. 45 years ago, using his DRÄGER helmet, checking the come-home bottle, which is integrated into the breast-weight)

Preamble

The following is along the traditional lines of a serious scientific paper, i.e.:

Introduction
Methods
Results
Discussion
References

The contents, however, may be regarded as something winkingly…

Introduction

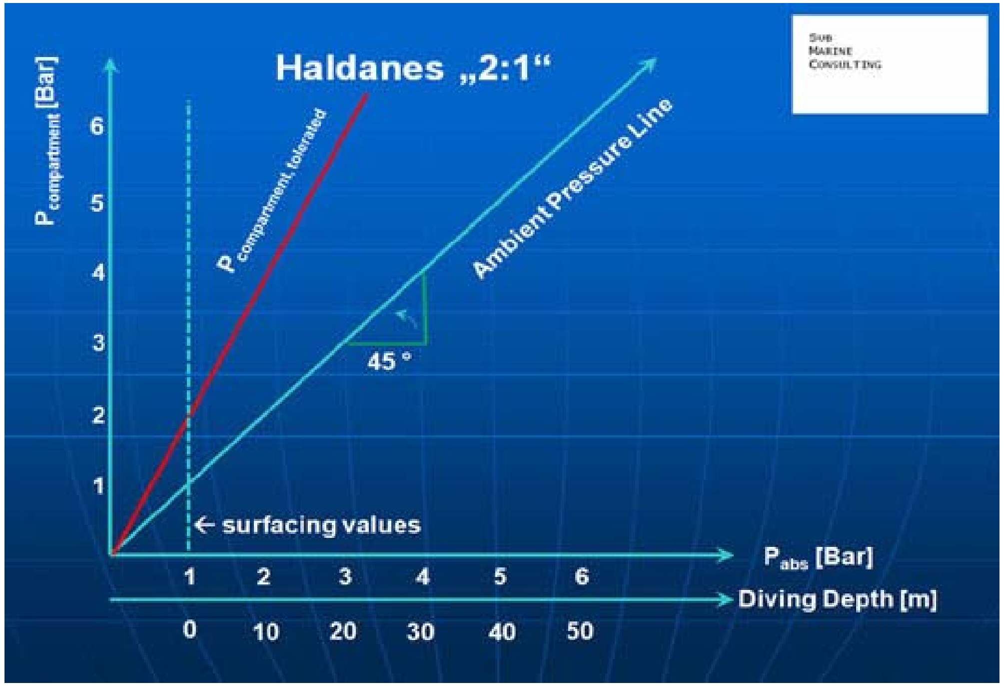
The famous scottish physiologist John Scott Haldane (1860 – 1936) and his co-workers published in 1908 a ground-breaking paper [1]. This is generally considered and accepted as the foundation of staged decompression diving. The paper featured twodiving tables in the attachment. The first of these tables became very successfull. In deed, Table I (loc. cit. p. 442) was adopted for regular use in the Royal Navy ca. a year (p.367) before and was so wildly successfull, that Haldane later on wrote ([2], p. 350):

> Since the introduction into the British Navy twelve years ago of the method of decompression embodied in the tables, with the corresponding regulations as to air supply and testing of the pumps, deep diving has been conducted with comfort and safety to the divers, so that compressed-air illness has now practically disappeared except in isolated cases where from one cause or

The work of these 3 gentlemen and their 85 goats and hundreds of smaller animals ([1], p. 379) is still the basis of most modern decompression tables, desktop deco-software and diver-carried dive computers: more than 800 dives with goats and more than 300 with the smaller animals have been analysed carefully. In the refs. [3] – [7] is ample material. The basic assumptions to calculate the tables have been:

- the model of a human body can be divided into 5 theoretical compartments with halftimes from 5 to 75 min
- inert gas uptake and elimination is exponential with the above halftimes and thus:
- symmetrical, provided no inert gas bubbles have been formed upon pressure reduction
- these compartments can withstand a certain supersaturation. Below this threshold value the risk of contracting decompression sickness is relatively low
- this particular threshold, the tolerated supersaturation, for these 5 compartments follows a „2:1" rule, that is: ([1], p. 424):

> **No symptoms are produced by rapid decompression from an excess pressure of 15 pounds, or a little more, to atmospheric pressure, *i.e.* from two atmospheres absolute to one. In the same way it is safe to quickly reduce the absolute pressure to one-half in any part of the pressure scale up to at least about seven atmospheres: *e.g.* from six atmospheres (75 pounds in excess) to three (30 pounds), or from four atmospheres to two.**



In the course of time and extensive usage it became clear, however, that there are operational shortcomings. Table I was overly conservative for short bounce dives and Table II was grossly inadequate for long and deep dives. This is discussed as well in [3], [7], [8 → 13] and the references therein. As well Haldane had caveats and mental preservations; one is there, [1] on p. 368:

In the case of men of exceptionally heavy build, and inclined to obesity, the time allowed after very prolonged exposures ought to be increased by about a third, although such men, particularly if over about 45 years of age, ought not to expose themselves to the risk of a prolonged stay in very deep water.

And another one in [1], p. 357 is this very clearly stated footnote:

Whether the law holds good for pressures much exceeding six atmospheres is still doubtful, as no experimental data exist.

It seems that these caveats have been forgotten, especially by designers of modern decompression software. Or, as Robert Henry Davis put it already that time [15], p. 8:

„In spite of this characteristic caution, later writers have mistakenly credited him with asserting that rapid decompression from *any* pressure „2n” to pressure „n” is safe.” And, on this particular page further down: „...10 atm, Haldane’s two to one law no longer held good, a finding for which he had prepared us.”

The basic shortcomings have been alleviated with:

- increased number of compartments, i.e.: 9, 14, 16, 20 or more
- greater spectrum of halftimes. i.e. from 2.5 min to 900; and
- variable supersaturations, i.e.: from ca. 3.4:1 to 1.1:1.

But despite these operational shortcomings there have been rumors about the internal design of the tables, i.e. if the calculations really follow the „2:1” principle; that is, what was stated on p. 355:

It seems perfectly clear that no symptoms occur with less than one atmosphere[1] of excess pressure, however long the exposure may be.

(Historical note: a lot of these calculations have been done by his son JBS Haldane, called Jack. Despite beeing a child, he co-authored already earlier papers with his father; he was considered a genius. As a reward he was allowed to take part in the diving experiments in open waters ([1], p. 436):

and Commander E. V. F. R. Dugmore, Lieutenant G. N. Hen Jack Haldane (age 13) all made descents in six fathoms of water.

Rumors

Since then, decompression researchers and divers have been speculating about this “2:1”. One explicit statement is from H. V. Hempleman in ref. [8], p. 233:

„One further important fact to be noted is that although the Haldane decompression ratio of 2:1 is much discussed by everyone studying this subject it was not used by Haldane for his calculations!”

1935

Already earlier this millenium Hawkings, Shilling and Hansen from the United States Navy (USN) had been writing in:

IN: U.S. Nav. Med. Bull. 1935; 33:327–338.

A SUGGESTED CHANGE IN CALCULATING DECOMPRESSION TABLES FOR DIVING [1,2]

By James A. Hawkins, D. Sc., Charles W. Shilling, Lieutenant, Medical Corps, United States Navy, and Raymond A. Hansen, Lieutenant, United States Navy

(From the Laboratory of the Experimental Diving Unit, Navy Yard, Washington, D. C.)

(loc. cit: p. 333):

„Actually we find when we calculate many of Haldane’s tables (1922) that he often goes to a ratio of 2.1 or even 2.3 to 1, but this is well within the safety factor.”

1945

In a publication from 1945 about „explosive decompression” with more than 400 animals (mice, rats, guinea pigs and rabbits) we find the following statement:

„… it would seem that Haldane deliberately abbreviated the final equilibration period by 10 – 20 min…”

(Source: J. Physiol. (1945) A STUDY OF THE EFFECTS OF RAPID ‘DECOMPRESSION’ IN CERTAIN ANIMALS BY P. EGGLETON, S. R. ELSDEN, J. FEGLER AND C. 0. HEBB)

1969

In a research paper from the Submarine Base Groton, Conn. (NSMRI Report No. 580, 1969: Decompression Patterns developed by an interdependent Electric Analog, Gary P. Todd) we find on p.4 (citation):

„… the original tables varied from 3,4 : 1 to 1,2 : 1 …”

1984

A very similiar, but more detailed, really in-depth analysis of 2 profiles is there [8] on the pages 233 – 242! It looks like that the supersaturation ratios, used to build the tables, are varying from 2,5 : 1 to 1,7 : 1, as well during all the deco stages! In clear words: from deco stage to deco stage these ratios have been changed from „2:1” to something differently!

1992

Last, but not least: my friend Karl Huggins put in his famous deco workbook (ref. [9], p. 2-6):

2-6 *THE DYNAMICS OF DECOMPRESSION WORKBOOK*

It is interesting to note that in some cases Haldane allowed the ratio of 2.3:1 to occur on the final decompression step to the surface. This causes a slight discrepancy between schedules that are calculated using the 2:1 ratio and Haldane's published tables. This type of table "*tweaking*" is not at all uncommon in the development of decompression tables.

Methods

We have been curious if these rumors and, sometimes harsh comments, have been assessed correctly. You could do it yourself with virtually any desktop deco software there is, provided it allows for a certain flexibility described below. We set out to check with our public freeware version of DIVE.

The allowed / tolerated compartment supersaturation follows a simple linear relationship (see the graph above), as in all well-known decompression-models based on compartment perfusion:

$$P_{\text{compartment, tolerated}} = (P_{\text{ambient}} / b) + a$$

This is the formula found for eg. in Bühlmanns books ([13], p. 117); a very similar equation in the notation from Bob Workman looks like that [14]:

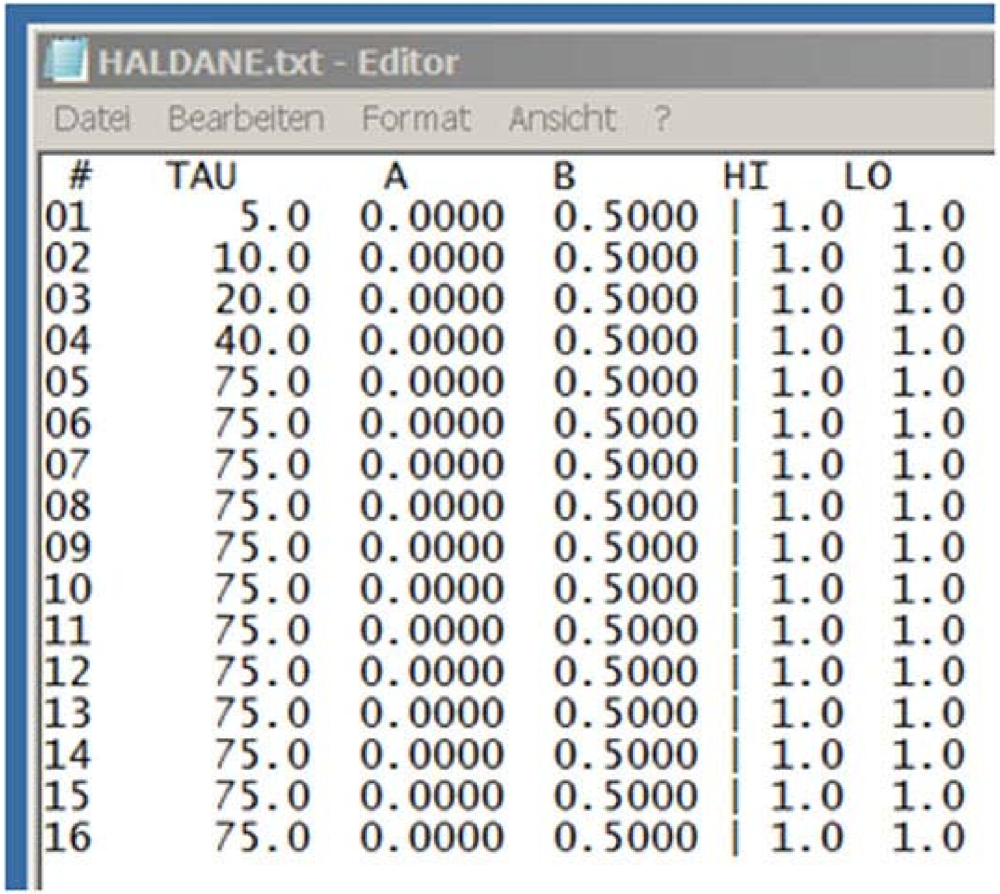
$$M = M_0 + \Delta M * \text{diving depth}$$

By combining the Bühlmann formula with the Haldane law and compare the 2 linear equations on the right hand-side you have now:

$$P_{\text{compartment, tolerated}} = (P_{\text{ambient}} / b) + a = P_{\text{ambient}} * 2$$

$$\rightarrow \qquad a = 0.0\ ,\ b = 0.5$$

With DIVE Version 3 this check is now easy and straightforward. Take the coefficients matrix and modify it, according to Haldanes specifications; i.e.: overwrite the first half-times (TAU) with the ones, Haldane used (5, 10, 20, 40&75 min.), then put a = 0.0 and as well b = 0.50, as you may infer from the graph above or from the formulas. In order to ensure that DIVE Version 3 does not go nuts with these things, you have to copy to last line (compartment #5) and fill up the matrix up to #16 with the identical values:


HALDANE.txt - Editor
Datei Bearbeiten Format Ansicht ?

```
#     TAU     A       B         HI    LO
01     5.0  0.0000  0.5000 |  1.0   1.0
02    10.0  0.0000  0.5000 |  1.0   1.0
03    20.0  0.0000  0.5000 |  1.0   1.0
04    40.0  0.0000  0.5000 |  1.0   1.0
05    75.0  0.0000  0.5000 |  1.0   1.0
06    75.0  0.0000  0.5000 |  1.0   1.0
07    75.0  0.0000  0.5000 |  1.0   1.0
08    75.0  0.0000  0.5000 |  1.0   1.0
09    75.0  0.0000  0.5000 |  1.0   1.0
10    75.0  0.0000  0.5000 |  1.0   1.0
11    75.0  0.0000  0.5000 |  1.0   1.0
12    75.0  0.0000  0.5000 |  1.0   1.0
13    75.0  0.0000  0.5000 |  1.0   1.0
14    75.0  0.0000  0.5000 |  1.0   1.0
15    75.0  0.0000  0.5000 |  1.0   1.0
16    75.0  0.0000  0.5000 |  1.0   1.0
```

(Ignore the values HI = LO = 1.0! These are reserved for the so-called

„Variable Gradient Method", the VGM, which we do not use now. And, to be honest, nobody used except some strange divecomputers, obsolete since long …)

But to reach at a meaningful comparison, you have to adapt as well the following values:

- Geometric diving depth / depth of decompression stages: from feet to m
- Rate of ascent; Haldane put it to ca. 30 feet / 1 min
- Density of seawater: most deco softwares use freshwater density or another cryptic, average value
- Inertgas content: deco software uses normally fN_2 = 0.79 or similar value +/- 2 % for air diving. Haldane et al. did not! They used instead fN_2 = 1.00! Regular desktop deco software may not allow fN_2 = 1.00 because this would imply a relatively unhealthy mixture without O_2.

To get a grip on that one you could use something like an „inverted EAD" (inverted equivalent air depth). From your EAN / Nitrox courses your are familiar with the regular EAD concept. This one here is just the inverse in the metric version:

$$(\text{depth}_{\text{Haldane}} + 10.0) / 0.79 - 10.0 = \text{depth}_{\text{calculation}}$$

Results

As just one paradigm, let's take the following dive from Table II to 132 – 144 feet for 90 min.

With the above adaptions in mind the results for the calculated inert gas partialpressurespN_2 in the leading compartments (the one with the highest N_2 pressures) looks like that:

Procedure	Leading Cmpt	pN_2 [Bar]	Ratio
on reaching the 12 m stage, after the 10 min stop	# 3	4.1390	1.88136
on reaching the 9 m stage, after the 10 min stop	# 4	3.6671	1.93005
on reaching the 6 m stage, after the 20 min stop	# 4	3.1195	1.94960
on reaching the 3 m stage, after the 30 min stop	# 5	2.5801	1.98460
on reaching the surface, after the 35 min stop	# 5	2.2058	2.20580
(extending the last stop to 52 min			2.0150)

For this dive, the deeper stops are more conservative and giving thus a reduced supersaturation, e.g. the first ratio of 1.88 gives something like a „Gradient Factor" of 94 %, aka „GF Lo = 0.94"; but the surfacing value is ca. 2.2 : 1 instead of 2.0 : 1. If the last stop at the 10 feet stage is extended from 35 to ca. 52 min, then a nearly „2:1" would have been reached.

Haldane 2.0

A couple of other dives end up in ratios for the deeper stops with ca. 1.6. This would give sometimes a GF Lo of 80%. So Gradient Factors are already in place since then! As well things like „accelerated deco" (p. 354, 371, 376), „EAN36" (p. 379), linear decompression only for saturation dives (p. 366), more and longer compartment halftimes (p. 376) and asymmetric de-saturation (p. 344, 350) have alreday been contemplated. So some diving magazines sell you these things as the latest cry from the TEC-scene: but obviously it's not. It has been around now for more than 105 years, just the terminus technicus, Haldane's wording, has been quite different.

Discussion and Conclusion

Basically we could confirm the above cited rumors, but as well Haldane's own caveat, which was clearly pronounced on p. 355:

> Whether any distinct symptoms ever occur with less than about 1·25 atmospheres (18½ lbs. per square inch or 41 feet of sea water) seems very doubtful: at any rate they are very exceptional. At pressures a little above 1·25 atmospheres occasional slight cases begin to be observed, and their frequency and gravity rapidly increase with higher pressures unless the time of exposure is limited or slow decompression is resorted to. The lowest pressure at which we have been able to find any record of a death occurring from caisson disease is 23 lbs. or 1·6 atmospheres[2].

In [1], p. 367 the authors state:

> only case in which these limits are allowed to be slightly exceeded is with short exposures in comparatively shallow water.

As well, on p. 361:

> The possible occurrence of slight symptoms after surface had been reached would not, however, be a serious matter: for this reason half of the last stop at 10 feet from surface might be dispensed with, which would save half an hour.

And, on p. 374:

> and the stoppages recommended during the divers' ascent after exceptionally long periods of exposure are somewhat shorter than would be desirable apart from the risks entailed by the long stay under water.

In summary, some of the last stopshave been obviously truncated, but, as well, it is clear from all these statements above copied from [1], that the tables *have been designed clearly with that in mind!*

Given the mathematical / operational possibilities of the time and the depth / time intervals of the tables, the „2:1" ratio is clearly followed, say by approx. +/- 20 % in Table II and by approx. +/- 10 % in Table I. This would be perfecly in-line with the accuracy of the available measurement methods for depth and time, and, as well with the clumsyness of a diving operation (dry suit + helmet + weights + boots + come home bottle + … at approx. 100 kg; lowering & lifting the diver with a stage, i.e. manually geared elevator).

(This is even adressed in modern diving operations: the stage with the 2 divers, called „team red" and „team green" is lowered in the water to ca. 20 feet, they turn around, make a bubble check and only thereafter the bottom time starts.)

If you consider also the basic restraint of Table I, i.e. a maximum TTS (time-to-surface) of about 30 min and the operational difficulties of implementing a new procedure to a military organisation, which, normally, behaves sort of beef-witted …

In clear and easy retrospect we would not join the choir of bleating from our colleagues but instead bow to these tables! Especially if you consider the lines of reasoning and the audacious transformation of the results from the goats in a deco-chamber to real human divers in water!

References (and literature for further reading)

A) General:

[1] Boycott AE, Damant GCC, Haldane JS. The prevention of compressed air illness. J Hyg. 1908;8:342–443.

[2] RESPIRATION BY J. S. HALDANEM.D., LL.D., F.R.S. FELLOW OF NEW COLLEGE, OXFORDHON. PROFESSOR, BIRMINGHAM UNIVERSITY. NEW HAVEN YALE UNIVERSITY PRESS LONDON: HUMPHREY MILFORD: OXFORD UNIVERSITY PRESS MDCCCCXXVII

[3] The Future of Diving: 100 Years of Haldane and Beyond; published by Smithsonian Institution Scholarly Press; ISBN-13: 978-0-9788460-5-3, ISBN-10: 0-9788460-5-2. Especially the chapters:

- J. S. Haldane, the First Environmental Physiologist. Alf O. Brubakk and Michael A. Lang, p. 5 - 10.
- Haldane Still Rules! David J. Doolette, p. 29 - 32.

[4] / and, as well: [119] Goodman, Martin (2007) Suffer and Survive: Gas Attacks, Miners‘ Canaries, Spacesuits and the Bends: the Extreme Life of Dr. J.S. Haldane, Simon & Schuster, London, ISBN 978-1-4165-2230-0

[5] A BRIEF HISTORY OF DIVING AND DECOMPRESSION ILLNESS. Chris Acott, SPUMS Journal Volume 29 No.2 June 1999

[6] JS HALDANE, JBS HALDANE, L HILLAND A SIEBE: A BRIEF RESUME OF THEIR LIVES. Chris Acott, SPUMS Journal Volume 29 No.3 September 1999

[7] TESTING JS HALDANE’S DECOMPRESSION MODEL. Chris Acott, SPUMS Journal Volume 30 No.1 March 2000

B) Special:

[8] / and, as well: [158] Shilling, C. W. Carlston, C.B. Mathias, R.A (1984) The Physicians‘s Guide to Diving Medicine, Plenum Press, N.Y.,ISBN-13: 978-1-4612-9663-8

[9] Huggins, Karl E. (1992) The Dynamics of Decompression, Workbook, 1st. edition. Ann Arbor, Michigan

[10] Hawkings, J.A., Shilling, C.W., Hansen, R.A. A suggested change in calculating decompression tables for diving,U.S. Nav. Med. Bul 1935; 33: 327 - 338

[11] J. Physiol. (1945) A STUDY OF THE EFFECTS OF RAPID ‚DECOMPRESSION‘ IN CERTAIN ANIMALSBY P. EGGLETON, S. R. ELSDEN, J. FEGLER AND C. 0. HEBB

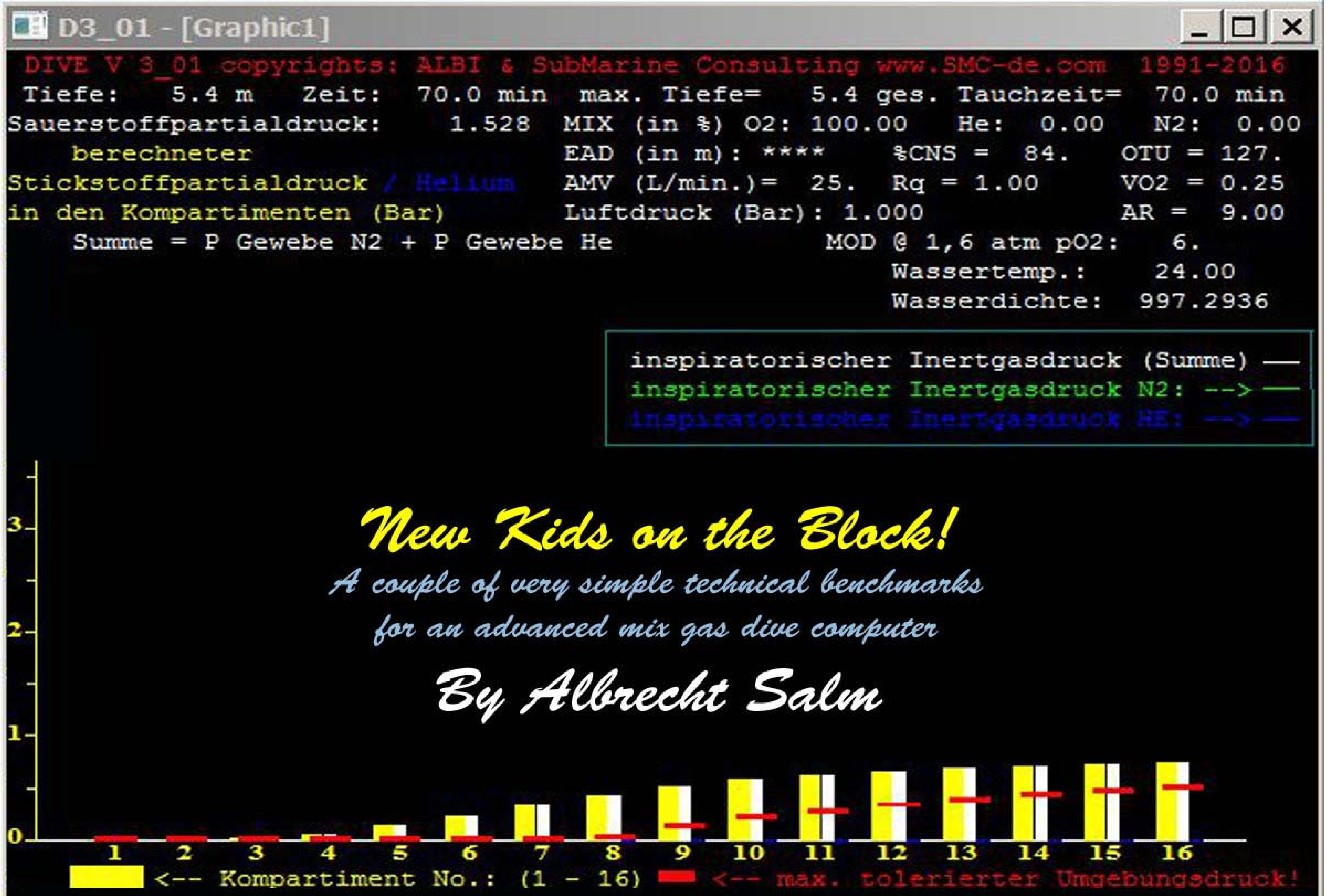
[12] NSMRI Report No. 580, 1969: Decompression Patterns developed by an interdependent Electric Analog, Gary P. Todd

C) Perfusion Models:

[13] / and, as well: [65] Bühlmann, Albert A., Völlm, Ernst B. (Mitarbeiter), Nussberger, P. (2002): Tauchmedizin, 5. Auflage, Springer, ISBN 3-540-42979-4

[14]Workman, Robert D. „Calculation of Decompression Tables for Nitrogen-Oxygen and Helium-Oxygen Dives,“ Research Report 6-65, U.S. Navy Experimental Diving Unit, Washington, D.C. (26 May 1965)

-/- a summary of all needed formula for decompression calculations



New Kids on the Block!

