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Technical Briefing

Dive computer decompression models and algorithms: philosophical and practical views

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Abstract

The functioning of diving decompression computers is based on predictive models that are made operational through algorithms. Relatively simple models can be constructed to manage diving decompression obligations with a high degree of confidence, as long as the dive profiles fall within the model's 'range of applicability'. The same degree of confidence cannot be assumed where dive profiles are outside of that range – for instance by diving deeper, or for longer or more frequently than what had been considered in the development of the model, or because of individual physiological particularities. A common method to deal with this is to increase the level of conservatism of the model by reducing inert gas load. Depending on the dive computer, this is achieved by allowing the diver to set predefined 'personal levels' or through 'gradient factors', which is a more transparent method of obtaining a reduced inert gas load at the end of a dive. This paper outlines models and algorithms in general, and then discusses gradient factors in further detail.

Keywords: dive computers, decompression models, decompression algorithms, range of applicability, *M*-values, gradient factors

1. Introduction

1.1. Distinction between model and algorithm

In its simplest form, a model is a mathematical representation of a physical event, while an algorithm is the coding of the model in a form that can be solved by a microprocessor. Models are developed in order to predict future outcomes, and algorithms are the tools to calculate this outcome based on given initial or boundary conditions.

Developing a model requires strong understanding of, and insight into, the phenomenon that is being reproduced. Moreover, the key to developing a good model is the ability to capture the essential aspects of the phenomenon and to identify those aspects that are, if not negligible, at least less relevant to the final result. For example, one could start with basic laws of physics such as conservation of mass, momentum and energy, applying them to the process at hand and deciding that, for the process being considered, heat transfer by radiation could be neglected in favour of conduction and convection because of the low temperatures involved. Radiation is very complex to model, computationally intensive for a microprocessor and only significant when temperatures are very high. Thus, when modelling the heat exchange of a first-stage regulator in water, the impact of radiation could be neglected, resulting in a simplification of the model without loss of accuracy in the result.

Writing an algorithm, on the other hand, requires a strong mathematical background and advanced programming skills. So modelling is really the world of physics and physicists, while writing algorithms is the world of programmers. Mathematics is a fundamental bridge between the two, because a physicist who cannot put their model into a mathematical formulation will not be able to communicate their ideas. Similarly, a programmer who cannot apply, for example, Taylor expansions will not be able to turn the formulas into step-by-step commands.

1.2. Empirical models

A model can be heavily based on theory, but some models are purely empirical, i.e. based primarily on observations of physical phenomena and interpretation thereof. An empirical model does not necessarily have to be correct to yield the correct results – that is, an empirical model can give the right results for the wrong reasons.

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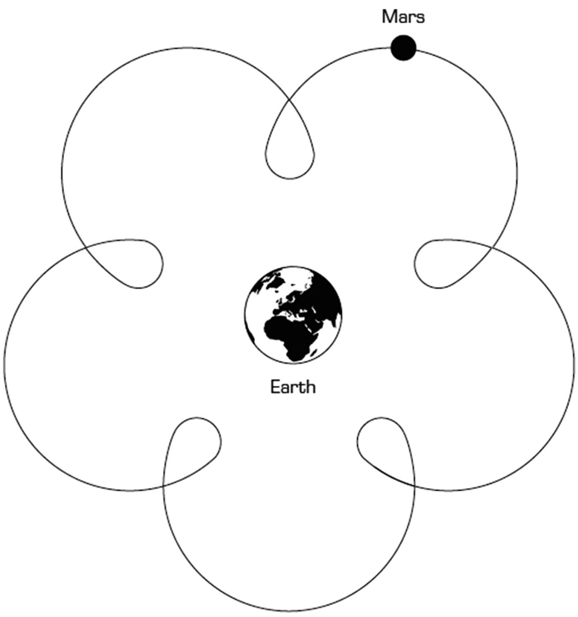

Fig 1: Ptolemy's prediction of the movement of Mars around the Earth

An example of this is Ptolemy and his predictions of the position of Mars with respect to the green planet in his Earth-centred model: here Mars revolves around the stationary Earth in a flower-shaped pattern, as depicted in Fig 1 (inspired by Singh, 2004). We know this to be completely wrong, but Ptolemy was able to predict with good accuracy where the planet would be in a week or three months. By having enough data points obtained from observing a certain phenomenon, it is possible to build a model that will yield exactly those data points. The constant repeatability of the motion of the planets lends itself beautifully to this approach because, once observed, a data point will reoccur at defined intervals and, once the model has been fitted to account for that data point, it will be perpetually correct.

This lends credibility to the model in spite of it being erroneous. This approach is called 'data fitting' and is based on empirical observations only. The model can be incorrect, as in this case, but it is difficult to dispute it since it continues to give accurate predictions. Galileo tried to dispute it, but when it became apparent that he was to follow Giordano Bruno's fate – who was burned at the stake for heresy – he recanted (Aquilecchia, 2017). But he left us the exquisite *e pur si muove* ("and yet it moves") expression.

1.3. Range of applicability

Data fitting can lead to mistaken interpretations, which in turn can lead to disastrous consequences. The