A couple of very simple technical benchmarks for an advanced mix gas dive computer

By Albrecht Salm

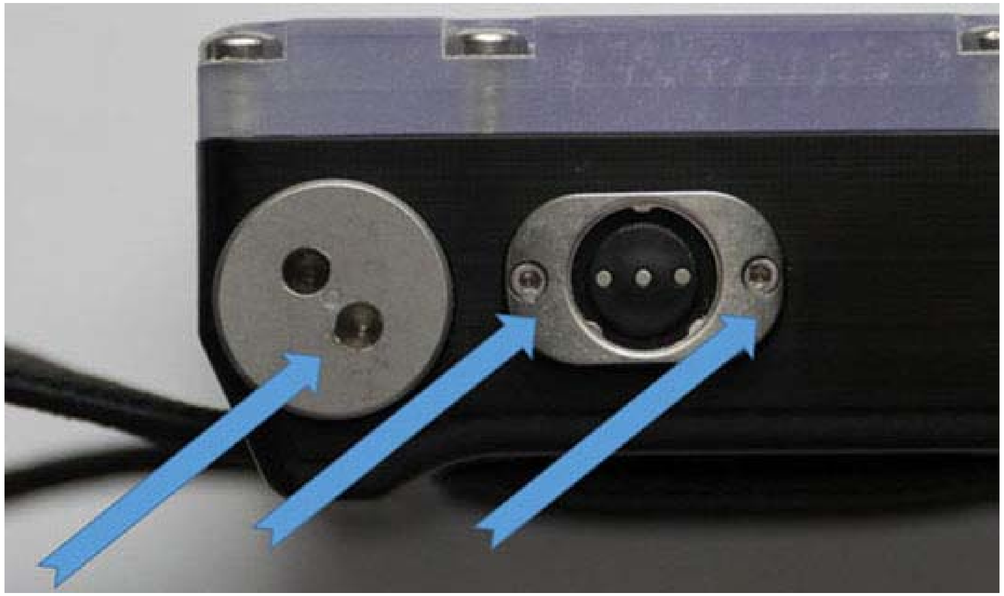
There is a bunch of new mix gas and wrist-watch type dive computers available; please have a look at: http://www.ratio-computers.com/

The real company behind this system is a well known Italian company: http://www.divesystem.com/

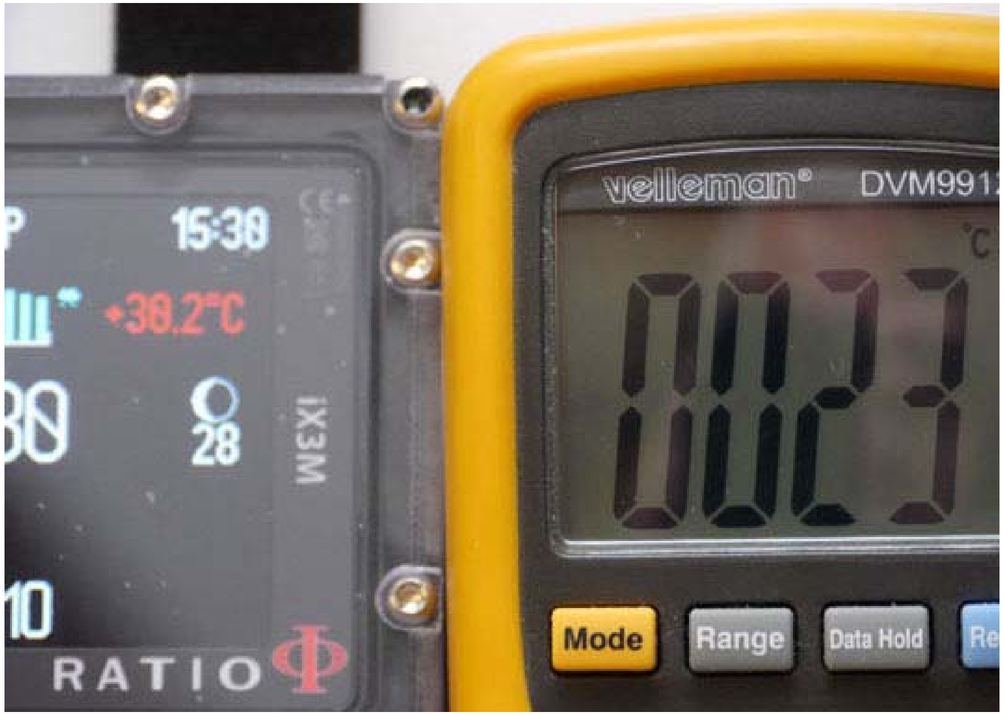
Thus we took one of these computers, the RATIO iX3M DEEP and played around with it a little bit in our laboratory. To be honest, our main focus (http://www.smc-de.com/) is a little bit different, pressure-wise, but we always have a lot of fun watching these little black boxes (or pieces of desktop deco-software) going nuts. Therefore here‘s the rationale for our benchmarks:

- ➔ helping manufacturers to make things better
- ➔ helping customers to reach an in-depth „informed decision“ more quickly

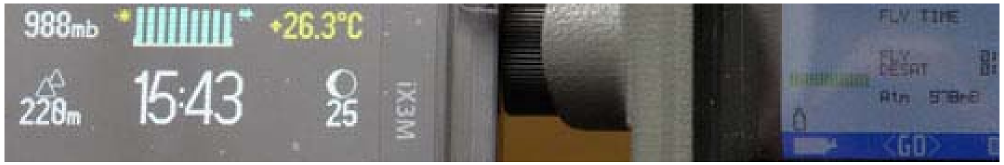
First we checked the hardware. You see the left side of the box with the USB plug (center):



This seems not to be a real super-precision drilled piece. So we looked at the environmental parameters and realized a somewhat different approach to these: the temperature measured with a calibrated PT 100 showed up differently, 30.2 vs. 23.00:



And, as well the ambient pressure, 988 vs. 978:

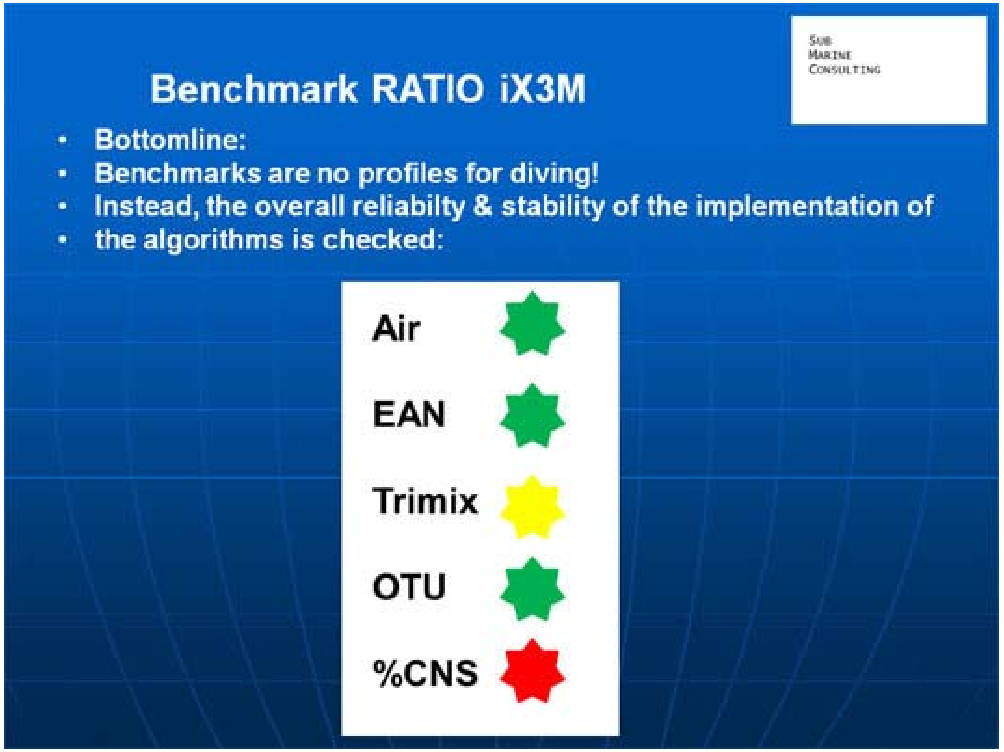


And, after cooling down the whole system, the temperature compensation for the pressure reading did not meet our expectations:

The „real“ values, assessed with calibrated laboratory equipment being: 993,0 mbar @ 22,0° C .... An average dive computer gets the depth reading via a pressure sensor. These usually work with the piezo effect on a little piece of silicon, bonded on one side into a vacuum chamber, thus able to measure the absolute pressure. Mechanical stress or strain on the silicon chip changes its electrical potential thus a voltage could be measured. A change in temperature brings for nearly all physical objects a change in volume. This is why a piezo sensor has to be „temperature drift compensated“ (among some other things, like drift due to its age, due to drift in the supply voltage and even more). An average piezo chip with media contact, that is for e.g. hot or cold water, signals on its own bus system (called „I^2C“) or on a serial line first the bits for the measured voltage resp. the pressure and with the second data word comes the temperature. So it is up to the application software from the dive computer making good use of these values: the pressure has to be modified according to the temperature via a little polynom. If you are interested in the details of these operations, check the specifications of the sensors, as an example take ref [1].

After that, we checked a couple of theoretical diving schedules with the integrated „Dive Planner“ and found an agreeable agreement with a lot of other tables:

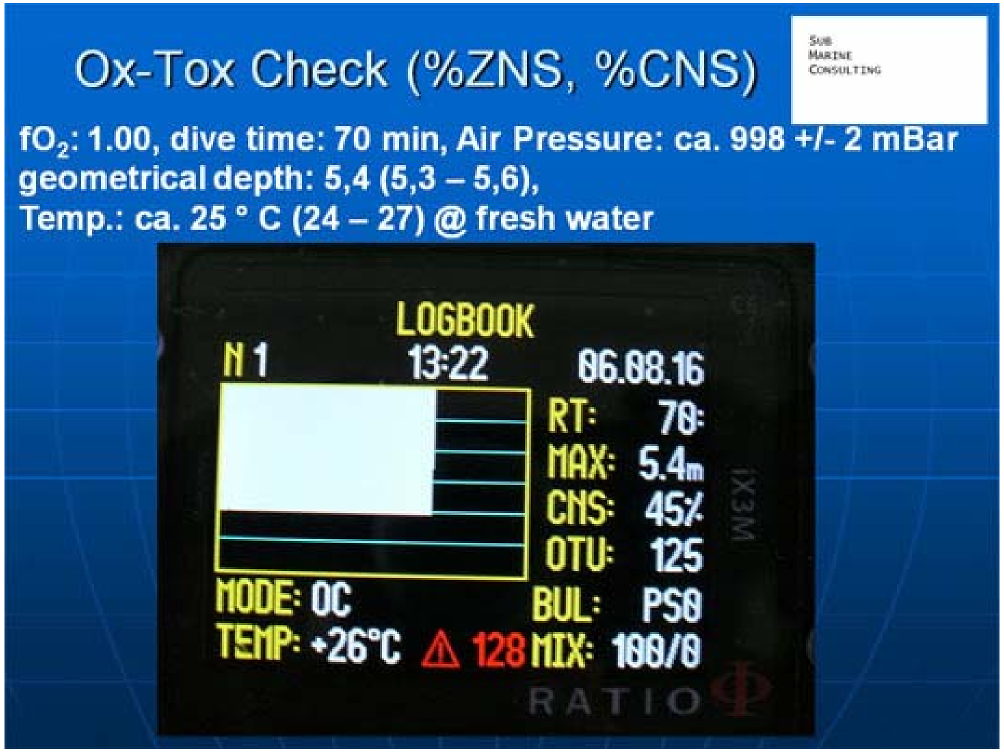
You could check these benchmarks at:
http://www.divetable.info/skripte/Benchmark_iX3M.pdf



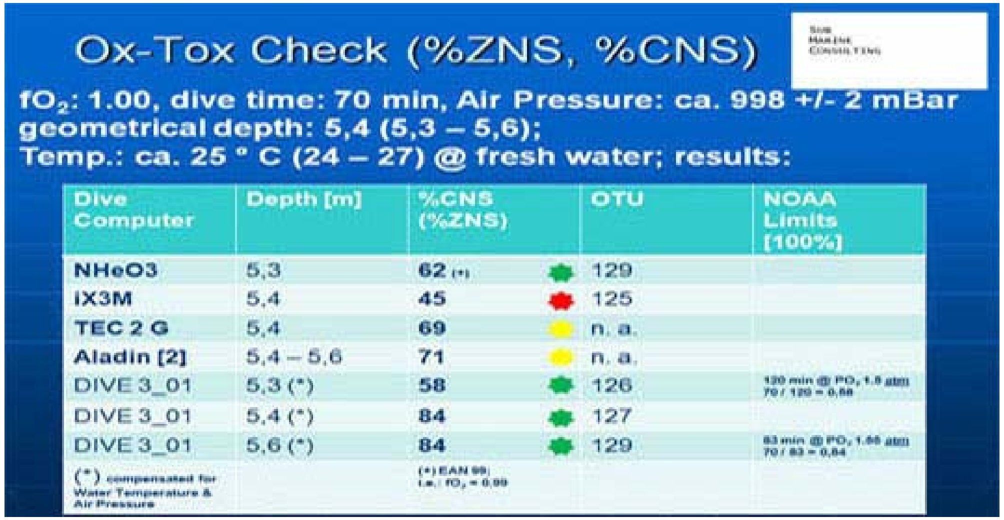
The results being: for Air & EAN it looks quite OK, hence the green traffic light. The Trimix benchmarks are open to conjecture (yellow traffic light). As well part of the Ox-Tox figures, the %CNS values (red traffic light) were not according to the historically accepted parameters. So we had to make an in-depth test in our pool because this build-in „Dive Planner“ starts at 18 m depth and stops at a maximum dive-time of 60 min:

After ca. 70 minutes in the pool:

We reached at the following results:



And everything together with all the other computers in one table:



fO2: 1.00, dive time: 70 min, Air Pressure: ca. 998 +/- 2 mBar
geometrical depth: 5,4 (5,3 – 5,6);
Temp.: ca. 25 ° C (24 – 27) @ fresh water; results:

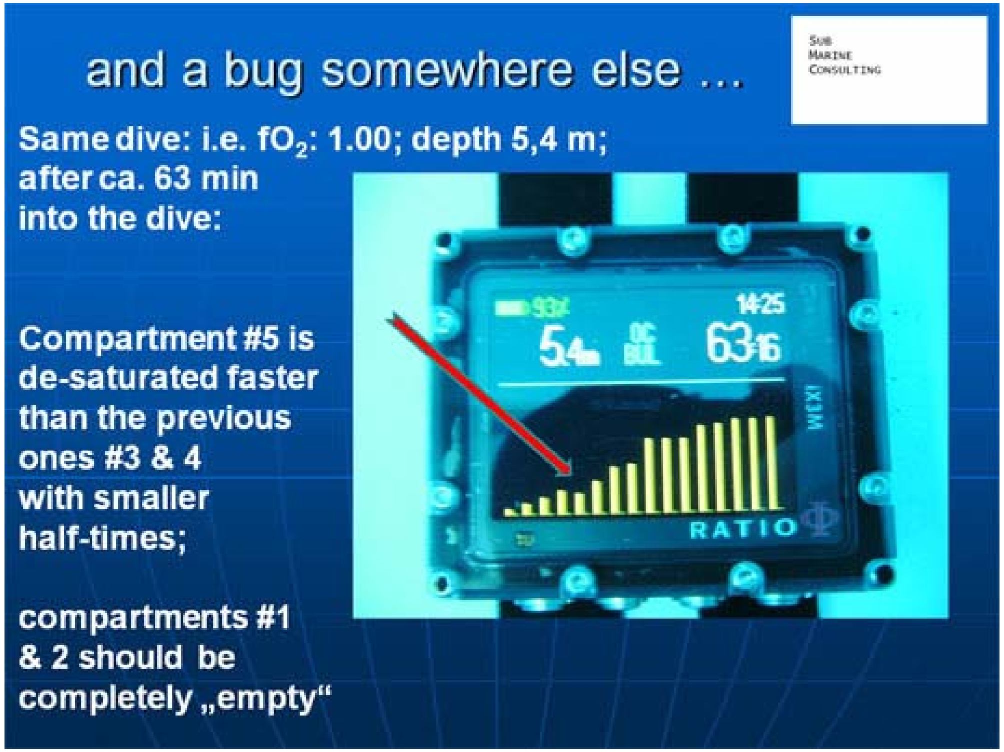
Dive Computer	Depth [m]	%CNS (%ZNS)	OTU	NOAA Limits [100%]
NHeO3	5,3	62 (*)	129	
iX3M	5,4	45	125	
TEC 2 G	5,4	69	n. a.	
Aladin [2]	5,4 – 5,6	71	n. a.	
DIVE 3_01	5,3 (*)	58	126	120 min @ PO2 1.6 atm 70 / 120 = 0,58
DIVE 3_01	5,4 (*)	84	127	
DIVE 3_01	5,6 (*)	84	129	83 min @ PO2 1.65 atm 70 / 83 = 0,84
(*) compensated for Water Temperature & Air Pressure		(*) EAN 99; i.e.: fO2 = 0,99		

The official benchmark here is the NOAA value (5.th column), the table for the 100 % CNS dose [2]; Table 4.5, p. 4-28.We checked these values with the 64-Bit Version of DIVE (more info about DIVE at: http://www.divetable.info/DIVE_V3/index.htm) because there you have the possibility to compensate not only for the air pressure prior to the dive but as well for fresh/sea water and the density change due to water-temperature. (And, as well, we know for sure, that this little programme is aware of such subtleties that all the official Ox-Tox values are in atm and not in Bar).

The corresponding algorithm for the OTU, the Oxygen Tolerance Unit was developed by Hamilton et al. and published as the „REPEX" papers [3]. You can find the appropriate table as well also in [2], Table 4.6, p. 4-29. The OTU seems to be quite ok, but is not really relevant to recreational TEC diving. For diving from a habitat or saturation diving it would be a completely different story …

En passant, we found a little inconvenience: breathing 100 % O_2, the compartments loaded with N_2 should de-saturate slowly, slowly. That is, after more than 60 min into the dive, all compartments with a half-time less than 60/6 = 10 min should be „empty" of N_2, completely. But this seemed not to be the case. As well the half-time of compartment #5 seems to be out of range: it should not de-saturated faster than the compartments on its left side.

If this is a problem of the implementation using fO_2 = 1.0, the half-times of the 16 compartments or just something with the view-port (the matching of real physical variables with the computer hardware, here with the display characteristics of the dive computer screen) we do presently not know.



One of the important features and a unique selling point in comparison to a lot of other dive loggers is the accompanying PC software (DiveLogger 3.2.3). It features the export of the logged dive profiles as DAN DL7 level 3 file (file extension: *.zxl).

Presently (09/2016) this does not work correctly with the topical DiveLogger version (3.2.3) or the topical version of the dive computer software (APOS 3.3.0):

As well you have to select and export each & every dive, one by one.

There is still another „feature", or, IT-Security wise, we would call this a blunder of major proportions: you have to run the DiveLogger as Administrator.

Bottom Line: up to now no real big disappointments, a very nice, clear display and a very intuitive handling with the 4 knobs, even with thick gloves. For details pls. cf. the manuals: (http://www.ratio-computers.com/support/manual.htm).

Which, btw, are very good! There is as well a bunch of interesting „Apps": that is little applications for the dive computer for compass and GPS, Stop Watch, Mix Analyzer, Moon Phase, Magnetometer, Lux Meter and the like.

Nevertheless there is always potential to grow:

- ➔ the energy consumption should certainly be reduced. Presently a 1-hour dive takes 5 to ca. 7% of the battery capacity. That is: the stamina in the manual is a little bit over-optimistic.
- ➔ this yields as well for the depth reading precision. A more realistic value would be appreciated. And, as well (pls. see below a screen shot from the DiveLogger): the indicated time-frame has never ever been spent on – 1.5 or so, but, instead, at the surface, i.e. 0.0!

➔ and, finally, as well the speed of the serial communication, i.e. the time it needs to transfer a dive from the RATIO to a PC, could be improved.

What we want to scrutinize, still, is the somewhat cryptic, because up to now not publicly documented, ASM, the „Adaptive Sigmoidal Model“ (*) for repetitive diving. We will check that in our recompression chamber facility with the following repetitive procedure: 50m, 10 min, Surface Interval(SI) 30 min, 35 m, 10 min.

We do that from time to time with various hardware (pls. cf. for e.g. http://www.divetable.info/skripte/2.pdf)

This schedule is, depending on the algorithm you use,something like 4 to 6 times more prone to DCS than a regular recreational scuba dive due to the very short SI: thus our tenders will get pure oxygen via the BIBS (Build-In-Breathing-System) starting from 15 or 12 m. This short SI is something we would not recommend.

If you are interested in the details on how to calculate this and the so-called P(DCS), the statistical probability on contracting a decompression sickness, pls. cf. [4], a past issue of this magazine and all the references therein.

(*) Only in the manuals of the pre-decessor hardware, the ORCA and FURYOdive computers from DiveSystems there are a couple of even more cryptic remarks on this.

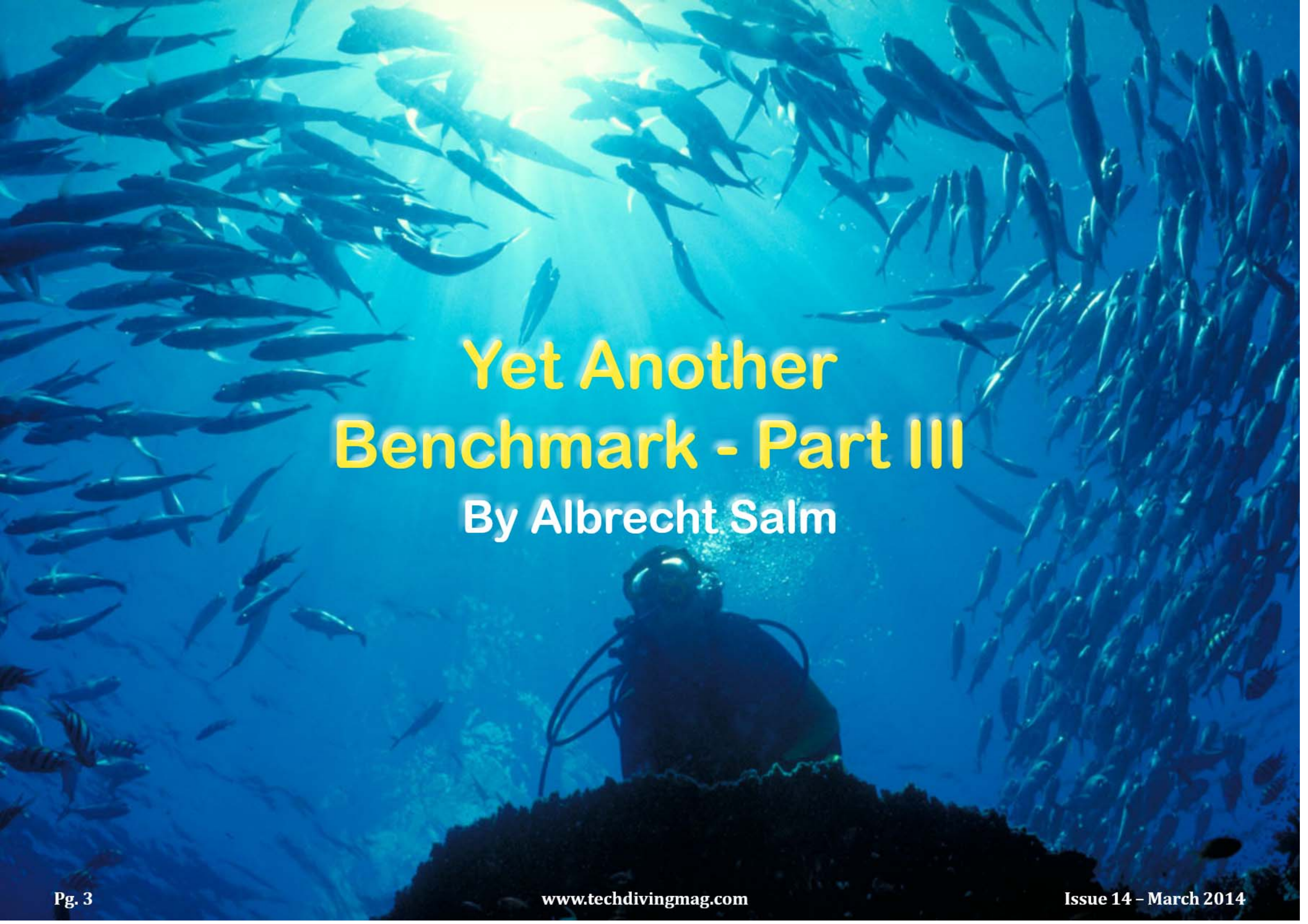
References

[1] www.meas-spec.com, you may look for eg. for: MS5541-30C.

[2] Dinsmore David A., Bozanic Jeffrey E. (2013) NOAA Diving Manual, Diving for Science and Technology,Fifth Edition, Best Publishing Company, Florida, ISBN 9781930536630
More infos there: http://www.divetable.info/books/149.pdf

[3] Hamilton, R.W., Kenyon, D.J., Peterson, R. E., Butler, G.J., Beers, D.M.(1988 May) Repex: Development of repetitive excursions, surfacing techniques, and oxygen procedures for habitat diving,NURP Technical Report 88-1A, Rockwell M.D., U.S. DoD)

[4] Tech Diving Mag, Issue 14 / 2014:Yet Another Benchmark, Part III: on the probability of getting decompression sickness (P(DCS)): http://www.techdivingmag.com/download014.asp



Yet Another Benchmark - Part III

By Albrecht Salm

This is short dive into the world of statistical modeling of dive tables. But before we submerge with pure numbers, read the short motivation from the Intro. This may tell you that concerning decompression sickness you should not rely on your intuition but look only for the real data, i.e. the outcomes of the dives (i.e.: YOUR dives!).

Intro

To put it bluntly, the occurrence of decompression sickness (DCS) in man (or girls) is:

- a random event
- not reproducible
- violating a deco table or a no-decompression limit (NDL) does not guarantee DCS (Source: [1])

And: more the worse, even the pure contrary of the last statement is valid! Let's take a look at the ca. 70 dives with healthy US Navy divers, done in the 50's (Source: [2] & [3]). These have been controlled chamber dives with the divers resting or exercising afterwards. The ascent rate was always uniform and prescribed with the then usual 25 feet/min (7.6 meters/min). There have been no decompression stops made.

Now: 4 men dived to 150 feet (45 meters) for 36 min on air, surfaced with these 25 feet/min (7.6 meters/min) and made no decompression stops.

Q: how many suffered DCS?
Remember the time-to-surface (TTS) of the two military decompression tables:
USN Air Table (2008) calls for ca. 128 min TTS, whereas;
USN Air Table (1957) calls for ca. 60 min TTS.

A: the result is: none! That is: no cases of DCS for these 4 men!

Now another one: more men to a shorter dive to the same depth: 11 men, 150 feet (45 meters) for 30 min on air, surfaced with 25 feet/min (7.6 meters/min) and no decompression stops.

Q: how many suffered DCS?
USN Air Table (2008) called for ca. 59 min TTS, whereas;
USN Air Table (1957) called for ca. 35 min TTS.

A: all! I.e.: 11 cases of DCS (5 cases of mild DCS, 6 cases of bends).

Basics and difficulties

There is a wealth of literature on the statistical formulation of decompression tables. We should not repeat that here, but have a look at the basic sources ([4] and [5]) and the 11-volumes series from NMRI / NEDU: "Statistically Based Decompression Tables: I -> XI" from 1985 – 1999, ca. 1,000 pages with short comments from my side at the end of this paper.

In a nutshell, it works like this: we collect not only hundreds but thousands of (very) well-documented dives. Well documented means here: there is a controlled and reproducible environment (breathing gas composition including humidity and CO2, water and air temperatures, workload, ascent and descent rates) and as well the controlled biometrics of the divers. Then we group them together per procedures: say, saturation dives in one group, EAN dives another, Heliox or constant pO2 the next ones, repetitive or multi-level in others and so on. As well the inert gas dose (time, depth combinations) should be comparable. The rationale for this is that it is very probable that no "unified deco theory" would allow for an explanation of all these phenomena.

The next step is to collect the outcomes of these dives. Either in scales of Doppler bubble grades (I to IV or so) or in a more digital black-and-white manner: DCS YES / NO.

Here starts, btw, one of the first difficulties of assessing DCS: how about vanishing niggles, a little skin rash or a short period of migraine? Does it count, or not at all? Do we attribute 10, 25 or 50% of a DCS case? Well: this is called the "pink noise" within the measurement.

And, there is another difficulty: in the past, much effort has been done to assess the relationship between age, gender, BMI (body-mass-index) and DCS or Doppler-bubbles. The relationship was found to be positive. The underlying statistical problem, which rendered the masses of papers more or less useless, was the so-called "multi co-linearity", which was not corrected in these publications. I.e. the real underlying parameter for the Doppler-bubbles was (probably) the aerobic capacity, which is the "fitness". Multi co-linearity describes the fact that a couple of parameters, like increasing age and increasing BMI go in the same direction as decreasing fitness. So the data was biased. And so were the conclusions drawn.

As was the case with the PFO, the patent foramen ovale, a little hole between the atria, the antechambers of the human heart, which approx. 30 % of the population has. There was a famous study, technically brilliantly designed to check for brain lesions (that is, little defects in your brain) with ca. 215 divers. The sensational result was, that if you do a lot of repetitive (more than 100 a year), Tec-like dives (deeper than 40 meters, decompression, cold fresh water lake) you are really prone to DCS-related brain impairment. But there has been no check for a PFO in these divers; to put it mildly, this little procedural error left the whole study open for controversy.

The point here to make is: if the biometrics of the guinea pigs (our divers) are not carefully screened, it may render a whole research-study useless.

After the assessment you have a numerical scale. Now you have to fit that to your gas kinetics model. Be it a dissolved gas-phase, a bubble-volume model or whatever combination thereof. The measurement of the goodness of a "fit" is usually done with the logarithmic scale of likelihood. The result is either a "label" for your dives, being, for example in the 1, 2 or 5% probability of DCS, the P(DCS). P(DCS) is the probability P of contracting a decompression sickness DCS. It follows usually a so-called dose-response curve, what is already well-known from drugs, O2 and antibiotics. In our case the dose is either depth d, time t, a combination thereof like d * square root (t) or another measure for a compartment saturation / supersaturation. The formula for this "Hill Dose Equation" looks like that:

$$P(DCS) = Dose^{a} / (Dose^{a} + b)$$

Or you tabulate like a standard decompression table, giving it the sobriquet of the predicted P(DCS) outcomes. So it may look like that:

Depth	USN 1957	USN VVAL18	Standard Air Model [min]		
[fswg]	[min]	[min]			
			2% P(DCS)	1% P(DCS)	3% P(DCS)
80	40	40	37	24	45
90	30	34	31	20	38
100	25	29	26	17	32
110	20	26	23	15	28

No-Stop Bottom-Time Limits from 3 Sources; Table 3, p.28; Excerpt taken from: A SIMPLE PROBABILISTIC MODEL FOR ESTIMATING THE RISK OF STANDARD AIR DIVES. Van Liew, Flynn: TA 01-07 NEDU TR 04-41[6].

Let's have a look at the 100 feet entry: the old USN table gave 25 min as a No-Stop limit, putting it near a P(DCS) of 2 % with 26 min. This is quite a lot: it would imply that approx. out of 50 such dives we would have one guy (or girl) ending up in the deco-chamber. The 1 % P(DCS) would yield a reduced No-Stop time of 17 min.

And, there is another problem, intrinsic to the very nature of DCS: it is the fact of small numbers. In the average, we have one case of DCS per 10,000 recreational dives. This is not much, and it is quite OK. Or as our friend Paul K. W. put it: "If you want to do research on DCS: you have to have it!"

For example, there have been publications in the past, telling that the use of dive computers is much safer than the use of the traditional dive tables. The story here is that we do not know how closely the dive computer users followed the profiles from the table users...

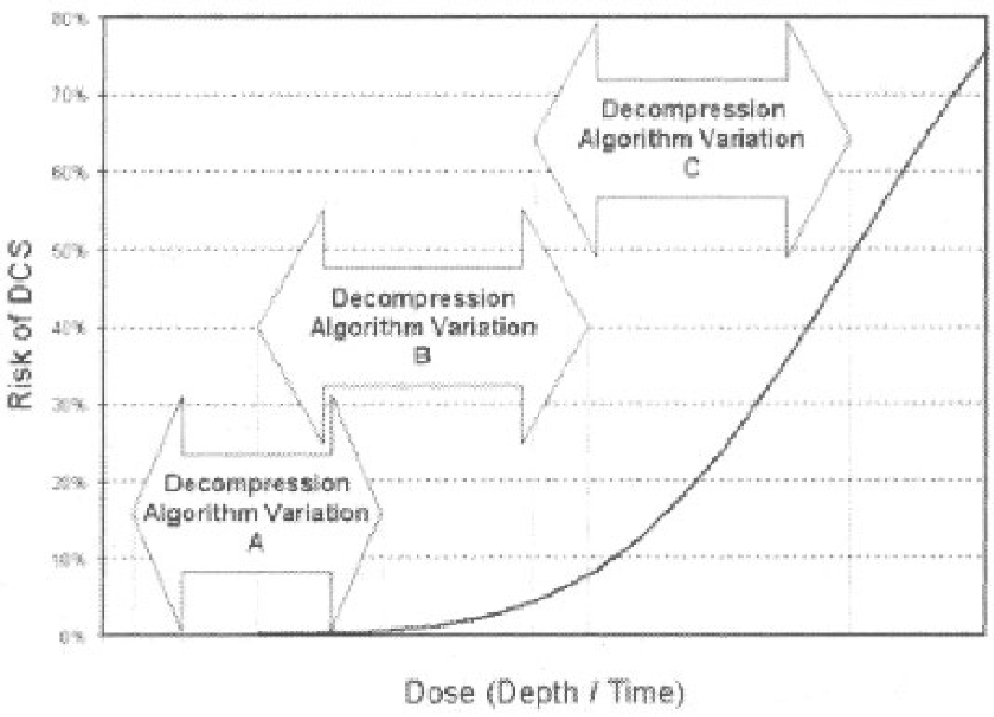
And this is the next problem: if your dive was safe, you do not know how closely you have been to DCS. To put it the other way around: a useful contribution to DCS research is only a validated case of DCS! The real endpoint of DCS is death: a point, clearly not so desired for human experiments. This is the rationale, why millions of small and not-so-small guinea-pigs have been sacrificed on the lord's table of the cruel mistress of science for the welfare of divers.

Concerning P(DCS) we normally speak about the dive profile, fO2, skin temperature and workload. We did not speak so far about: blood chemistry, the so-called "MPs" (micro particles) and the lining of the blood vessels. But this is where topical DCS-research is aimed at.

Results

So what is it now all about this statistical modeling when we have so many variables to control? Wasn't that ole' Haldane model not much more simple and didn't it work? Well, it did, really. Up to a certain extent. But if the dive was very short or very deep, it didn't! As well Haldane himself was already aware about the limitations and the problems with age and adiposity (old and fat divers). Nowadays we have a lot more models, a couple of them dealing not only with the dissolved gas phase, as Haldane did, but also with the free gas phase, the bubbles. And subsequently started a sometimes heated debate, which of the models is now better. And the down side of this debate is that it leaves the diver completely in the dark: have a look at the tables with the big variations in the TTS for our "test dive" (pls. cf. the "Yet Another Benchmark" Parts I & II in Tech Diving Mag Issue 11, p. 6 & 7; and Issue 12, p. 4 & 5). But the proponents of each of these models forgot a basic wisdom: all of these models are wrong, basically! And there is an elegant way out of this debate: these kinds of traditional models try to predict the outcome of the dive before, based on the model assumptions. This is why these are sometimes called: "deterministic". The statistically based models avoid this and work the other way around: in hindsight the outcomes of the dives are analyzed. And based on this analysis there is an interpolation or extrapolation for similar dives.

A generic plot of a P(DCS) resp. the risk versus a dose looks like that (Source: [8], p. 89):



A P(DCS) of 0 means you have none whereas a P(DCS) of 1 means you ended up in the deco chamber. But in between is a big gray area of individual and intra-individual susceptibility, where this is not so clear and humans or guinea pigs do not react in a proper digital Yes/No manner on a varying inert gas dose. So, next question.

Q: when you have been bent like a pretzel on your last dive, is it more probable than not, that you may get bend for another time?

A: statistically speaking: yes! Why so? Not speaking about the personal susceptibility for DCS which really plays a dominant role in all these statistics. If you look at the collections of many dive outcomes, preferably with the same subjects (for e.g. from the big offshore diving companies or the organizations for public health), you will see that there are DCS-candidates, divers which will contract DCS more easily than others.

But statistically speaking the story is the following: tossing a coin and betting for head or tail is like getting DCS, a binominal distribution. And it is more likely than not, getting a run of 3 tails (or 3 heads) in a sequence. Here the probability in 10 tosses is 864/1,024, i.e. ca. 82% [7]. So this is more likely than getting a head after a tale, or vice-versa!

Lessons learned for TEC diving

Lesson #1: donate your dive computer log files to DAN's PDE.

In the first place, the biggest part of dives, being Tec or recreational or whatever, does not match the required basic quality criteria described above: they cannot be used for a proper statistical analysis. This yields even as well for the big DAN PDE database: neither the skin temperature nor the workload, nor complete biometrics are available. As well the DCS assessment is questionable. Normally, if there are Doppler readings these are not taken double-blinded. But, as we pointed out here in "Yet Another Benchmark, Part II" in Tech Diving Mag, Issue 12, p.9.:

- It is a good starting point!
- And you have to start somewhere!!
- And you should contribute your log files to DAN's data base!!!

In any case this is by much better than another data base, very often cited within papers, gloating about a DCS rate of 19 from 2,823 deep and multi-gas TEC-dives and thus trying to insinuate the safety of a certain undocumented decompression algorithm. There are no logfiles for public scrutiny and the input was obviously partly from "wrist slates of seasoned divers". This is just scientific garbage! So DAN's idea to collecting the very details of the profiles via the DLT #7 file format directly converted from the dive computer logfiles is the only way out to get a broad data base where a ballpark of the inert gas dose could be re-evaluated even years later.

Lesson #2: question your extrapolations.
(pls. cf. as well: Tech Diving Mag Issue 5, p. 41 - 53). What a normal desktop deco software or an implementation into a mixed gas dive computer does outside the safe and proven envelope is standing on statistically relatively thin and fragile leggies: but this is just, how the algorithm works with larger values! Resilient data from longer and deeper mix gas dives with a lot of O2-deco is still missing. And resilient means: not just anecdotal experience from one TEC dive which was successful. But you probably want to know, where along the P(DCS) curve your deco-software or your dive computer puts you! [8]

Lesson #3: monitor your dives / your DCS outcomes.
That is: do Doppler measurements after all your dives, record the profiles along with your settings (e.g. gradient factors and the like) with your measurements and your self-assessment.

Lesson #4: caveat boundaries!
There is no way of extracting a useful deco procedure from a pool of data, when yours does not match the decompression procedure or the inert gas dose! Do not even try! Or you have to accept, that doing dives like the record dives Mark Ellyatt once did [9], will put your P(DCS) in close proximity to 1.

Lesson #5: mistrust small numbers!
That is, do not believe in publications, relying on small numbers of divers / dives. A couple of years ago there have been rumors concerning cancer-markers (biochemical traces in the blood, resulting from growing of ill-behaving cells) found after EAN-dives. Here we had the usual problem, that this study covered only a handful of divers, doing just a couple of dives: the error margins have been exceeding the original values.

Lesson #6: (the bitter pill for people like us).
We should not sell NDLs. At least not in the careless way it is done by a couple of diver training agencies and dive computer manufacturers.

Finale furioso

If the intro did not beam you away, well, then, here is the last, a personal one: during our Guinness world record of underwater indoor cycling (yep, we did that, 12 years ago) we made 9 dives on air to 8.5 meters (ca. 27 feet in warm fresh water) in our diving tower. We stayed in teams of 3 divers there for exactly 60 min cycling on an underwater-ergometer (well, not so much, but ...), surfaced slowly, stayed approx. 3 to 5 min at 3 to 2 meters (10 to 6.6 feet) as a safety stop and had a surface interval of precisely 3 hours. So in the end this was a "near / sub-saturation" dive for 36 hours. In the background at the upper part of the little picture, near my air-bubbles, you could see our "deco-rig" hanging around in our diving-tower:

OK: no deco table and no deco-software from this mean ole' world did call for these deco stops, not even the DCIEM table with all security features enabled. In the end, that is, around dive #6 and 7, nearly the complete team had various problems. And two divers had niggles and one a serious DCS Type I (me! (Being that time already the old grand-pa of the complete team). I took some normobaric O2 (and a couple of Aspirins®). And then I did something stupid but responded very well to re-compression: I did the dives #7, 8 & 9 with EAN36 and extending the deco stops to 10, then 15 and finally to 20 min with EAN60!).

* * *

So, this is the very end of the series "Yet Another Benchmark" of 3 somewhat lengthy and "dry" articles. If you want to go through the mathematical details of the screen shots in "Yet Another Benchmark, Part II" in Tech Diving Mag, Issue 12, p. 7; pls. cf. as well there the detailed references to these sources. Here we are:

Method I; Southerland, p. 77, 78, 82; with:
Logit (DCS) = ln (P/(1-P)).
Logit (DCS) = -25.95 + 6.64 * Ln(Depth) + ß2 * (Ln(Depth))2 + 5.31 * Ln(Time) - 0.33 *
(Ln(Time))2 + ß5 * Ln(Depth) * Ln(Time)
with: ß2 = ß5 = 0

Method II:
is an expanded PME Model. PME means: "Parallel Mono-Exponential" and has been developed during the middle 80's based on ca.1,700 air dives. The thus calibrated parameters have been compared to 10,391 well-documented dives in the volume I of the NMRI/NEDU series "Statistically Based Decompression Tables", p. 5-7 & p. 31. We have taken this thing and expanded it even further to 6 compartments and fitted the parameters to our helium dives.

Method III:
is a simplified integral over a risk function which we took from the volume VI, "Statistically Based Decompression Tables", p. 5 & p. 55. For the fun of it, DIVE calculates the upper & lower error boundary from the given standard deviations.

Method IV; NEDU TA 01-07 TR 04-41, p.8 & p. 11:
Logit(DCS) = a + b * (D – c) * (1 – exp(- d * T f)) / (TDT –g)
with:
a = -6.022169
b = 86.596315
c = 25.091718
d = 0.002929
f = 0.918547
g = -170.304442
D: Depth (fsw)
TDT: Total Decompression Time (min)

Method V; NEDU TR 2009-03, p. 9, 11:
Logit (DCS) = ß0 + ß1 * Ln(fsw) + ß2 * Ln(Time) + ß3 * (Ln(Time))2 + ß4 * Ln(Ascent Rate)
with:
ß0 = - 53.0
ß1 = 7.97
ß2 = 3.32
ß3 = 0.04
ß4 = -0.03

Literature cited

[1] UHMS ASM 2012, Session D71:Estimating DCS risk for Emergency Conditions; Paul K. Weathersby & Keith A. Gault. Naval Submarine Medical Research Laboratory, Groton CT and Navy Experimental Diving Unit, Panama City FL

[2] Van der Aue et al, NEDU Report 8-49: The Effect of Exercise during Decompression from increased barometric pressures on theincidence of Decompression Sickness in Man, 1949

[3] Temple et al, NMRC Report 99-02, 1999

[4] Weathersby, P.K., Homer, L.D. and Flynn, E.T.: „On the likelihood of decompression sickness",J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 57(3): 815-825, 1984.

[5] Berghage, T.E., Wolley, J.M. and Keating, L.J. (1974) The probabilisticnature of decompression sickness. Undersea Biomed. Res. 1(2): 198-196

[6] Van Liew, Flynn: A SIMPLE PROBABILISTIC MODEL FOR ESTIMATING THE RISK OF STANDARD AIR DIVES,TA 01-07 NEDU TR 04-41

[7] du Sautoy, Marcus (2011): The Numbers Mysteries: a mathematical odyssey through everyday life, Palgrave Macmillan,p. 113 & 114

[8] Huggins, Karl E.: Decompression Algorithms, Chapter 5: p. 81 - 94, in:Fife, Caroline E, St. Leger Dowse, Marguerite (2010) Women and Pressure, Diving and Altitude,Best Publishing Company, ISBN 978-1-930536-60-9(more infos under entry [146] at:
http://www.divetable.info/books/index_e.htm)

[9] Ellyatt, Mark (2005) Ocean Gladiator, Battles beneath the Ocean,Emily Eight Publications Ltd., ISBN 978-0-9551544-0-9, (more infos under entry [128] at:
http://www.divetable.info/books/index_e.htm)

For further reading

- the 51st. UHMS workshop: „Survival Analysis and Maximum Likelihood Techniques as applied to Physiological Modeling", 1989
- „Logistic Regression and Decompression Sickness"; David Graham Southerland, Duke University, 1992
- „Statistical Bubble Dynamics Algorithms for Assessment of Altitude Decompression Sickness Incidence", Gerth, W. A. & Vann, R.D., July 1995, Duke University Medical Center

Statistically Based Decompression Tables, an 11-volume series of papers from the NMRI

Naval Medical Research Institute, Bethesda, Maryland:
NMRI 85-16, Part I: Analysis of Air Dives: 1950 - 1970
NMRI 85-17, Part II: Equal Risk Air Diving Decompression Schedules
NMRI 86-50, Part III: Comparative Risk using U.S. Navy, British, and Canadian Standard Air Schedules
NMRI 86-51, Part IV: Extension to Air and N2-O2 Saturation Diving
NMRI 89-34, Part V: Haldane-Vann Models for Air Diving
NMRI 91-84, Part VI: Repeat Dives on Oxygen/Nitrogen Mixes
NMRI 92-85, Part VII: Selection and Treatment of Primary Air and N2O2 Data
NMRI 92-73, Part VIII: Linear-Exponential Kinetics
NMRI 96-05, Part IX: Probabilistic Models of the role of Oxygen in Human Decompression Sickness
NMRI 96-06, Part X: Real-Time Decompression Algorithm using a probabilistic Model
NMRC 99-01, Part XI: Manned Validation of the LE Probabilistic Model for Air and Nitrogen-Oxygen Diving

Private comments on the above listed sources I --> XI

Part I:
Table 9 (p. 37) features DCS incidences during operational use of the USN 1957 Table, depths from 100 to 300 feet, bottom times from 10 to 50 min. From 10.391 dives there are 83 cases of DCS. The reported incidence range within the CI goes from 0.1 up to 4.6 (eg. at 200 feet). The problem with "operational use" is that there is only a written log of the dive. So the time & depth recordings in the logs are somewhat "creative" (i.e. irreproducible).

Part II:
Fig. 5 (p. 14) features a graph of the "Risk Surface" for a certain dive. The trough of the 3-dimensional hyperbola shows the optimum distribution of stop times at various depths, thus minimizing the calculated P(DCS).

Part III:
states on top of p. 1: "... if no cases (of DCS) were seen in a trial with 10 divers, the 95% confidence limits still allows an actual incidence of 31 % DCS. A single case in a 30 man trial could come from 0.1 to 17 %underlying incidence. Hundreds of replicated dives are needed for greater precision."

Part V:
on p. 3, Table 1, describes their decompression data sets A, B, C, D & L. These are covering 1.835 dives with 101 cases of DCS and a range of 1.3 to 45.7 % DCS.

Part VI:
features a good mathematical overview on the whole subject.

Part VIII:
gives a nice overview on the LE models (linear - exponential),on Table 5 (p. 48) is a summary of the used data sets: 5 risk categories in 2.5 % intervals, for eg. with 2.383 dives and 139 observed cases for DCS for the 0-model. The 0-modelcomes with a predicted # DCS of 139 cases, but unevenly distributed along these categories. On Table 7 (p. 50) the data sets NOT used for modeling with 1.985 dives and a DCS range from 1.0 --> 21.3 % DCS.

Yet Another Benchmark - Part II

By Albrecht Salm

Motivation

In “Yet Another Benchmark (YAB), Part I” (pls. cf. Tech Diving Mag, Issue 11, 2013, p. 3 – 10) we wanted to compare a couple of dive computers, diving tables and desktop deco software products with our notorious 42 m, 25 min dive on air. This, as such, isprobably not a real tec dive to talk about for this magazine but a dive an ambitious recreational diver could do as well as a one tank dive. As well we wanted to lay in Part I the foundation to get the idea what is going on now in this issue, in Part II of this article.

Part II will cover the same dive and basically the same procedure but with a somewhat more technical, i.e. a non-standard mixture of Heliox20 (20 % Oxygen, balance Helium).

Basically we are going to discuss shortcomings not only of decompression algorithms in general but as well their implementations. This is more or less valid for all algorithms,be it a standard perfusion-dominated model likethe Buehlmann-Hahn (ZH-L), Workman, diffusion-oriented like DCIEMor any colours of bubble models (VPM and VPM derivatives, RGBM, ...)

The Heliox Test Dive

Let’s recap YAB Part I, Table I:the air dive. Thearithmetic mean of the TTS averaged at ca. 40 min, the standard deviation being ca. 18 min:that is, the most of the TTS fall into the region from 22 to 58 min.

Now here in YAB Part II, at Table II we have, again with the following data input:

- depth 42.00 m (freshwater, compensated for 25° C)
- instantaneous descent
- ascent with 9.0 m / min
- bottom time: 25 min
- 20 % O_2, balance Helium, dry compressed air
- respiratory quotient = 1.00
- no workload
- ambient pressure at depth = 0m: 1013.00 mBar
- all standard gradient factors = 1.0 (i.e. 100 %), i.e.:no gradient factors at all
- no conservativism or J-factors
- no temperature adaption
- no travel- or deco gases (the complete dive is done on the back gas)
- for ZH-L implementations, useage of the ZH-L 16C coefficients without the “1b” compartment

Table II; Test Dive: 42 m, Bottom Time 25 min, Heliox 20 / 80

Type / Model / Version	time-to-surface (TTS) [min.]
NHeO3 (11/2011)	528 (Conservativism = 50)
VR3 3.03 aC	295 (Conservativism = 0)
Proplanner	206 (Conservativism = 0)
NHeO3 (11/2011)	196 (Conservativism = 0)
Suunto Dive Planner 1.0.0.3	177
Professional Analyst 4.01.j Cochran EMC-20H	159; Conservativism= 50.0 (184 with version t; 181 with version u; 190 with version v)
Zplan v1.03	113
Deco Planner 3.1.4	107 (VPM = 2)
Trust Trimix 2.2.17	102
M-Plan V 1.03	95; with Pyle Stops
HLPlanner V 1.x	90 (VPM = 0 %)

Professional Analyst 4.01.j Cochran EMC-20H	87; Conservativism= 0.0 (93 with version t; 91 with version u; 98 with version v)
GAP 3.0.425.6	83; RGBM Recreational
OSTC Planner v 434	82; TDT: 107
DIVE V 3_0	81; ZH-L 16 C (full blown numerical solution)
GAP 3.0.425.6	80; ZH-L 16 C
Decotrainer V 3.01	77; ZH-L 16 C mit p_{H20} (without: TST = 67)
M-Plan V 1.03	72
Ultimate Planner 1.2	70, TDT: 95
Deco Planner 2.0.40 & 3.1.4	70
OSTC Planner v 470 Beta	66; TDT: 91
VGM ProPlanner Beta	66 (default)
Multilevel 1.6	65
GAP 2.1	63; ZH-L 16 C
GAP 2.1	53; RGBM aggressive (GAP 3.0.425.6: 30)
GAP 3.0.425.6	50; RGBM nominal
OSTC 3, V 0.9 from 05/2013	41; 12/2', 9/5', 6/10', 3/19'

➔ legend to Table II: pls. cf. Tech Diving Mag, Issue 11, 2013, p. 7.

In order that these entries become comparable,i.e. that the inert gas dosis is more or less the same for all these schedules,we had to fiddle a little bit with the desktop deco-software products. Not all of them have all the parametersneeded and some have unchangeable defaults.

This yields as well for the standard diving tables. There we have thephenomenon what we would call "undocumented features".For e.g. for the USN 1983 table these are just some typoos, or, later on for the 2008 version, as Ed Thalmann put it: "executive editing". Just to put the results of Table II a little bit into perspective with regular and somewhat validated procedures in the US and the Canadian Navies, we have here Table III:

Table III; Military Tables: 42 m, Bottom Time 30 min, Heliox 16/84

Stage / Method:	18 m	15 m	12 m	9 m	6 m	**TTS**	Rem.: (*) 100 % O_2
[min.]						**[min.]**	
U.S.N. old		10 (*)	45 (*)	-	-	**58**	140 feet
U.S.N. 2008				18 (*)	30 (*)	**72 (+ 10)**	140 feet, + 2 * Air Breaks, each 5 min
DCIEM	2	4	4	37 (*)	-	**55**	In-Water decompression
DCIEM SurDO2	2	4	4	7 (*)	-	**72 (40 min *)**	40 min Chamber decompression, with 5 min Air Break

Pls. note the various differences in the procedures (+ 5 min bottom time, dry decompression resp. SurD02, the surface decompression with Oxygen) and 4 % more inert gas, the various deco gases and the high pO_2 for the deco stages.So this is something you should not try out by yourself in open waters …

The validiation for each of these table sets is in the range of a couple of thousand dives, normally chamber dives with a controlled water temperature and a certain workload.

The underlying decompression model for the USN tables is a standard perfusion model with the compartments in parallel, whereas for the DCIEM it is a diffusion-based model with 4 compartments in series. Despite the very different decompression models, the TTS match a bit closer than those in Table II.

So let's look back to Table II: in the right column, the output of the TTS. Once again, our test diver will input all the TTS values into a spreadsheet. Then she will have fun letting it calculate the statistics: an arithmetic mean average of ca. 120 min, a standard deviation of ca. 98 min. This is a far broader range than for the previous TTS with the air dive in Table I.And this is, b.t.w., <u>the rationale why we put such a relatively unorthodox mix for recreational TEC divers.</u> As well the deco-procedure would turn out to be a bit cumbersome because no oxygen enriched gases were used. The deviations and / or errors in the various tables/dive computers/desktop deco software are thus much more pronounced:the more helium, the more! (pls. cf. Tech Diving Mag, Issue 5, 2011, p. 41 ff)

As well our test diver will notice the relation of 528/41 = ca. 13. To narrow this a little bit down, she will eliminate from the list all TTS < 60 min and > 180 min. Because our girl had had a really good training during her career as a professional diver, she takes Table III into account and she will call TTS < 60 min somewhat dangerous and TTS > 180 min somewhat experimental, or, at least impractical, to put it mildly.

As well this mix makes clearly visible, if a procedure works with tampered ZH-L coefficients: the original values are linkeddirectly to the halftimes of the compartments;i.e.: basically the reciprocal of the perfusionrate (neglecting solubilities for the time being). These deviations from the standard ZH-L a- & b coefficients in the medium fast to slow compartments are brought to light via extremely long decompression stops in the shallow … You may call this an "undocumented feature", or, to put it bluntly, errors in the calculationsor negligent calculational procedures.

For professional use, i.e. construction and repair diving or saturation diving this Heliox20 is a more or less regular mix:but probably nobody in the commercial field would rely on the procedures or desktop deco software products ordive computersof Table II! One could as well question the wisdom of leaving a diver 3 to 8 hours decompressing for such a bounce dive (pls. cf. the 4 first entries at the top of Table II ...).

On P(DCS)?

So the question would be, besides operational considerations like having enough gas or keeping a diver safe and warm for 3 to 8 h (and letting her [or him] pee and drink during these elongated periods …): is there sort of objective reasoning, something like an Occam's razor, to separate the good TTS from the bad? Yes, there is, at least partially….In YAB, Part I, we saw, that there are a couple of prominent factors, besides depth, time and fO_2, influencing the outcome of a dive. The outcome is: DCS, Yes or No? These factors are, among a lot of others, the skin temperature and the workload. So if your procedure is factoring these ones in: go with it!

And, btw., if you do, what a lot of other TEC divers do, i.e.: checking your dive comrades after a serious trimix-dive for inert gas bubbles with a little utrasound doppler device, then you will collect your own data on how you will use your gradient factors or not.

And there is still another one: it is the calculation of the P(DCS). P(DCS) is a measure of the statistical probability for a certain dive profile, if you would contract a decompression sickness or not. So a P(DCS) of 1.0000 (or 100 %) would mean that surely you will get bend, whereas a P(DCS) of 0 would imply the pure contrary, that is a relatively safe dive profile. The details and procedures we will cover in YAB, Part III, coming in this magazine early next year.

If we stay in this picture of Occam's razor, with the P(DCS) we are now working with a scalpel for microsurgery …To arrive at a reasonable figure for P(DCS), we need thousands of thoroughly controlled dives with the medical outcome diligently documented. In the end there is a big pool of data where you can dip in your own dive and see if you could conduct your specific profile as planned, or if you should alter it a bit: i.e. make it shorter or shallower or more O_2, or all of it. So to discuss the quality of the various TTS in Table II there are a couple of methods which rely on the TTS as such. One of them was developped by the United States Navy and by checking in the 2 screenshots below the entries designated as:

"Methode IV, NEDU Report 12/2004"

you will get a feeling why we are talking here about a very small razor. For our Heliox test dive the outcomes are for a

TTS of 40 min, P(DCS) is 0.11254 (1st. screenshot)
TTS of 400 min, P(DCS) is 0.10463 (2nd. screenshot)

pls. cf. the following screenshots:

```
 was jetzt?pdcs

Eingabe der TTS (fuer Methode IV) in min:
40
 Methode I:   Southerland 1992,                P(DCS) =   .19506
 Methode II:  PME enhanced 6 Compartments      P(DCS) =   .14138
 Methode III: Stat. Tables Part VI, Model 4    P(DCS) =   .20849
 Methode III: obere Fehlergrenze,              P(DCS) =   .36221
 Methode III: untere Fehlergrenze,             P(DCS) =   .16917
 Methode IV:  NEDU Report 12/2004,             P(DCS) =   .11254
 Methode IV:  untere Fehlergrenze,             P(DCS) =   .00643
 Methode IV:  obere Fehlergrenze,              P(DCS) =   .99988
 Methode V:   NEDU Report 03/2009,             P(DCS) =   .18064
 SDEV =    .03973                              MEAN   =   .16762
```

```
 was jetzt?pdcs

Eingabe der TTS (fuer Methode IV) in min:
400
 Methode I:   Southerland 1992,                P(DCS) =   .19506
 Methode II:  PME enhanced 6 Compartments      P(DCS) =   .14138
 Methode III: Stat. Tables Part VI, Model 4    P(DCS) =   .20849
 Methode III: obere Fehlergrenze,              P(DCS) =   .36221
 Methode III: untere Fehlergrenze,             P(DCS) =   .16917
 Methode IV:  NEDU Report 12/2004,             P(DCS) =   .10463
 Methode IV:  untere Fehlergrenze,             P(DCS) =   .00627
 Methode IV:  obere Fehlergrenze,              P(DCS) =   .99982
 Methode V:   NEDU Report 03/2009,             P(DCS) =   .18064
 SDEV =    .06293                              MEAN   =   .20753
```

(The rest of the figures and methods will be described and discussed in YAB, Part III)

With a TTS for 40 min we reach a P(DCS) of ca 0.11, i.e.: 11 %, which means that in ca. 11 dives out 100 there will be DCS-related problems. Standard Navy procedures try to achieve approx. 3 to 5 %, the PADI RDP for eg. falls within a 2 to 3 % range. So staying additionally 6h in water decompressing will give you a statistical benefit of ca. just a half percent … One important thing for the P(DCS) discussion is that your specific dive profile you want to check falls well within the parameters of the dives from the above cited data pool.

And bubble models?

In contrast to the above cited perfusion models from Workman, Hahn, Buehlmann and others which rely on the dissolved gas phase only, the so-called “bubble models” try to consider the free gas phase. The free gas phase is just another word for “gas bubble”. As Haldane was pointing out already some 110 years ago, bubbles would hinder mechanically the blood flow und thus de-saturation. In the meantime it became quite clear that there is much more than blocking a blood vessel to DCS: there is a wealth of bio-physical and bio-chemical effects, primary and even secondary in nature, hard to reproduce and even harder to understand! Even micro-bubbles, unable to block but the smallest dead-ends of alveoli or just the surface, the gas-blood interface, of a gas bubble can do harm to you.

And this is basically the rationale why some think, that bubble models are somewhat superior to perfusion models. But this is more or less like Einstein’s relativity theory is somewhat superior to Newton’s mechanics. True, but only in certain aspects. For the day-to-day operations or walking ‘round the corner, driving in a car, and even flying in a hyper-sonic airplane, this superiority does not meanvery much to us regular folks.

Let’s have a very quick, only superficial look, at one of the most prominent bubble models, the VPM (Varying Permeability Model). For the time beeing we neglect here the “RGBM”, the Reduced Gradient Bubble Model, because there is no cohesive and complete documentation of all the parameters and equations used. For the VPM, the inert gas partial pressures in the various compartments are calculated with the same method as the perfusion models do, it uses as well the same half-times. For determining the safe ascent depth (deepest deco stop, as you will have it), a couple of more parameters are needed, but these do not appear through a natural law or pure reasoning, but insteadthrough a best-fit of these free parameters to two traditional diving tables and the TEKTITE experiment. These have been the old U.S.N. and the RNPL air tables. The TEKTITE experiment beeing a saturation dive which happened to be in 1971 in the carribean, at the St. Johns island at 100 feet for 60 days with Nitrox10.

On the other hand it became as well quite clear that perfusion models with compartment half-times > 700 min are as well already “simulating” bubbles. This “simulation” of a mechanical hindered de-saturation came just with these long half-times, meaning a very limited perfusion.

My model is better then your model!

Well, basically NO! All models are wrong, in principal. And some are even “wronger” than others;but a handful of them are at least useful to a limited extend.

Is there a the way out?

The above described method for getting at a P(DCS), that is an “a posteriori” analysis of the dive-outcomes, i.e.: “DCS yes-or-no”after a dive and a subsequent surface intervall is a path, which has already been taken by various navies. But as well for recreational or TEC-rec. divers there could be a way out, if they are willing to contribute: it is DAN’s “PDE”! PDE is the “Project Dive Exploration” (more info at: http://www.diversalertnetwork.org/research/studies/project_dive_exploration). DAN is collecting successfull decompressions, i.e. the logfiles of the dive computers. Divers using the following dive computers: Cochran, Dive Rite, Suunto and Uwatec may contribute and send the logfiles to DAN for collection and subsequent statistical analysis. The basic problem of these huge data tomb of DAN’s is the following: the biometrics and specifically the skin-temperature and the workload are not fully covered by the data sent in through thousands of divers. But anyway: it is a first and very important step towards the right direction!

What else?

As well since the turn of the millennium there are things called "hybrid models". These are combinations of perfusion- and/or bubble-oriented algorithms with ultrasonic doppler measurements. One of these hybrids is called "COPERNICUS". It is a theoretical framework concerning bubbles, including the full scale of biometric parameters like:gender, age, aerobic capacity, BMI, workload and the like. The feedback through ultrasound doppler measurements at human divers is combined into the "deco stress". The goal of all these hybrid models is to minimize this particular deco stress.

So after considering Part I & II, that is Table I & II, the very easy and basic take-home message is:

"It doesn't matter which model you use, provided it has a soundimplementation!"©ALBI 2008, Tech Austria

Literature cited and sources for more information:

VPM; the real source beeing:
- D.E. Yount, D.C. Hoffman, On the Use of a Bubble Formation Model to Calculate Diving Tables. Aviation, Space, and Environmental Medicine, February, 1986: 57: 149 - 156. The rest of what is out there in the Internet is more or less padding; except the previous doctoral dissertation of Hofman himself:
- Donald Clinton Hoffman, Dissertation August 1985:On the Use of a Gas-Cavitation Model to generate prototypal Air and Helium Decompression Schedules for Divers
Sea Grant HAWAU-Y-84-003 C3

COPERNICUS:
- UHMS ASM (Undersea and Hyperbaric Medical Society, Annual Scientific Meeting) 2008 Session T134,and, as well:
- UHMS ASM 2010, Session F10: CopernicusDecompression Procedures: NTNU, Brubakk et al.
- A Dynamic Two-Phase Model for Vascular Bubble Formation During Decompression ofDivers, Christian R. Gutvik and Alf O. Brubakk. In: IEEE TRANSACTIONS ON BIOMEDICALENGINEERING, VOL. 56, NO. 3, MARCH 2009.
- Christian R. Gutvik, Richard G. Dunford, Zeljko Dujic, Alf O. Brubakk: Parameter estimationof the copernicus decompression model with venous gas emboli in human divers, Med BiolEng Comput (2010) 48:625–636 DOI 10.1007/s11517-010-0601-6)

U.S.N.:
U.S. Navy Department. U.S. Navy Diving Manual. Washington, DC: U.S. Government Printing Office, 1970; NAVSHIPS
0994-001-9010.

DCIEM:
Defence and Civil Institute of Environmental Medicine: Diving Manual, Part 1 & 2, March 1992, DCIEM No. 86-R-35, published by UDT, Inc.

Tektite:
Beckman EL, Smith EM. Tektite II: Medical supervision of the scientists in the sea. Tex. Rep. Biol. Med. 1972; 30:155-69.

RNPL:
Air diving tables. Alverstoke, Hants; Royal Naval Physiological Laboratory, 1968. (London, HMSO, 1968).

Yet Another Benchmark - Part I

By Albrecht Salm

We wanted to compare a couple of dive computers, diving tables and desktop deco software products with our notorious 42 m, 25 min dive on air. This, as such, isprobably not a real tec dive to talk about for this magazine but a dive an ambitious recreational diver could do as well as a one tank dive. As well we want to lay in Part I the foundation to get the idea what is going on in Part II.

Part II will cover the same dive and basically the same procedure but with a somewhat non-standard mixture of Heliox20 (20 % Oxygen, balance Helium). The rationale for this we will cover in part II, appearing in this magazine by the end of 2013.

But our diver will readily get a good feeling concerning the variability in outcomes, if she wants to: the extreme positions in TTS (time-to-surface) in Table I for this dive are:

- 16 or 17 min for a Standard RGBM model via
- 85 min (from my friend Dr. Max Hahn, who calculated a conservative table for recreational diving with a tolerated constant inertgas overpressure of 0.4 Bar([1], [4]) up to
- 102 min with another bubble model software at the very other end.

But before we go into details of Table I, we found out that there is no real standard definition of TTS to which everybody would adhere to. We found various ways to calculate the TTS:

A) TTS = BT + TST + AT
B) TTS = TST + AT
C) TTS = TST = TDT

Legend:
TTS = time-to-surface
BT = Bottom Time (effective time at bottom, normally including descend time)
AT = Ascend Time (normally maximum geometric depth divided by the ascend rate)
TST = Total Stop Time, basically the sum of all stop times
TDT = Total Decompression Time, in principal: TST + AT, but sometimes as well:
TDT = Total Dive Time = BT + TST + AT

Most software products and tables are using definition B) for TTS. Well, but not everybody and not always ...

To make comparability even worse we had to fiddle with a couple of parameters in the dive computers or the PC software: our goal was that the dose of absorbed inert gas should be the same for all outcomes!

Our definition of the "absorbed inert gas dose" is straightforward: it is the time-integral (the area) under the dive profile (i.e. depth vs. dive time). For a rectangular box profile from a table it is just:

depth * time

Thus we had to fiddle about with:

- ascend and descend rates
- barometric air pressure at begin of dive
- temperature
- water density
- pre-defined gradient factors
- set of coefficients for calculation of the allowed / tolerated supersaturation.

Even worse for this comparison are the intrinsic gradient factors of, say a couple of, RGBM implementations. These run internally a straight-forward ZH-L ("RGBM folded over ZH-L" as Bruce Wienke would have it) but had modified the original so-called a- and b-coefficients from the ZH-L mother via gradient factors, called "f-factors" in these frame works.

Products for professional use (i.e. construction & repair diving or saturation diving) could allow for:

- workload (oxygen consumption)
- skin temperature and even the
- respiratory coefficient (volume ratio of carbon dioxide production to oxygen consumption).

If the product was based on the notorious ZH-L 16 system from Albert Alois Buehlmann [2], we tried to force it to use the "ZH-L 16 C" set of coefficients. The ZH-L 16 C is a somewhat little bit more conservative set than the ZH-L 16 A used for the ZH-86 dive table, and is said to accomodate for the peculiarities of an on-line dive computer produced schedule [l.c.: p. 158].

If we lost this battle, say for a fixed and printed table, we put a remark in the right-most column. And, finally: we are not talking about variations, say, in the "sub-5-minute" or "Modulo 2 minute domaine" but rather when it comes to a factor of 2 oreven more!

But our test-diver could have fun when she calculates the arithmetic mean and the standard deviation of all these TTSs …

The basic, primary variation in the TTS, especially within a group of same computers, results of the statistical error in measureing the basic parameters (pressure, temperature, time and the fO_2 via an analyzer). These errors in physical measurement can easily sum up to 10 to 20 % of the calculated TTS. This is why we won't splitt hairs here about smaller variations in the TTS: these could readily be masked by random behaviour of mother nature.

To breath a little bit more life into this: have a look at the title picture. There you see 3 dive computers after a common dive from one diver (me! I took this one a couple of weeks ago here, 'round the corner in El Qusier, Red Sea ...) , exactly on the same depth but with 3 different depth readings and, for sure: with 3 different "NDL"s (= "no decompression limits", which I put in inverted commas: because there is no such thing like a no decompression dive …) respectively 3 different stop times. Let's put these readings in a little table for a clear overview:

Computer: brand & type	**depth reading [m]**	**„NDL" / stop time [min.] (*)**
COCHRAN: EMC-20 H	**16,4**	**+ 5**
VR Tech.: NHeO3	**16,8**	**- 3 (1'/ 3 + 2'/ 17)**
UWATEC: Aladin TEC 2G	**16,9**	**+ 10**

(*) 1st. dive of the day, i.e. no repetitive dive, max. depth ca. 31 m, topical run time ca. 42 min for all boxes: <u>no special features</u> (conservativisms, level stops etc. ...) <u>activated</u>.

Here, Cochran's EMC-20 H (left most box) gives the minimum depth with he shortest NDL: it is sporting an automatic adaption to water density via conductivity measurement. The longest NDL is given by Uwatec's / Scubapro's TEC 2G (box on top), programmed to fresh water density. Our little friend from UK (right most box) forced me already to do a “micro bubble avoidance stop” around 17 m for 2 min and wanted to do as well a real deco stop for 1 min @ 3 m. This is the reason that the right part of its display changed to red and gave me the 2 min break for making this little photography.

So, in this picture we have everything in common:

- deviations of the measurements
- deviations of the outcomes

The real bad message here is: the longer and deeper the dive, the more the deviations. This is probably not so interesting for recreational air diving: but this one will hit the TEC diver, wanting to do a little bit longer and deeper than usual.

And there is another bad message which you learned already from another past issue of this magazine (Tech Diving Mag, Issue 5 – December 2011, p. 41 - 53): the more Helium you put in your mix the more pronounced are these deviations for bad or negligent software implementations, be it in a dive computer or in a piece of desktop deco-software.

Table I: Test Dive on Air, depth: 42 m, bottom time: 25 min

depth of stop → / stop times	24 m	21 m	18 m	15 m	12 m	9 m	6 m	3 m	**TTS min**	Remarks
RGBM				1	2	3	3	7	**16**	Table (pls. cf. legend)
GAP				1	3	3	3	7	**17**	RGBM -2
EMC					2	2	3	8	**19**	Conservative = 0
USN old							2	14	**20**	
MDv 450/1							5	15	**20**	+ ca. 4.2 !
Deco Trainer						1	5	13	**24**	V 3.01
OSTC 470							6	14	**25**	TDT = 50
Ultimate Planner 1.2							6	15	**25**	TDT = 50
IANTD Air					1	4	3	18	**26**	Table
BGV C23						3	7	17	**30**	only „total deco time“
DIVE 3_0						1	6	16	**27**	TDT = 52 (*)
OSTC Planner v 434						1	6	16	**28**	TDT = 53
DIVE 2_905						2	6	16	**29**	TDT = 54
USN 2008							26		**31**	140 feet
USN 09-03							28		**33**	140 feet
ZH-86						4	7	19	**33**	42 m / 27 min
DECO 2000					1	4	8	16	**33**	
Trust 2.2.17						4	7	19	**34**	TDT = 59
DCIEM						7	8	17	**36**	

NHeO3	26/2		2			1	8	21	**36**	Version 11/2011
TEC						3	k. A.	k. A.	**36**	L0 (Level Stop)
DP			1	1	3	4	9	19	**37**	GF: 45 / 90
GAP		1	1	1	2	4	9	19	**37**	GF: 45 / 90
VPM		2	2	3	4	6	8	14	**39**	138 feet
VR3	2	-	2	-	-	2	8	22	**40**	3 m -> 4.5 m
TEC					1	k. A.	k. A.	k. A.	**40**	L1
GAP		2	2	4	4	6	10	12	**40**	RGBM recreational
HLP 1.x			2	3	4	6	9	16	**40**	Default
EMC			2	1	3	4	8	19	**41**	Conservative = 50
VPM	1	2	3	3	5	6	9	14	**43**	Buehlmann safety factor = 145.4 feet
TEC					3	k. A.	k. A.	k. A.	**45**	L2
DP (**)		1	2	2	4	6	11	19	**46**	VPM Rel 3.1.4
Hahn DC-12					5	5	9	25	**47**	24 min BT
TEC				1	k. A.	k. A.	k. A.	k. A.	**50**	L3
TEC				3	k. A.	k. A.	k. A.	k. A.	**57**	L4
HLP		2	3	4	6	8	13	24	**60**	VPM 10 % Safety factor
TEC			2	k. A.	k. A.	k. A.	k. A.	k. A.	**65**	L5
NHeO3	27/2	20/2			1	8	13	39	**69**	Cons.: 50
SDP	1			1					**73**	P2 / A0
Hahn									**85+**	
HLP 1.x	2	3	4	6	8	13	22	44	**102**	VPM 30 % Safety factor

Legend (in alphabetic order):
BGV C23 = (replaced the old VBG 39), means the german legal/safety procedures for commercial in-land diving with air from 01.04.2001
DC-12 = UWATEC / Scubapro dive computer with the P-6 set of coefficients from Dr. Max Hahn; pls. cf. at: www.divetable.info/kap4_e.htm
DCIEM = Defence & Civil Institute of Environmental Medicine) since 01.04.2002: Defence R & D Canada - Toronto, DRDC Toronto, Air Table in the "Diving Manual" DCIEM No. 86-R-35 March 1992, p. 1B-14
DECO 2000 = table from Max Hahn for rec/air diving, released 2000; used in europe, especially by CMAS. Tables, as well for EAN and mountain lake diving, available at: www.vdst-shop.de
Decotrainer: www.decotrainer.de
DP = DecoPlanner Version 2.0.40 resp.:
DP(**)=DecoPlanner Version 3.1.4, www.globalunderwaterexplorers.org
EMC = Cochran EMC-20 H, Version j, www.divecochran.com
GAP = GasAbsorptionProgram Version 2.3.1665
Hahn = custom table with inertgas overpressure 0,4 Bar, [4]
IANTD = Intl. Assoc. of Nitrox & Tec Divers;Technical Diver Encyclopedia, May 1998, p. 233; www.iantd.com
HLP 1.x = HL Planner Version 1.0.2314, www.hlplanner.com/
MDv = Marine Dienstvorschrift 450/1 Anlage 6 (matches the old DRÄGER Table 210, last version from 1970 and 1984), this is the

table used for german military diving; classified information.
NHeO3 = successor of the VR3 computer from DeltaP technologies, which was withdrawn from the market due to a many a lot of problems, now: www.techsupport.technologyindepth.com, somewhat strangely modified ZH-L (****)
OSTC = Open Source Tauchcomputer / Planner; www.ostc-planner.net
RGBM = Reduced Gradient Bubble Model, table bought in 2003 from rgbmdiving.com (***),
SDP = Suunto Dive Planner 1.0.0.3, www.suunto.com
TEC = Uwatec / Scubapro Aladin TEC 2G computer, which allows for user adjustable level stops (L0 → L5)
Trust : www.keimes.de which is a freeware, but requires Java (☹), which is also free
TTS = time-to-surface (after end of BT)
Ultimate Planner: www.techdivingmag.com/ultimateplanner.html
USN = United States Navy; the NEDU (Naval Experimental Diving Unit) is taking care about these things. The topical diving manual Rev. 6 with all the tables is available at NAVSEA: www.supsalv.org ; resp.: www.supsalv.org/pdf/Dive%20Manual%20Rev%206%20with%20Chg%20A.pdf
VPM = Varying Permeability Model, here an Excel Version from Eric Baker (for XP or older OS, so no longer available)
VR3 = mix gas computer from DeltaP with up to 10 mixes, ZH-L based, once it was king of the road ... ; see above at NHeO3
ZH-86 = Zuerich air table from 1986, [2, p. 225]
(*) DIVE 3_0 with full blown numerical solution, no rounding up; whereas DIVE 2_9x is not …
(***) this company went bankrupt ca. 2004, as well there have been a couple of rumours after the dcs treatments of Mark Elyatt after his various record-dives with RGBM schedules ... a specimen copy is available at: www.divetable.info/skripte/ntable.pdf
(****) have a look at: www.divetable.info/kap8_e.htm

What was a little bit disturbing for us where two things:

1) The variation of TTS with a factor of ca. 6 (102 / 16)
2) The variations of different versions from a given software, especially prominent with the Heliox20 dive (Table II in Part II)

Nota Bene: the difference from the multiple USN entries is not "just another version", but instead is a complete change of mindset within the decompression paradigm. It changed from the old Workman 1965 work horse to the VVAL 18 LEM model from Ed Thalmann. The old work horse from Bob Workman was a modified Haldane-model, embellished with a couple of more compartments and his famous "M-Values". Haldane himself put the constraints of his table #1 very clearly: less than 50 m, less than 30 min TTS, no repetitive dives, not for old (>40 years) and men inclined to obesity! [3]. As well he pointed out, that his table is only for "uneventful decompression", i.e. NO BUBBLES! His argument was, that bubbles would mechanically hinder the perfusion, i.e.: the blood flow. But an unhindered blood flow is essential for the de-saturation with inertgas. This is why Ed Thalmann said:

"... at NEDU our exponential uptake on off-gassing led us into a brick wall. I injected the V-VAL 18 into it, the exponential uptake and linear off-gassing model."Captn. Dr. Edward D. Thalmann, Naval Forces under the Sea: The Rest of the Story, p. 293.

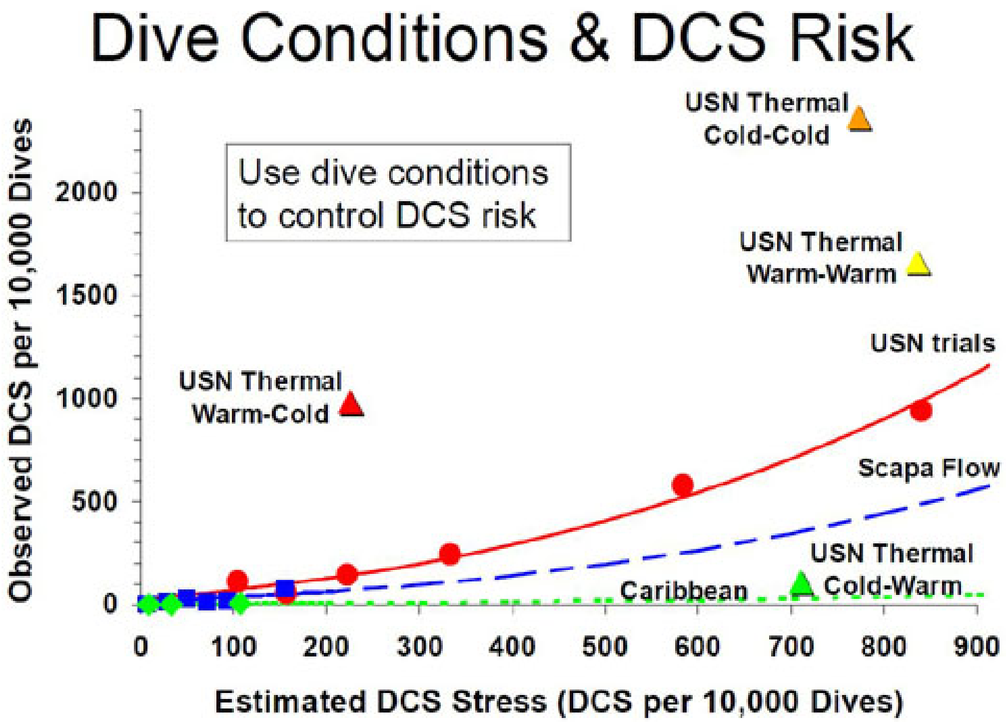
Thus the new USN table (Rev. 6, 2008) prolonged all the deco stops and as well shifted all the 10 feet (3 m) stops down to 20 feet (6m)!

The standard question on looking at this table of TTSs is the following:

Is the longer TTS safer?

I.e.: is a TTS of 100 min+ really "6 times" safer than the shortest RGBM schedule? Well, probably not so:decompression sickness is a relatively seldom event. It appears ca. 1 – 2 times in 100.000 scientific dives, in 10.000 recreational dives, ca. 3 times in approx. 10.000 military dives (normal operation), 1 – 2 times in 1.000 to 2.000 commercial dives and, appeared exactly 338 times in 7.755 USN experimental dives done by the NEDU.

There is another nice result from Dick Vann (UHMS, ASM 2008, p. 251) covering these topics:



Basically it's not only depth, time and fO_2: but as well workload and skin temperature (besides a very lot of other stuff and: de-hydration, fitness and age ☺).

And we shall not forget, how Michael Powell put it in the past issue of this magazine:

"No tables have been tested with subjects haling tanks on the surface." [Tech Diving Mag, Issue 10, 2013], p. 26.

A couple of weeks ago I gave a lecture on these topics during a GTUEM meeting (www.gtuem.org) on the occasion of an anniversary celebration for a recompression chamber facility in the frankfurt area (germany). We discussed these things with the doctores Arne Sieber (www. seabear-diving.com) and Adel Taher (who is running the deco chamber in SSH): one argument was, that despite the great variation in TTS, theP(DCS), the statistical probability of getting hit with adecompression sickness, would be more or less the same for the whole bunch of these TTS's. Mathematically speaking, this is quite true but these are just numbers which would not help for our real world diving.As well the true discrimination of a 1% P(DCS) margin from one TTS to anotherwith zero or only one or 2 hits of DCS within reasonable statistical accuracywould require something like additionally 300 controlled dives [private communication, 02. Feb. 2013, 15th. anniversary of HBO-RMT, Wiesbaden, after a couple of beers …].Or, to put this one into your perspective of real diving: if you made one DCS-free mix gas dive the last weekend and would like to question if the next one, absolutely identical dive, will be as well DCS free the next weekend then your confidence intervall ranges from almost nearly 0 % (unknown) to ca. 90% (relatively sure).

So the simple take-home message is:
none of these models (inert gas book keepers, tables, dive computers, …) have a lease on the ultimate truth. NONE!

(to be continued with: Heliox20 and a little bit about bubble models) …

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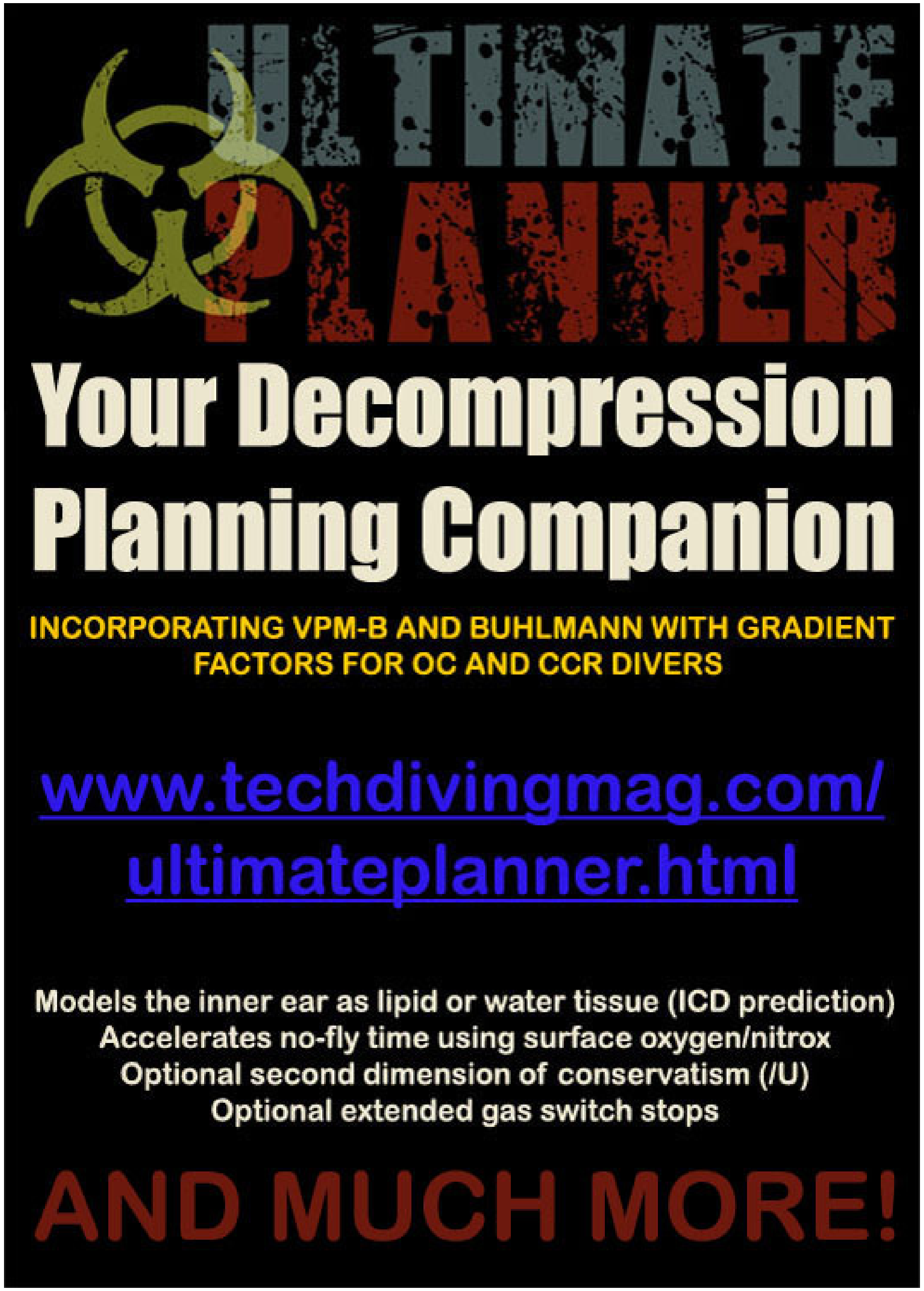
Cited literature

[1] Hahn MH. 1995. Workman-Bühlmann algorithm for dive computers: A critical analysis. In: Hamilton RW, ed. The effectiveness of dive computers in repetitive diving, UHMS workshop 81(DC)6-1-94. Kensington, MD: Undersea and Hyperbaric Medical Soc.

[2] Tauchmedizin, Albert A. Bühlmann, Ernst B. Völlm (Mitarbeiter), P. Nussberger; 5. Auflage in 2002, Springer, ISBN 3-540-42979-4

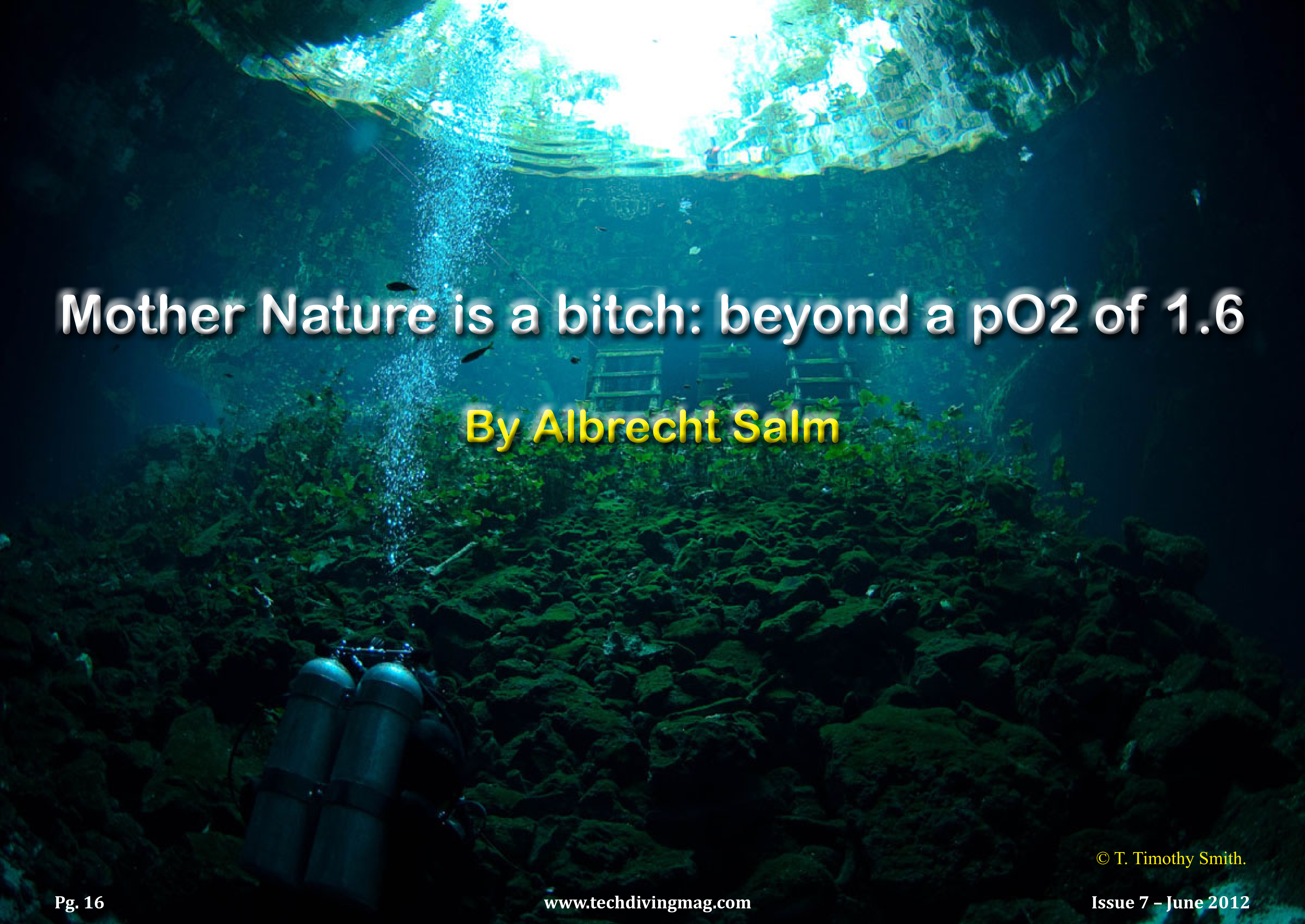
[3] Boycott, A.E., Damant, G.C.C., & Haldane, J.S.: The Prevention of Compressed Air Illness, Journal of Hygiene, Volume 8, (1908), pp. 342-443.

[4] Hahn M, Wendling J: No-Bubbles Decompression Tables. In: Safety Limits of Dive Computers, UHMS workshop 1992, pp. 68 – 72



Mother Nature is a bitch: beyond a pO_2 of 1.6

By Albrecht Salm

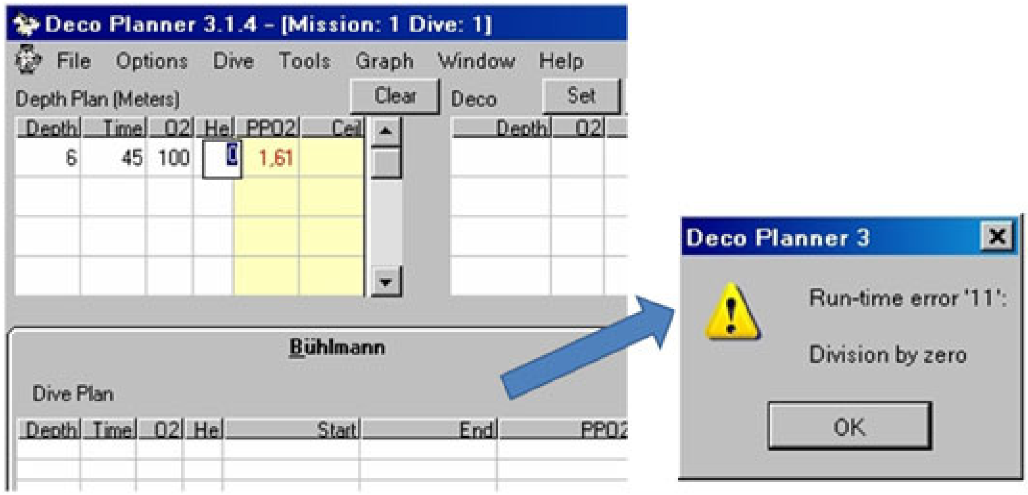


© T. Timothy Smith.

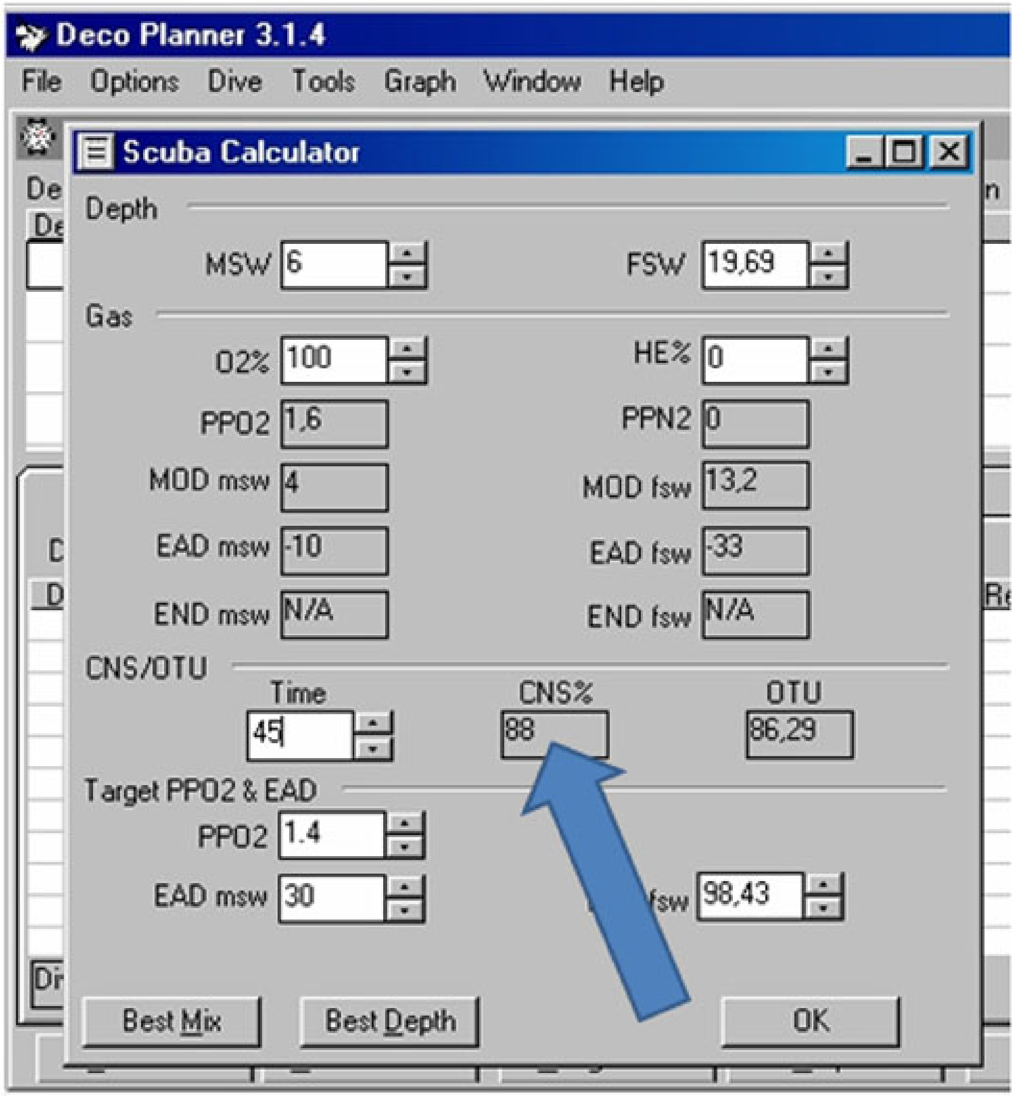
Let's consider the following scenario: you are a technical diving instructor having a bunch of enthusiastic divers, and you're diving with them all weekend long. The next day early morning you should go on a scheduled flight to your next job at another dive site. So waiting the recommended 24 hours is way out of any possibility. What are your options? Cancelling the last dive doesn't only give you hassle with re-scheduling the whole set-up with tanks and transportation, but you will as well lose customers and money. Cancelling the flight even more so!

How about that one: you do the dives, but you handle the shallow decompression stops of the last dive aggressively with oxygen, resulting in a far more expedited inert gas off-gassing (with a high risk of a CNS ox-tox hit, for sure). Anyway, you have the equipment, the expertise, the experience with thousands of dives and the bravado to do it. Your TEC students will not notice it, when you start breathing down your oxygen tank at, say 9 or 12 m. The guys are fumbling with their reels and trying to deploy their SMBs ... So, you even stay longer at 6 m, doing all the stops there for the last stages. Why did you choose 6 m? Well, besides the much higher oxygen partial pressure than at 3 m and thus a higher efficiency, there you have as well a higher ambient pressure, which gives, thinking in terms of avoiding micro bubbles which would hinder the off-gassing an even more efficient decompression(*).

Well, everything went fine this time. You sit comfortably in your jump-seat enjoying the flight, but now you switch on your laptop and try to assess your ox-tox risk from this very dive. You take your latest piece of PC deco-software and try to simulate just the oxygen decompression, nothing else (the fractions F being: $FN_2 = FHe = 0$, $F0_2 = 1$).You key that in, and:BOOOOOM! Off we go:



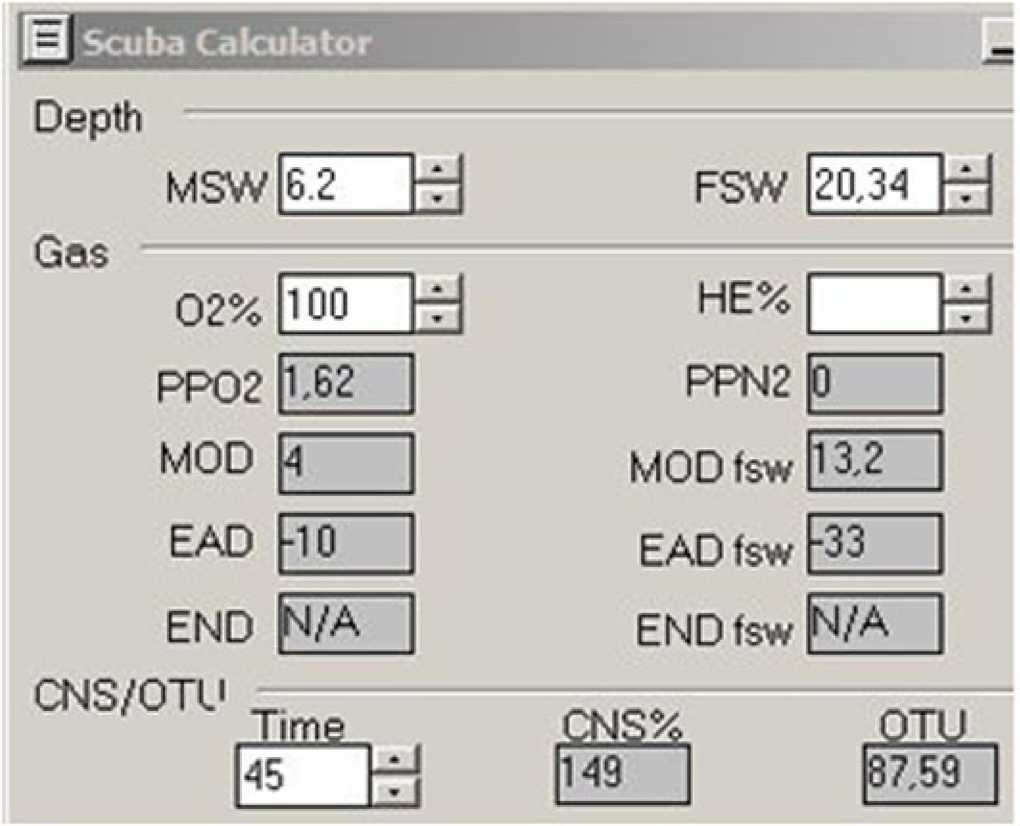
Well, you blew the software: not your fault! Due to an error, obviously sloppy work on the programmers side who did not initialize very-well all his variables with an inert gas saturation as a boundary condition for dive time t = 0 min, so you try something else out of the tool-box:



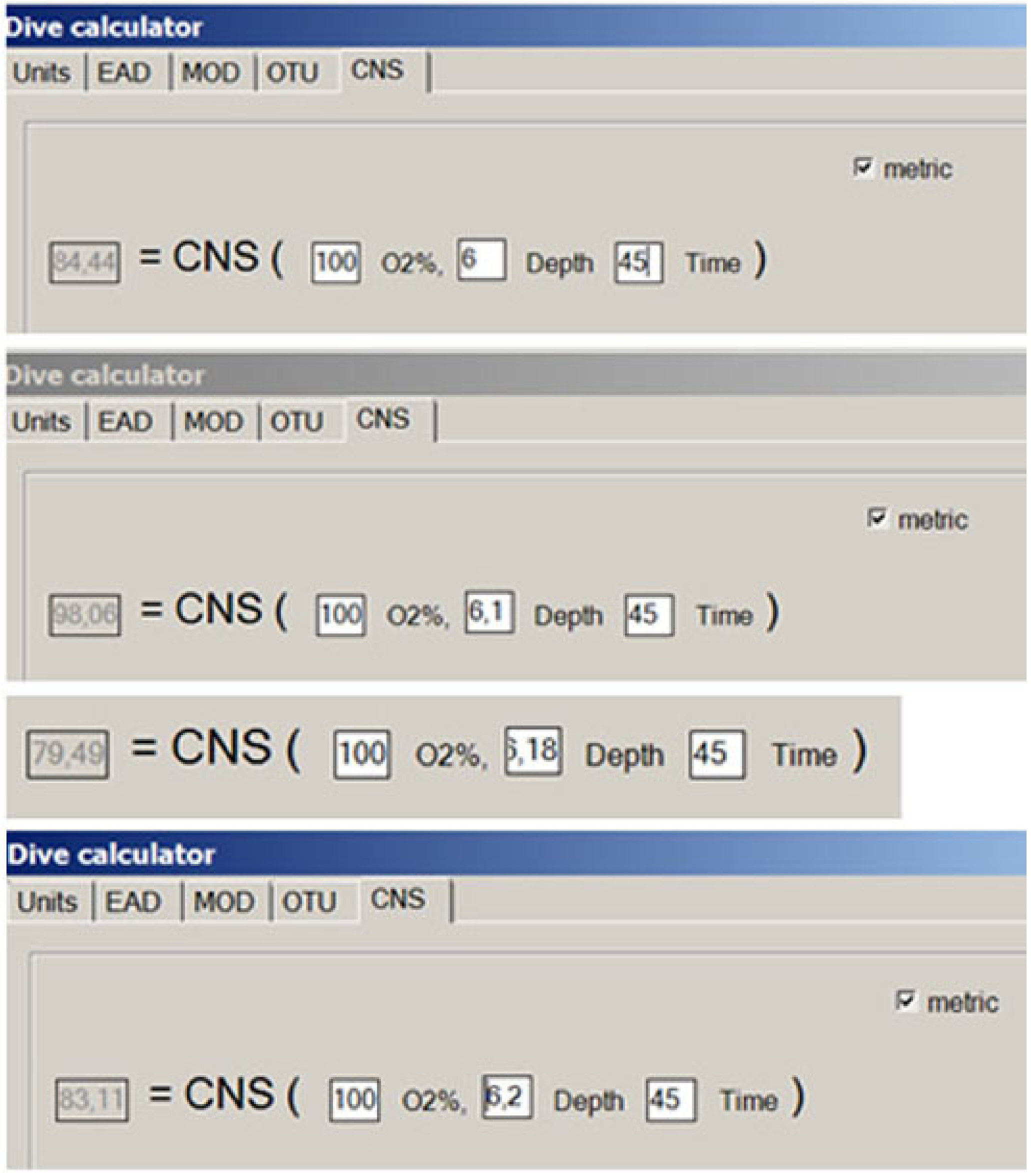
OOOOOOOOOOps: wow! Shouldn't there be something like 100% of a CNS dose with a $pO_2 = 1.6$ and 45 min? Well, another oops: by checking your NOAA diving manual (1) on p. 3-23 (4th edition, section 3, table 3-4), you see that these guys are always talking about atm, which, in this case, is not the automatic teller machine you searched for urgently at the airport but: [Atmospheres], a unit of pressure; instead of the [Bar] to which us regular diver folks are easily accustomed to. But as the expert you are, you know that approximately 2% are missing, pressure wise (1.308 to be a little bit more accurate), so you add a little bit to the deeper side. In terms of depth you add at 6 mca. 0.2 m to receive the requested 1.6 atm for pure oxygen.

p amb [Bar]	**pO2 [atm] @ f = 1.0 O2**
1,5000	1,4804
1,6000	1,5791
1,5199	1,5000
1,6212	1,6000

This is all but just „circa“! Why? Well, even 10 m of water column do not give exactly one Bar. For pure (fresh) water the conversion factor is 0.98065, for seawater it is 1.00522 [(4), p. 893], everything dependent on the specific density of the water you dive in (or your deco software thinks, you are in … ☺).



So, this one above goes from 88% to 149%. WOW: now you get suspicious and you double-check with a completely other piece of new deco-software, keying in a couple of depths, increasing from 6.0 to 6.2 m:



Here we have 84.4% to 83.1%: decreasing with increasing depth! And, as well with a somewhat peculiar peak in between at 98% and with 8 cm more depth we reach a certain trough at 79%. Well, well: we shall not split hairs here and a deviation of, say +/- 3% would be still in the green. But this one is far, far away from the NOAA rules and seems to be not very reliable … Even if you have right away 1.6 atm of pO_2: this is just reached at the mouth-piece from your second stage. Down your trachea the oxygen becomes quickly diluted with air saturated with water vapor, further down the airways it becomes even more diluted with your old, used air i.e. with carbon dioxide and the residual N_2 or He from your previous inert gas uptake.

And, as well concerning the dive time we could exceed the 100% CNS limit. Say at 1.6 we would stay 49 min instead of the 45, thus giving around 110%. Computational-wise this should be a piece of cake since the NOAA rule is linear in time: for half the time we would expect half the dose, i.e. 50%, or, in this example with 4.5 min the result should be 10% of the CNS dose. For your convenience, we checked a couple of deco software also in various releases concerning these two aspects,putting the results together for comparison; that is around the 100% limits in the pressure- and the time-domain to check the linearity:

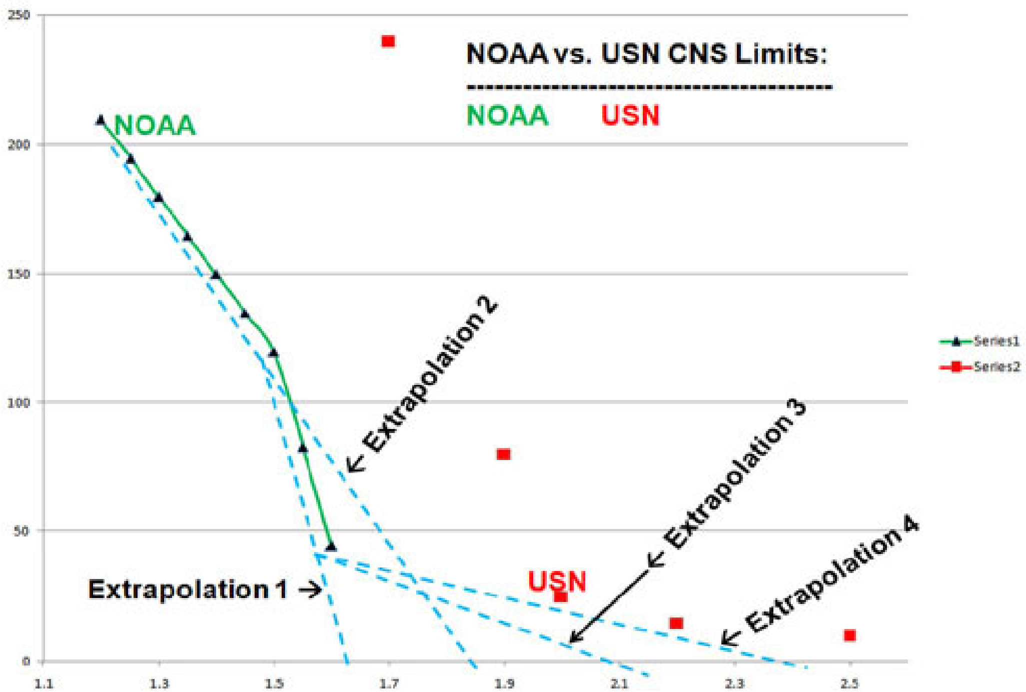
pO2 [atm]	divetime [min]	NOAA CNS dose [%]		DIVE V2_903	GAP V 2.3	GAP V 3.0.425.6	Deco Planner V 2.0.40	Deco Planner V 3.1.4	Ultimate Planner V 1.1
			d= 5.2 m		(d = 5)				
1.5	108	90		90	90.4	96.00	98	98	90.4
1.5	120	100		100	100.4	106.60	109	109	100.4
1.5	132	n.a.		110	110.5	117.30	120	120	110.4
			d = 6.0 m						
1.58	40.5	-		90	89	76.00	80	80	90.1
1.58	45	-		100	100.3	84.40	88	88	100.1
1.58	49.5	-		110	109	92.89	97	97	110.1
			d = 6.2 m						
1.6	40.5	90		90	n.a. (*)	74.80	134	134	102.9
1.6	45	100		100	n.a.	83.11	149	149	114.3
1.6	49.5	n.a.		110	n.a.	91.42	164	164	125.7
		exceptional exposures, Extrapolation #3	d = 7.2 m		(d = 7)				
1.7	33.75	90		89	336	371.70	389	389	198.1
1.7	37.5	100		99	377	413.00	432	432	219.9
1.7	41.25	110		108	417	454.40	475	475	241.6

Ultimate Planner's data provided by Asser Salama

To make a long story's end: obviously there is ample leeway for a programmer to implement the ox-tox scene. To put it even more bluntly: nobody told these guys, especially around the 100% and the 100%+ dose. So let's go back to the old masters, the NOAA (1) and the USN (3): this is how they did itaround $1.2 < pO_2 < 2.5$ atm:

	pO2 [atm]	NOAA [min]	USN [min]	
	1,2	210		
	1,25	195		
	1,3	180		
	1,35	165		
	1,4	150		
	1,45	135		
	1,5	120		
	1,55	83		
	1,6	45		
	1,65			
	1,7		240	
	1,75			
	1,8			
	1,85			
	1,9		80	
	1,95			
	2		25	
	2,05			
	2,1			
	2,15			
	2,2		15	
	2,25			
	2,3			
	2,35			
	2,4			
	2,45			
	2,5		10	

Remark: the NOAA exceptional exposure limits are suggested from Dr. C. Lambertsenand were published in the 1991 Version of the diving manual. Bob Hamilton oncedescribed them as "best judgment" in the DAN Tec proceedings ((2), Session D2-3). The USN limits however ((3) Volume 4, table 19-4, p. 19-14) are single depth exposure limits on pure oxygen for standard procedures, not for exceptional exposures (and, as well not for mixed-gas diving!). How could we proceed with our scenario from the beginning of this story: obviously there are a couple of ways to look at it in the high-pressure regions:



Let's discuss these extrapolations. But, please keep in mind: these are just mathematical things! That is not a recommended diving procedure! (Well, I still want to keep my instructors licenses, at least a couple of them). But we want to suggest a reasonable algorithm a programmer or developer of deco-software could easily follow. The added value would be that with various deco-software, at least the ox-tox doses would become comparable ... Well, there is much more on the road that the inert-gas doses resp. the decompression times become comparable: even if the deco software tools share the same basic algorithm there is much space for interpretation! (This is already covered in your favorite TEC-magazine: have a look at Tech Diving Mag, Issue 5, page 41).

These extrapolations are a simple and linear by nature. Why? Well, we could have used some polynomial or another complex exponential approach. But this would not have helped us either: it just complicates the matter. The other important boundary condition is not to violate the USN limits!

If we look at the chart: the green line is the NOAA standard, the red dots are the USN marks and the blue-dashed lines are 4 linear extrapolations. Ex #1 ends at ca. 1.7 atm, Ex #2 at 1.9 atm. Those two do not give us much freedom in terms of depth: a small surge, a little wave, a quick helping hand for your diving comrades…The 9 m depth line can be easily exceeded. On the other hand, Ex #4 ends at 2.5 atm and is relatively nearto the USN limits: let's avoid this one. So the straight line of choice would be Ex #3: giving ample leeway up to 2.2 atm of pure oxygen pressure but nevertheless a little bit more conservative than the USN limits.

p O 2 [atm]	NOAA [min]	NOAA except. exp.	U S N [min]	Ex. 3 [min]	Ex. 4 [min]
1,2	210				
1,3	180	240			
1,4	150	180			
1,5	120	150			
1,6	45	120		45	45
1,7		75	240	37,5	40
1,8		60		30	35
1,9		45	80	22,5	30
2		30	25	15	25
2,1				7,5	20
2,2			15	**0**	15
2,3					10
2,4					5
2,5			10		**0**

Bottom line is:
- we thought: let's share this information about the shortcomings of the deco software
- and: let's challenge a feedback from the wild
- and: let's suggest a possible and easy way out

(1) NOAA Diving Manual, U.S. Department of Commerce, 2001, Fourth Edition
(2) DAN Technical Diving Conference Proceedings, January 2008 (available for free as a PDF at: www.diversalertnetwork.org)
(3) US Navy Diving Manual, SS521-AG-PRO-010 0910-LP-106-0957, Revision 6, 15. April 2008
(4) The Underwater Handbook, Charles W. Shilling (ed.), 1976, Plenum Press New York

(*) At least, mathematically wise. After ca. 15 min or so your heart beats a little bit slower than normal and your blood vessels become a little bit narrower, thus reducing the efficiency a little bit. The doctors call the former "bradycardia" the latter "vasoconstriction". These things have been investigated as well through the USN, the DCIEM and the NMRI since long. But up to now not much deco software have implemented these "oxygen correction" factors.

Decompression calculations for trimix dives with PC software; gradient factors: do they repair defective algorithms or do they repair defective implementations?

By Albrecht Salm

Abstract

If there is more than one inert gas in the breathing mixture, the calculation of the decompression-time t_d has to be done numerically. We analyzed 480 square dive-profiles in the TEC/REC range with one freeware, two commercially available software-packages and via numerical methods (depth range: 30 - 80 m, bottom times: 20 - 60 min, helium percentage: 5 - 80 %, only normoxic mixes i.e.: no travel- or enriched deco gases, only ZH-L model, no adaptations with gradient factors). There are significant differences in the calculation of the decompression-times t_d with trimix gases, obviously dependent on the helium percentage. In the present analysis, these differences do not come from variations in the decompression algorithms.

Side Note

This is an abbreviated version of a paper which appeared in: CAISSON 2011, 26(3): 4 – 12. Several parts of this paper I presented during a lecture for which I was invited to the 12.th scientific meeting of the GTUEM (www.gtuem.org) , 03/20/2011 in Regensburg, Germany; the abstract is under: CAISSON 2011, 26(1): 61. The extended German version you will find at http://www.divetable.de/skripte/CAISSON/Extended_2011_03.pdf

Introduction

An „Algorithm“ is just a mathematical rule for inert gas bookkeeping during an exposure to overpressure. An „Implementation“ is the practical translation of this algorithm into a piece of software, be it for a dive computer or a desktop deco software. A „Gradient Factor“is a factor < 1. It is used to multiply the allowed / tolerated inert gas partial pressures in the various body tissues; thus a more conservative decompression method is forced via mathematics. With “ZH-L” a certain group of dissolved gas deco models is denoted, the researchers names are: Haldane, Workman, Schreiner, Mueller, Ruf, Buehlmann and Hahn (pls. cf. the references).

The classical, perfusion-limited decompression algorithms after Haldane et al. describe the absorption of inert gases per compartment through a mono-exponential function. Normally the term „Haldane Equation“ is used:

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

Variable	Definition
$P_t(t)$	Inert gas partial pressure within a compartment with the constant k [Bar] at time t after an instantaneous change in pressure
P_{t0}	initial partial pressure of the inert gas within the compartment at time t=0 [Bar]
P_{alv0}	the constant partial pressure of the inert gas in the alveoli [Bar], for t = 0 and thus for all t due to the boundary conditions
k	a constant, dependent on the compartment [min^{-1}], with k = ln 2 / τ
t	time [min]

The exponent k is basically the perfusion rate, i.e. the inverse of the half-time τ of a model tissue. These model tissues are called „compartments“. The adaption of a purely mathematical algorithm to a physiological system is done via a flock of these compartments, typically 6, 9 or 12, 16 and sometimes as well 20 (or even more). The variability comes with the different halt-times into play. A typical spectrum of these half-times is from 1.25 to 900 minutes; for e.g. in a dive computer for professional use, the EMC-20H from Cochran and the corresponding desktop deco-software Analyst 4 (www.divecochran.com).

The mainstream sources for these perfusion algorithms are well known and listed in the appendix. But now we want to try something new and draw upon a source which is relatively rarely used:

> [102] Hills, Brian Andrew (1977), Decompression Sickness, Volume 1,
> The Biophysical Basis of Prevention and Treatment

Formula (1) is on page 111, the relationship between the half-times and the perfusion rate is on page 113.

Limits of the perfusion-models

The perfusion-models for Air/Nitrox/EAN and Heliox as breathing gases are based worldwide on a very broad number of well-documented dives. They are mathematically straightforward and have since the papers of Buehlmann ([4], [5], [65]) enjoyed popular implementations in many dive computers and PC programs (Desktop-Deco-Software). The technical diver as such wants to dive deeper / longer and thus is inclined to forget the trusted envelope. Nonetheless this envelope is already published at length (e.g. in [63], p. 449 and 463) and is dealing with a couple of the following points, here just as a short overview and not limited to:

- only „inert gas-bookkeeping", only mono-exponential for one compartment
- these compartments are all in a parallel circuit, the linear connections like spleen -> liver & bowel -> liver are not considered
- inconsistent consideration of the metabolic gases O_2, CO_2 and H_2O
- „uneventful" decompression, only the gas in solution is considered and not the free gas phase (bubbles)
- no allowance is made for short-term pressure changes which are small against the fastest half-times
- the calculation of inert gas saturation and de-saturation is done in a symmetrical manner, i.e. with the identical coefficient in the exponential terms of (1)
- clientele / biometrics and adaption are not reflected in the algorithms
- as well not these circumstances, which affect tec divers even more due to massive impact on blood-perfusion: workload, temperature and excessive oxygen partial pressures
- and: the 2nd. inert gas; the 2nd. (n-th) repetitive dive; and, and, and, …

Just a small choice of sources to these points:

Thalmann, ED; Parker, EC; Survanshi, SS; Weathersby, PK. Improved probabilistic decompression model risk predictions using linear-exponential kinetics. Undersea Hyper. Med. 1997; 24(4): 255 – 274; http://archive.rubicon-foundation.org/2276

Tikuisis, P; Nishi, RY. Role of oxygen in a bubble model for predicting decompression illness. Defence R&D Canada, 1994; DCIEM-94-04; http://archive.rubicon-foundation.org/8029

Doolette DJ, Gerth WA, Gault KA. Probabilistic Decompression Models With Work-Induced Changes In Compartment Gas Kinetic Time Constants. Navy Experimental Diving Unit, Panama City, FL, USA; in: UHMS Annual Scientific Meeting, St. Pete Beach, Florida, June 3-5, 2010, Session A6.

Hahn MH. 1995. Workman-Bühlmann algorithm for dive computers: A critical analysis. In: Hamilton RW, ed. The effectiveness of dive computers in repetitive diving. UHMS workshop 81(DC)6-1-94.

Kensington, MD: Undersea and Hyperbaric Medical Soc. http://archive.rubicon-foundation.org/7998

Trimix tables

For Heliox (oxygen & helium mixtures) there is a great abundance of validated tables: quite in contrary to Trimix (oxygen, helium and nitrogen). There are none (almost). Surely enough there is anecdotal evidence of successful trimix-decompressions, but limited to a couple of custom mixes, with a limited group of test persons and limited in the dive profiles. But „validated" here means a completely other league of game. It is a journal-led procedure in a decompression chamber, run for a big number of various depth/time combinations, each of them with big numbers of dives. The journal is a detailed and reproducible log of the following parameters: biometrics of test persons, time of the day, depth, time, ascent- and descent-rates, surface interval (even multi-day), breathing gas composition and- humidity/ -temperatures, temperatures in the chamber and wet-pot, type of immersion and work-load. The outcomes (DCS or # of Doppler detected bubbles) have to be checked via double-blinded operators. And when the number of test-persons exceeds the 3-digit limits and the number of test-dives is in the 4- or even 5-digit range (as with NEDU, DCIEM and COMEX tables) then there might be a certain tenacity. But none of the known trimix tables is meeting these requirements. Maybe a laudable exception is the NOAA trimix 18/50 Table from Hamilton Research Ltd., 1993, 1998.

Just for the fun of it we draw from the „Journal of Applied Physiology" the number and temporal distribution of research papers concerning "trimix" (title & keyword) from 1948 to 2010 and compared with other topics (Tables (1a) & (1b)):

title & keyword:	1948 – 2010	1976 - 2010
(air	13.466	10.845)
oxygen window	14	
decompression	709	572
ean / nitrox	128	
helium	1313	
trimix		**41**

Table 1a

The papers concerning „air" are in brackets and only to compare the absolute numbers since the relationship to exposure to overpressure is not always the case. The first paper was around 1976; the graph below shows the last 20 years and features a peak in the year 2007. This results from short discussion-papers concerning the (in)-validity of Henry's Laws, especially with binary (half/half) gas-mixtures:

Year	#		Year	#
1990	-		2001	1
1991	1		2002	-
1992	-		2003	3
1993	-		2004	-
1994	1		2005	1
1995	2		2006	-
1996	-		2007	8
1997	1		2008	-
1998	-		2009	2
1999	-		2010	1
2000	1			

Table 1b

The somewhat singularly paper in 2010 is from Ljubkovic et al. (pls. cf. the references), and reflects very well our topic here, however with a VPM / bubble model and is really interesting for hyperbaric (-diving) physicians. But generally speaking we have here the tendency that trimix plays only a somewhat junior role in serious research. To put it bluntly:

<u>the heavily exposed trimix diver is his own guinea pig.</u>

The decompression time t_d for un-ary mixes (i.e. only one inert gas like EAN or heliox) can be calculated directly with the Haldane equation (1). This is documented already and elsewhere (for e.g.: http://www.divetable.de/workshop/V1_e.htm), here is the analytic expression for the decompression time $t = t_d$:

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

The criteria for „safe“ decompression within the perfusion-models is a simple linear (straight line) equation ([65], p. 117, resp.: [102], p. 119 ff):

$$P_{t.tol.}ig = P_{amb} / b + a \qquad (3)$$

Variable	Definition
$P_{t.tol.}ig$	tolerated inert gas partial pressure, for each compartment, (analogue to M) [Bar], the sum of all inert gas partial pressures
a	limit of a theoretical ambient pressure of 0 Bar, i.e. the axis intercept [Bar]
P_{amb}	ambient pressure, absolute pressure of all breathing gases [Bar]
b	1/b pressure gradient: increase per unit of depth (dimensionless), i.e.: the slope of the straight line

These a-/b-coefficients are constants, tabulated for look up, e.g.: in [4] p. 27, in [5] p. 108 & 109, as well in [65] on p. 158.

A direct mapping of equation (3) onto other perfusion models, e.g. the „M-Value“ model of Workman or Schreiner, is done via a comparison of the parameters and the conversion of the SI-units to imperial; described elsewhere and, as well, here: http://www.divetable.de/workshop/V1_e.htm)

During the course of the century the number and absolute values of the coefficients changed from author to author: this is mostly the reflection of an increasingly conservative decompression, that is: longer deco stops (pls. cf. Egi et al.).

The analytical expression (2) 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. With Tri-Mix we have 2: N_2 (nitrogen) and He (helium). Thus we have to calculate the inert gas absorption for these 2 separately. This is a standard procedure, already described by Buehlmann in [65], p. 119:

$$P_t(t) = P_{t,\,He}(t) + P_{t,\,N2}(t) \quad (4)$$

The differences are in the molecular weights, the solubility coefficients and the diffusion constants (pls. cf.: Rostain JC, Balon N. Nitrogen Narcosis, the High Pressure Nervous Syndrome and Trimix. In: Moon RE, Piantadosi CA, Camporesi EM (eds.). Dr. Peter Bennett Symposium Proceedings. Held May 1, 2004. Durham, N.C.: Divers Alert Network, 2007; as well: [102], p. 118)

But now the criteria for „safe" ascent has to be adapted as well to 2 inert gases, (3) changes simply to (3*):

$$P_{t.tol.}ig = P_{amb} / b^* + a^* \quad (3^*)$$

Here as well there is a simple procedure to determine these new a* and b* -coefficients. The old a- and b-coefficients (table look-up) for both of the gases are normalized with the prevailing inert gas partial pressures for each of the compartments (pls. see the remark in [54] on p. 86). Thus we have for any combination of a- and b-values for each compartment at any time t:

$$a^* = a\,(He + N_2) = [(P_{t,\,He} * a_{He}) + (P_{t,\,N2} * a_{N2})] / (P_{t,\,He} + P_{t,\,N2})$$
$$b^* = b\,(He + N_2) = [(P_{t,\,He} * b_{He}) + (P_{t,\,N2} * b_{N2})] / (P_{t,\,He} + P_{t,\,N2}) \quad (5)$$

Please see as well the examples in [4], p. 27; [5], p. 80 and Rodchenkov et al, p. 474.

The ascent criteria is now time-dependent by itself, the a*- & b*-coefficients are via (5) married with the time-dependent exponential expressions of saturation/desaturation and no longer any constants as per air/EAN or heliox.

The mapping of the compartment halftimes from N_2 to He is normally done according to Graham's law with the square root of the proportion of the molecular weights (i.e.: ca. 2.65). This factor is now keyed in, uniform to all compartments. And exactly at this point we meet the criticism of serious researchers in the field: D' Aoust et al, p. 119 & 121; as well: Lightfoot et al, p. 453 and: Voitsekhovich, p. 210. In experiments we see the perfusion rates quite differently! The pivotal 2.65 is, so it seems, really valid only for saturation exposures (Berghage et al, p.6). But saturation is a state which even the bold tec-diver does not reach easily … (Well, there are bold divers and there are old divers. But there are no ... Ok, Ok: you already know the rest of the story ...)

Methods

To put it simply: the deco time t_d is now on the left and the right hand side of eq. (2), a simple analytical expression to solve for t_d is not possible due to the exponential sums. How can we then evaluate t_d?

Basically there are at least 3 simple methods. We look at them only skin-deep because they are described elsewhere (for e.g.: http://www.divetable.de/workshop/V3_e.htm)

A- „Trial-and-Error": for small increments in time, e.g. 1 second or 0.1 minute, we calculate all relevant terms and check if the ascent criteria is met. This is called a classical „numerical" solution.

B- „Quasi-Analytical": we accept tacitly an error by using eq. (2)

without changes. Thus we consider the a*-/b*-coefficients as constants for each phase of the decompression.

C- An approximation method: all the exponential terms are approximated via a polynomial expression, aka „Taylor Expansion" (Bronstein, Chapter: Expansion in Series).

For commercially available off-the-shelf (COTS) desktop deco software method A) should be preferred since the computing power of topical PC hardware does not impose any waiting-time for the users. Thus quite in contrary to standard mix gas diving computers. Due to the relatively high cost of development for water-proof hardware and, in comparison to other mobile electronic devices like Smart Phones, virtually negligible lot sizes, there are regularly no full-custom ASICs in favour of relatively cheap standard chips. These standard chips are somewhat "slower" and brilliant in a gigantic energy consumption ...

The numerical solution A) consumes, in comparison to method B) more computing power and thus time and more variables and memory: all of the 3 we do not have plenty under water! It is thus self-evident to insinuate method B) where cost is at premium and we need a result on the spot.

How is this handled with commercial standard products? The crux is that producers of dive computer hardware and deco software are regularly not willing to answer such inquiries with hints to company secrets. Or, answers are cryptic and thus give room for conjecture!

But to answer this question halfway satisfactorily, we have developed the following experimental method: 480 square dive profiles from the TEC- and REC- domain with the depth range: 30 - 80 m (6 profiles at 10 m distance), and bottom times : 20 - 60 min (5 profiles in 10 min increase), with helium fractions: 5 - 80 % (16 profiles in 5% increments), only with one normoxic mix (i.e.: no travel gases and no EAN deco mixes) have been evaluated each with 4 software products and compared:

- two commercially available off-the-shelf deco softwares,
- one Freeware/Shareware version of DIVE (source: http://www.divetable.de/dwnld_e.htm , version 2_900), and, as well
- a private version 3_0 of DIVE.

This version 3_0 had implemented exactly the method A), the public version 2_900 is flawed with the "blunder" of method B). For the 2 COTS products there are no reliable statements available despite insistent and repeated inquiries.

As a first step, these 4 products have been tested against each other with 40 different air- and 40 different Nitrox/EAN32 profiles. Thus we checked the actual convergence of the numerical method A with the COTS products. As one paradigm we have the following table (2) with the TTS values for a square dive to 40 m with the bottom times ranging from 20 to 60 minutes:

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

Table (2): TTS vs. the 4 products; TTS = time-to-surface, i.e. sum of all deco stop times + time for ascent

As well a sensitivity analysis was made for the numerical solution in order to make sure that minor variations in the starting parameters do not lead to mathematical artefacts. In the end we compared the 4 against the „Gold Standard", the „Zuerich 1986 table for air dives"

(ZH-86) of A. A. Buehlmann ([65], p. 228). Here we have deviations of + / - 2 min per deco stage, as well sometimes the staging begins 3 m deeper in comparison to the table. This comes mainly from the different sets of coefficients: the ZH-86 table uses the ZH-L 16 **B** set ([65], p. 158), whereas deco software or dive computers are using normally the ZH-L 16 **C** set ([65], l.c.). As well printed tables are treating truncations in a completely different way than dive computers. Even the great ex-champion from the NEDU (the United States Navy Experimental Diving Unit), Captain. Dr. Edward Thalmann had to admit, that a published diving table does not jar with a computer-output:

> "I think some were just manually adjusted. They just went in and empirically added five minutes here and five minutes there, yeah."

(Source: Edward Thalmann, [113] Naval Forces under the Sea: The Rest of the Story, p. 63 – 70, 197, 274, 361 and as well, the CD "Individual Interviews").

Similar things may have been happened as well with OSHA tables for caisson/tunnel work (until 1979). But these have been coined as „typographical errors" (Kindwall, p. 342).

To force comparability all the calculations are based solely on the set ZH-L 16 **C** ([65], p. 158) and there are no manipulations via gradient factors. As well there are slight adaptations of the dive profiles via ascent- and descent rates to make sure that the bottom times and the inert gas doses are matching.

Results

Evidently there are significant differences in the calculation of the deco times in dependence of the helium-fraction and the amount of decompression obligations, vulgo the inert gas dose, see chart (2). These differences are not due to variations in the decompression algorithm but rather <u>exclusively through different ways of calculation.</u>

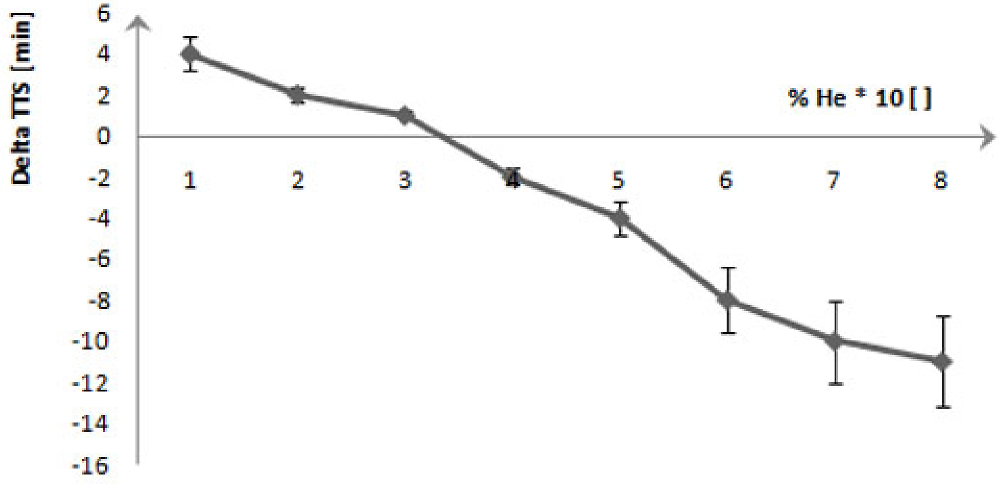


Chart (2): Delta TTS for a dive to 40 m, bottom time = 40 min.

Chart (2) shows the deviation of the TTS in dependence of the helium fraction, here as an example for a dive to 40 m with a bottom time of 40 min.:

x axis: percentage of helium in the breathing mix: from 10 to 80 %

y axis: Delta TTS is a difference of the numerical solution to an arithmetic mean out of the 3 TTS according to**:** $\mathbf{\Sigma (t_{d,1} + t_{d,2} + t_{d,3}) / 3}$ **;** the $t_{d,i}$ being the calculated $\mathbf{t_d}$ of the products i = 1 - 3 (DIVE 2_900, product 3, product 4). The x axis is defined as the zero baseline of the TTS of the numerical solution. An "error" in [minutes] is coined as 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 3 products. The absolute errors (see the vertical error margins) are increasing with the increase of the inert gas dose and with the increase of the helium fraction. The above represented curve progression is more or less universal for all of the 480 square profiles. Speaking simplified, qualitatively:

- in the region of the helium fractions 5 % up to ca. 25 % the TTS is overrated: positive error; i.e. the TTS is too great, the decompression is too conservative.
- in the region of helium fractions which is relevant to most tec divers, that is ca. 30 – ca. 40 %, the error vanishes: Delta TTS -> 0, and
- increases with increasing helium fraction. In this region the error is negative, i.e. the TTS is too small, the decompression is too liberal.

Discussion

The results of the 2 COTS products and DIVE 2_900 came very close to each other thus a somewhat similar calculation method is supposed. But this „similar" method means in plain language: the „blunder" of DIVE 2_900 could be repeated in the implementations of the 2 COTS products ... To put it even more bluntly: the relative identity of the absolute values and the prefix leave room for the guesswork that the 2 COTS products are using method B). Well, there are quite a couple of other factors who could have been responsible for these deviations. To name just a few:

- 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 helium and as a consequence:
- small deviations from the original helium ZH-L spectrum of half-times (i.e. a mismatch of a and b with the half time)
- utilisation of the so-called „1b" compartment instead or additive to compartment „1" ([65], p. 158);
- ascent rates varying with depth
- different approach to truncations

„Walking stick" solutions for software implementations due to restrictions of the hardware have been quite common in the early days of dive computers: for e.g. there was a product in Europe which could only interpolate linearly between stored values instead of calculating a full-blown saturation/desaturation. But even today there are implementations which rely on a modified ZH-L instead of the promised (advertised) RGBM model ...

But it seems that there are implementations taking this topic seriously. Amongst others there is a shareware with a VPM model (http://www.decompression.org/maiken/VPM/VPM_Algorithm.htm): „The analytic, logarithmic expression for stop times ... was replaced with a numerical solution of the restriction on the sum of He and N_2 partial pressures."

Conclusions

What shall we do with these, admittedly rather theoretical considerations? By no means this should be made a public example for the developers. And in no case there is ample evidence to draw any solid conclusions, as described above. These are the reasons not to reveal any brand names. As well there is to consider, at least in Germany, the fair trade law, especially the §§ 4, 5 and 6.

But the situation stays very unsatisfying concerning the intransparent status of some implementations and the lack of open documentation of the „defaults“ and constants. To put it in tec-lingo:

<u>Is there really a ZH-L inside when the label reads ”ZH-L”???</u>

But the clear message is the following: a decompression time in a digital display, be it on a dive computer or a PC, is subject to interpretation! And this not so much due to errors in the measurements (pressure, time, temperature, ...) and other statistical contemplations but rather due to the method of programming and the choice of a solution for a mathematical algorithm; i.e.: the software technology, the implementation. The range for these interpretations is not only in ppm or per mill but rather, dependent on the inert gas dose and the helium fraction , in the one- or even two digit percent range …

To answer the question posed in the title finally:

1) Yes, with gradient factors we could repair defective perfusion algorithms. But the perfusion models work by far more satisfying than the topical hype around the bubble models tells. To underline this one with a historical one-liner:

<u>“Haldane works if you use it properly!”</u>

(R.W. Hamilton, Decompression Theory: 17th UHMS workshop, p. 135; 1978)

2) Yes, we need gradient factors to haul up to the safe side bad or negligent implementations for mix gases!

In a nutshell we have it here for a dive (depth 42 m, bottom time 25 min, mix: 20 % O_2, 80 % He) on chart (3): it is a screen copy of DIVE Version 3_0:

```
maximale Ceiling: 12.56
Vorschlag Haldane 2:1 [m] =   15
Vorschlag Hills, B. A.: DEEP STOP [m] =   27
PDIS fuer TAU =  15.98 min:  27.76 [m]
PDIS fuer TAU =  23.44 min:  21.89 [m]
PDIS fuer TAU =  34.67 min:  16.44 [m]
Eingabe der Austauchstufe in Metern & cm:(m.cm):
          Austauchstufe ist zu hoch:
          niedriger wie Ceiling waehlen!
 Deko Prognose:
15m Stopp Prognose Dekozeit:  1.00  Komp.#:  5
12m Stopp Prognose Dekozeit:  3.00  Komp.#:  5
 9m Stopp Prognose Dekozeit:  8.00  Komp.#:  7
 6m Stopp Prognose Dekozeit: 15.00  Komp.#:  8
 3m Stopp Prognose Dekozeit: 33.00  Komp.#: 10
TTS =   64.00
 Deko Prognose numerisch:
15m Stopp APPROXIMATION :       .25 Steps N=      1.
12m Stopp APPROXIMATION :      3.25 Steps N=     13.
 9m Stopp APPROXIMATION :      7.75 Steps N=     31.
 6m Stopp APPROXIMATION :     14.75 Steps N=     59.
 3m Stopp APPROXIMATION :     48.00 Steps N=    192.
TTS =   78.20
 Deko Prognose mit Gradientenfaktoren:  GFHI=    .9
18m Stopp Prognose Dekozeit:  3.00  GF =    .65  Ko
15m Stopp Prognose Dekozeit:  3.00  GF =    .70  Ko
12m Stopp Prognose Dekozeit:  6.00  GF =    .75  Ko
 9m Stopp Prognose Dekozeit: 10.00  GF =    .80  Ko
 6m Stopp Prognose Dekozeit: 20.00  GF =    .85  Ko
 3m Stopp Prognose Dekozeit: 47.00  GF =    .90  Ko
TTS =   93.00

 was jetzt? * * * 42 m, 25 min, 20 % 02, 80 % He *
```

Chart (3)

At first we see a couple of deep stop strategies and then the projection in details: the 1st. block (according to method B) with the deco stages and the TTS @ ca. 64 min is likely to be found with the COTS programs. The 2nd block (TTS = 78, method A) is the numerical solution, not truncated. For a printed table or a COTS product the rounding-on at every deco stage would result in a TTS of ca. 81 min. Application of gradient factors (block 3) with for eg. GF high = 0,9 and GF low = 0,65 yields a TTS of ca. 93 min. Thus feigning a safety buffer of 93 – 64 = ca. 30 min which we do NOT have in reality, because the „real" numerical solution converges @ ca. 81 min.

Thus the deviations are in an order of magnitude where even the differences between the various deco models / algorithms become blurred, pls. look at table A in: http://www.divetable.de/workshop/Vergleich2_e.pdf. The discussions on which model is „better" and which became here and there sometimes overheated could now be put into a cooler context. To put this one as well into tec-lingo:

„It doesn't matter which model you use, provided it has a sound implementation!" (© Albi, CE 2009)

Acknowledgements

are for the entire crew of GTUEM for the possibility to give a lecture on this topic at the 12th scientific meeting of the GTUEM 03/20/2011 in Regensburg/Germany. Especially to Willi W. (Prof. Dr. Willi Welslau, president of GTUEM, Vienna) for a constant peer review and to Jochen D. (Prof. Dr. Jochen D. Schipke, University Medical Center for experimental surgery, Duesseldorf) for the lot of editorial work and for patience with my oft unorthodox approach. As well to a couple of my tec-diving students in Eilat/Israel for fiddling about the deco softwares...

References

The numbers in square brackets [ ] relate to the corresponding entry in a book list at: http://www.divetable.de/books/index_e.htm

The other internet links are pointing to the abstract page at the Rubicon research repository: http://archive.rubicon-foundation.org/

The sources for the perfusion algorithms are the following, generally well-known and respected and the already cited famous standard books of diving medicine, pls. cf.: CAISSON 2010; 25(1): 9;

- Boycott, A.E., Damant, G.C.C., & Haldane, J.S.: The Prevention of Compressed Air Illness, Journal of Hygiene, Volume 8, (1908), pp. 342-443
  http://archive.rubicon-foundation.org/7489

- Workman, Robert D. "Calculation of Decompression Tables for Nitrogen-Oxygen and Helium-Oxygen Dives," Research Report 6-65, U.S. Navy Experimental Diving Unit, Washington, D.C. (26 May 1965)
  http://archive.rubicon-foundation.org/3367

- Schreiner, H.R., and Kelley, P.L. "A Pragmatic View of Decompression," Underwater Physiology Proceedings of the Fourth Symposium on Underwater Physiology, edited by C.J. Lambertsen. Academic Press, New York, (1971) pp. 205-219

- Müller, K. G.; Ruff, S.:

- Experimentelle und Theoretische Untersuchungen des Druck-Fall Problems, DLR, Forschungsbericht 71-48, Juli, 1971; as well:
- Theorie der Druckfallbeschwerden und ihre Anwendung auf Tauchtabellen, DVL / Bericht – 623/ 1966

[4] Dekompression - Dekompressionskrankheit, A. A. Bühlmann, Springer, 1983, ISBN 3-540-12514-0

[5] Tauchmedizin (Barotrauma, Gasembolie, Dekompression, Dekompressionskrankheit) A. A. Bühlmann, Springer, 1993, ISBN 3-540-55581-1

[54] Enzyklopädie des Technischen Tauchens, Bernd Aspacher

[62] „Diving & Subaquatic Medicine“, Carl Edmonds, Lowry, Pennefather, Walker, 4 th. Ed., Arnold, ISBN 0-340-80630-3

[63] „Benett and Elliott‘s Physiology and Medicine of Diving“ Alf Brubakk, Neuman et al., 5 th Ed. Saunders, ISBN 0-7020-2571-2

[64] „Textbook of Hyperbaric Medicine.“, Kewal K. Jain; 3rd. Revised Ed., Hogrefe & Huber, ISBN 0-88937-203-9

[65] Tauchmedizin, Albert A. Bühlmann, Ernst B. Völlm (Mitarbeiter), P. Nussberger; 5. Auflage in 2002, Springer, ISBN 3-540-42979-4

[75] “Bove and Davis’ DIVING MEDICINE”, Alfred A. Bove, 4 th. edition, Saunders 2004, ISBN 0-7216-9424-1

[102] Hills, Brian Andrew (1977), Decompression Sickness, Volume 1, The Biophysical Basis of Prevention and Treatment, John Wiley & Sons, Ltd.. ISBN 0 471 99457 X.

[113] Naval Forces Under the Sea: The Rest of the Story; 2007, Best Publishing Company, ISBN-13: 978-1-930536-30-2, ISBN-10: 1-930536-30-5

Berghage TE (ed). Decompression Theory. 17th Undersea and Hyperbaric Medical Society Workshop. UHMS Publication Number 29WS(DT)6-25-80. Bethesda: Undersea and Hyperbaric Medical Society; 1978; 180 pages. http://archive.rubicon-foundation.org/7986

Berghage, T.E., T.D. David and C.V. Dyson. 1979, Species differences in decompression. Undersea Biomed. Res. 6(1): 1 – 13 http://archive.rubicon-foundation.org/2837

Bronstein – Semendjajew: Taschenbuch der Mathematik, Verlag Harri Deutsch

D’Aoust, B.G., K. H. Smith, H.T. Swanson, R. White, L. Stayton, and J. Moore. 1979, Prolonged bubble production by transient isobaric counter-equilibration of helium against nitrogen. Undersea Biomed. Res. 6(2): 109 -125 http://archive.rubicon-foundation.org/2840

Egi SM, Gürmen NM. Computation of decompression tables using continuous compartment half-lives. Undersea Hyper Med 2000; 27(3): 143 – 153. http://archive.rubicon-foundation.org/2341

Kindwall, EP. Compressed air tunneling and caisson work decompression procedures: development, problems, and solutions. Undersea Hyperb. Med. 1997 Winter; 24(4): 337 – 345, http://archive.rubicon-foundation.org/2267

Lightfoot EN, Baz A, Lanphier EH, Kindwall EP, Seireg A. Role of bubble growth kinetics in decompression. In: Shilling CW, Beckett MW, eds. Underwater physiology VI. Proceedings of the sixth symposium on underwater physiology. Bethesda, MD, 1978: 449 – 457

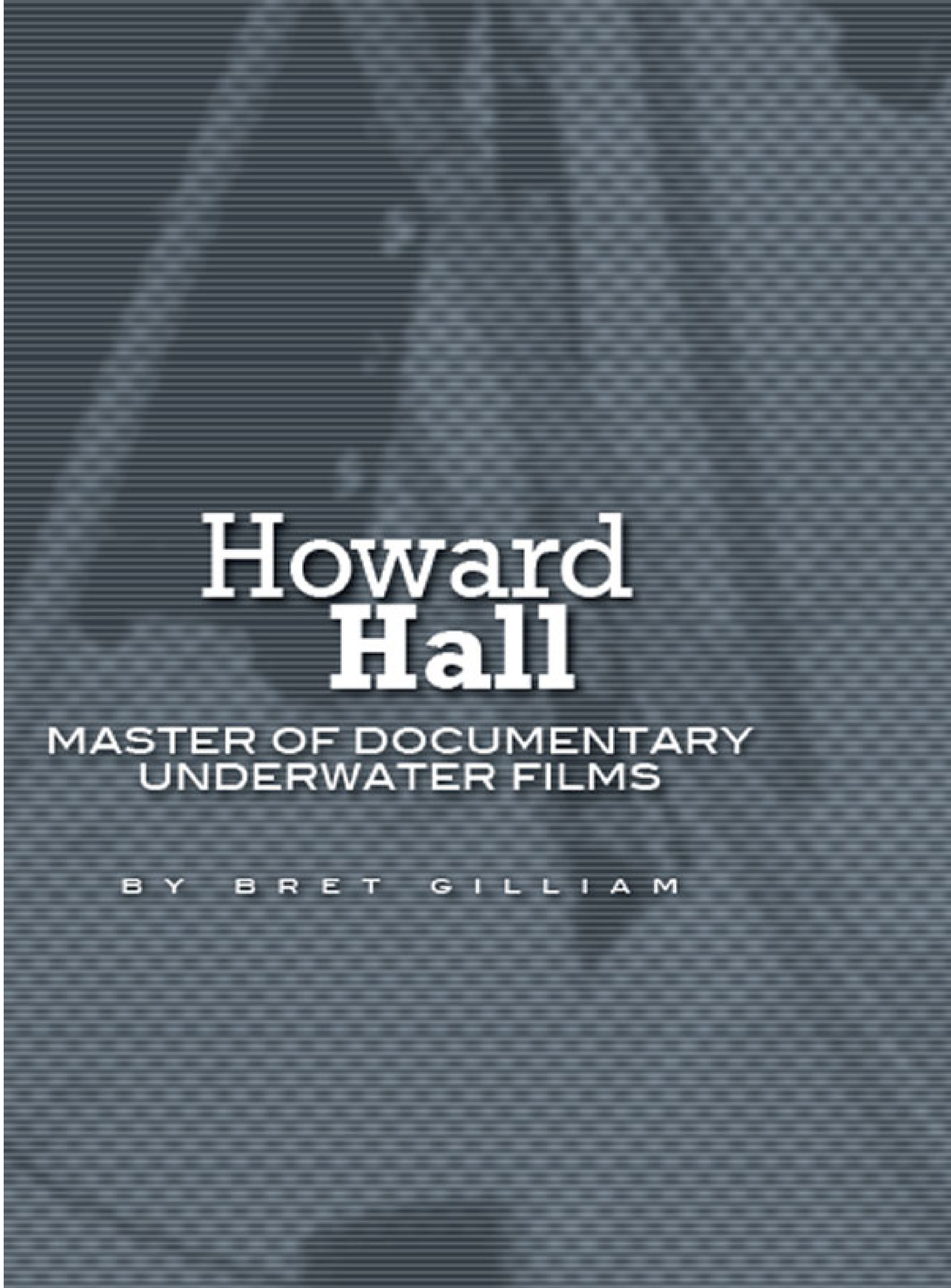
Ljubkovic M, Marinovic J, Obad A, Breskovic T, Gaustad SE, Dujic Z. High incidence of venous and arterial gas emboli at rest after trimix diving without protocol violations. J Appl Physiol 109: 1670 - 1674, 2010

Moon RE, Piantadosi CA, Camporesi EM (eds.). Dr. Peter Bennett Symposium Proceedings. Held May 1, 2004. Durham, N.C.: Divers Alert Network, 2007 http://archive.rubicon-foundation.org/9053

Rodchenkov SV, Skudin VK. Saturation decompression schedules based on a critical tissue supersaturation criterion. Undersea Biomed. Res. 1992; 19(6): 472 – 481 http://archive.rubicon-foundation.org/2736

Voitsekhovich, I. A mathematical decompression model based on biophysical and physiologic laws. Undersea Hyperb. Med. 1994 Jun; 21(2): 209 - 13. http://archive.rubicon-foundation.org/2400

COCHRAN Consulting Inc.; www.divecochran.com
COMEX: Compagnie Maritime d'Expertises; www.comex.fr
DAN: Divers Alert Network; www.dan.org
DCIEM (old label, now): Defence Research and Development Canada; www.drdc-rddc.gc.ca
Journal of Applied Physiology: http://jap.physiology.org/
NEDU: Navy Experimental Diving Unit; www.supsalv.org/nedu/nedu.htm
NOAA: National Oceanic and Atmospheric Administration; www.noaa.gov (resp. NOAA diving: http://www.ndc.noaa.gov/)
OSHA: Occupational Safety and Health Administration; http://www.osha.gov/, (the topical caisson tables are at: Part Number 1926.)
UHMS: Undersea & Hyperbaric Medical Society; www.uhms.org



post-publication comment on:

Dive Risk Factors, Gas Bubble Formation, and Decompression Illness in Recreational SCUBA Diving: Analysis of DAN Europe DSL Data Base

https://doi.org/10.3389/fpsyg.2017.01587

This work of european DAN is not only intellectualy stimulating but as well of paramount importance to the further development of safety for recreational divers. It may also help to mitigate the somewhat heated and superfluous debate in the (technical) diving community as to which decompression model (perfusion, diffusion, dual phase) or which dive computer might be the best.

Nevertheless there are a couple of boundary conditions which will probably evade the non-diving reader.

1a) The 83 : 17 relation of participants, which yields a ratio of ca. 4,9 of males over females is an imbalance which probably may not reflect properly the european recreational divers population. This might be a first indicator of a biased database.

1b) As well the „mean" age seems to reflect a somewhat non-standard diver population; the majority of divers being usually younger. As per nearly all human activities, there is a drop-out rate: for ca. one instructor/TEC/advanced diver there are approx. 100 freshman. So here the beginner and intermediate diver population seems to miss.

1a & 1b could be checked against the statistics of the issued diver certifications of the major training agencies like PADI and/or SSI.

2) 320 cases of DCS would yield:

- ➔ an average rate of ca. 64 p.a.
- ➔ and an overall rate of 320 / 39.099 of ca. 0,81 % which, both, are substantially more than reported elsewhere (ca. 1: 10.000 in [1], p.544; and as well in [2], p. 151).

Certainly, the divisor is not known and the rates are taken as a surrogate. And, as well, other, more elaborate studies, would reveal, for eg.: **Decompression illness in divers treated in Auckland, New Zealand, 1996-2012.** (Ref.: https://www.ncbi.nlm.nih.gov/pubmed/24687481): that there are 520 DCI cases in 17 years, which would equate to ca. 31 p.a. and thus yield a factor of ca. 2 lower.

Similarily a recent study showed (Ref.: Svendsen Juhl C, Hedetoft M, Bidstrup D, Jansen EC, Hyldegaard O. Decompression illness treated in Denmark 1999–2013. Diving and Hyperbaric Medicine. 2016 June;46(2):87-91.) 205 DCI cases over 15 years; reduced to recreational cases, the rate is ca. 11 p.a. The factor male/female ca. 3.8. This study reveals that ca. 80 % of the DCI victims are up to an intermediate certification level, and ca. 50 % consider themselves as with relatively little experience.

Another example, albeit taken from the military diving community (**DJRS, the Dive Jump Reporting System of USN** (United States Navy); Ref.: http://divingresearch.scripts.mit.edu/militarydivingdata/) which sports with with 4 cases of DCS and 5 of missed decompression out of 768,851 dives, collected from 2008 to 2015.

This might be as well a 2nd. indicator of a biased database.

3) 39,099 dives per 2,629 divers would yield ca. 15 dives per diver. It might be somewhat speculative, but 15 dives out of an average diving carreer do probably not represent an average sample concerning both dive depth an dive time. Thus this could imply that the uploaded samples have been the most recent ones or the most spectacular ones (with a topical tendency from October 2017 of 63.248 from 5.326 divers, giving an average of 12, sinking). Especially when considering that approx. 15 to 20 individuals, each donating in the average ca. 500 dives, thus contributing a substantial amount of profiles and thus decreasing the average of the rest.

4) Studies with volunteer participants regularly imply often a self-selected group, the sample usually not reflecting the real population. This could imply another, i.e. the 3rd. bias: participants which like to deal with the technical pecularities of transferring log-files from a dive computer to a PC, then converting the stored dive log-files to a DAN compatible format, then uploading these files from the PC to the DAN DSG portal and finally filling in the ca. 20 statements per uploaded dive.

5) The average dive depth / dive time given as mean ± standard deviation, would imply, at least for a somewhat naive reader, sort of normal distributions for these variables, which would be, in my personal experience,

relatively unprobable. Otherwise the study fails to reveal the statistical connection between diver B doing a dive in country X to depth z with a buddy-pair C, diving in country Y to depth to 0,5 * z with diver A (me) contributing in country DE a controlled dive in a decompression chamber to depth 2 * z, the mean being clearly z, but obviously of only limited intellectual value (Ref.: https://www.divetable.info/skripte/50m_deco.pdf. The funny side of things is that these profiles normally earn a big yellow smiley in the DAN DSG portal, thus warning of an already medium DCS risk).

For eg. the above cited USN study reveals clearly skewness, with a slope (note the log scale!) from shallow to deep and more probably of a certain Poisson type than Gaussian. <u>Thus, a frequency analysis in appropriate classes (depth bins with 5 or 10 m resp. for the dive time) would have given a clearer picture.</u>

6) As well the mean of 27.1 m (range 5–104), where the .1 is clearly a statistical artefact, which could have been dropped happily: dive computers tend to give the first digit not precisely. Anecdotal reports [3], [4] and controlled laboratory experiments [5], [6] indicate this very clearly. Additionaly, a lot of dive computer manufacturers fail to demonstrate a proper temperature drift compensation for their products.

The value of 27 could be as well an indicator of a certain bias: the suspected missing of beginner and intermediate dive-profiles, being in the 6 to 18 m range for beginners and in the 15 to 30 m range for intermediate divers. Even more so, when considering beginner and intermediate divers as relatively neutral to decompression-theories, -calculation and -tables; some of them not even owning a dive computer.

7) To exclude Trimix makes sense, probably there is another mechanism of bubble arterialisation and other inert gas kinetics due to Helium (for the non-diving reader: Trimix is a breathing gas, consisting in various fractions of the 3 gases Oxygen, Helium and Nitrogen (thus Tri-), whereas simple compressed Air or Nitrox are not.) As well the ZH-L framework from Buehlmann et al. [7], used in this study, has been, up to now, not really challenged with trimix for multi-level diving. (And b.t.w. this algorithm is diverging around a compartment half-time of 1,005 min, which, used unmodified, would render it useless for the intended analysis of breathhold diving).

8) Dives, for eg. to 104 m depth on air, will yield profiles of an extreme spike form which are probably not in line with common diver behaviour, be it recreational, military or commercial: the limitation of breathing gas supply makes bottom times very short, especially when dived with a single tank; which the study tacitly implies. If done otherwise, the study should reveal it.

9) Also, for the non-diving reader: a dive on Air in the 3-digit range is subjected to inert gas narcosis, which is likely to start beyond 40 m and oxygen toxicity, beyond 80 m, which makes these profiles, operationally wise, not only relatively dangerous, but, to put it mildly, somewhat „experimental“: the ascent and descent rates are not in line with standard procedures. <u>Thus one could question the statistical wisdom of not excluding these experimental dives.</u>

10) In conclusion, the study leaves open a couple of questions resp. room for improvement:

- ➔ Diver biometrics and dive circumstances are entered through the divers themselves. How is the quality of these inputs assessed?
- ➔ Screening for PFO or other individual susceptibilities?
- ➔ Blinding of operators, recieving the doppler signals? Control group?
- ➔ Table 3 reveals a conundrum of multi-collinearity: how is this adressed?

11) Nobody should be caught by surprise, that the mapping of a deterministic perfusion model (ZH-L) to a stochastic phenomenon (DCS) is of only limited success. Thus the relative failure of printed decompression tables or dive computers. Once again, as per remark # 7, the ZH-L (or, basically all perfusion models) was never really challenged with extended multi-level or reversed dive profiles, common in recreational diving. The described modifications ([7], p. 157, 196) to allow for real-time calculation being marginal: the clear message is that the M-values (or, in ZH-L parlance, the a- & b coefficients) derived from box-profiles, and, maybe, the spectrum of compartment half-times need repair.

This even more so, when considering that dive computers are „black boxes“ for the diver: leaving the user completely in the dark, how a decompression algorithm is implemented and which constants are used. Thus it is also of no surprise that for a given box-profile the calculated stop times for the decompression stops differ easily with a factor of 4 to 8; even if the manufacturers in question claim to have implemented a „real ZH-L“ (Ref.: https://www.divetable.info/skripte/HBO-RMT.pdf and [10]).

One of the really important findings is, that the dives seem to be basically in the „safe zone“: thus nobody should be caught by surprise, that the group of „medium“ compartments is involved. The mentioned slower ascent rate, although not specified in the study, and „deep“ or deeper and longer stops, give the fast compartments time to de-saturate while the medium and slow ones still saturate. For real world recreational diving, the take home message seems to be:

„If you go slow, go even slower!“ (especially in the shallow 9 to 6 m zone).

12) Now, finally in taking points # 1) to 4) as a basis, chances are that there could be a bias of the actual database; one of the confounding factors being diver experience and another one the liking of handling purely technical problems. My private speculation and personal experience is, that this relatively special group of highly trained and motivated (mediterranean) divers, which dedicates a lot of their spare time for the DAN DSG portal tends to dive in a way that is, in some way or another, disjunct with the population of recreational divers, thus prone to a higher rate of DCS.

I would not go so far as with Altman, who states: „Misuse of statistics is unethical, as well it is shoddy science.“ [8]; but clearly a couple of tenthousand non-DCS dives with moderate time/depth profiles have to be added. As well a functional peer-review process, in-line with established statistical thinking would be a benefit.

References:

[1] Bennett and Elliott's Physiology and Medicine of Diving, Alf Brubakk, Neuman et al., 5 th Ed. Saunders,

ISBN 0-7020-2571-2

[2] Bove and Davis' DIVING MEDICINE, Alfred A. Bove, 4 th. edition, Saunders 2004,

ISBN 0-7216-9424-1

[3] https://www.divetable.info/skripte/Ox_Tox.pdf

[4] https://www.divetable.info/skripte/G2_OX_TOX.pdf

[5] UHMS: ASM 2012, Session F118; NOT ALL ARE CREATED EQUAL – OPERATIONAL VARIABILITY IN 49 MODELS OF DIVING COMPUTER. Azzopardi E, Sayer MDJ, UK National Facility for Scientific Diving, Scottish Association for Marine Science, Dunstaffnage Marine Laboratories, Dunbeg, Oban, Argyll, Scotland

[6] Elaine Azzopardi and Martin Sayer (2012) Estimation of depth and temperatures in 47 models of diving decompression computer. International Journal of the Society for Underwater Technology, Vol. 31, No. 1, pp 3 - 12

[7] Tauchmedizin, Albert A. Bühlmann, Ernst B. Völlm (Mitarbeiter), P. Nussberger; 5. Auflage in 2002, Springer, ISBN 3-540-42979-4

[8] Douglas G. Altman: Misuse of statistics is unethical, BMJ, 281, 1. Nov 1980, p. 1183

[9] Edmonds, Carl; Bennett, Michael et al.(2016) Diving and Subaquatic Medicine, Fifth Edition, CRC Press; ISBN 978-1-4822-6012-0

[10] Salm, A. (2012) Variations in the TTS: where do they come from? International Journal of the Society for Underwater Technology, November 2012. SUT, Vol. 31, No. 1, pp. 43 - 47, 2012

doi:10.3723/ut.31.043 International Journal of the Society for Underwater Technology, Vol 31, No 1, pp 43–47, 2012

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; Hahn, 1995; Bühlmann et al., 2002). 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 employed 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:

- only inert gas loading;
- mono-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
- mono-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 (Lightfoot et al., 1978; D'Aoust et al., 1979; Rodchenkov and Skudin, 1992). Especially in newer experiments, the perfusion rates are viewed quite differently (Doolette et al., 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 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)

40m, 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

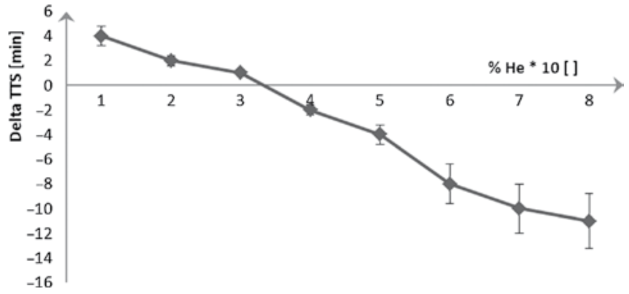

Fig 1: Delta TTS versus percentage of He in the breathing mix dive to 40m with a bottom time of 40min

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 with positive 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 other 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 is 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 is 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 above); 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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References

Berghage TE, David TD and Dyson CV. (1979). Species differences in decompression. *Undersea Biomedical Research* **6**: 1–13.

Boycott AE, Damant GCC and Haldane JS. (1908). The Prevention of Compressed Air Illness. *Journal of Hygiene* **8**: 342–443.

Bronstein IN and Semendjajew KA. (1979). *Taschenbuch der Mathematik.* Frankfurt: Verlag Harri Deutsch.

Brubakk A and Neuman T.S. (2003). *Bennett and Elliott's Physiology and Medicine of Diving*, 5th edition. London: Saunders, 800pp.

Bühlmann AA. (1983). *Dekompression – Dekompressionskrankheit.* Berlin: Springer.

Bühlmann AA. (1993). *Tauchmedizin: Barotrauma, Gasembolie, Dekompression, Dekompressionskrankheit.* Berlin: Springer.

Bühlmann AA, Nussberger P and Voellm E. (2002). *Tauchmedizin*, 5th. edition. Berlin: Springer.

D'Aoust BG, Smith KH, Swanson HT, White R, Stayton L and Moore J. (1979). Prolonged bubble production by transient isobaric counter-equilibration of helium against nitrogen. *Undersea Biomedical Research* **6**: 109–125.

Doolette DJ, Upton RN and Grant C. (2005). Perfusion-diffusion compartmental models describe cerebral helium kinetics at high and low cerebral blood flows in sheep. *The Journal of Physiology* **563**: 529–539.

Hahn MH. (1995). Workman-Bühlmann algorithm for dive computers: A critical analysis. In: Hamilton RW. (ed.). *The effectiveness of dive computers in repetitive diving.* UHMS workshop 81(DC)6-1-94. Kensington, MD: Undersea and Hyperbaric Medical Society.

Hills BA. (1977). *Decompression Sickness: The Biophysical Basis of Prevention and Treatment*, vol 1. New York: John Wiley & Sons.

Joiner J, Russell J and Lasky K. (eds.). (2007). Naval Forces Under the Sea: The Rest of the Story. Flagstaff, AZ: Best Publishing Company.

Lightfoot EN, Baz A, Lanphier EH, Kindwall EP, Seireg A. (1978). Role of bubble growth kinetics in decompression. In: Shilling CW and Beckett MW (eds.). *Underwater physiology VI: Proceedings of the sixth symposium on underwater physiology.* Bethesda, MD: Undersea Medical Society, 449–457.

Müller KG and Ruff S. (1966). Theorie der Druckfallbeschwerden und ihre Anwendung auf Tauchtabellen, DVL/Bericht – 623.

Müller KG and Ruff S. (1971). Experimentelle und Theoretische Untersuchungen des Druck-Fall Problems, DLR, Forschungsbericht 71–48.

Rodchenkov SV and Skudin VK. (1992). Saturation decompression schedules based on a critical tissue supersaturation criterion. *Undersea Biomedical Research* **19**: 472–481.

Schreiner HR and Kelley PL. (1971). A Pragmatic View of Decompression. In: Lambertsen CJ (ed.). *Underwater Physiology IV: Proceedings of the Fourth Symposium on Underwater Physiology.* New York: Academic Press, 205–219.

Workman RD. (1965). Calculation of Decompression Tables for Nitrogen-Oxygen and Helium-Oxygen Dives. Research Report 6-65. Washington, DC: U.S. Navy Experimental Diving Unit.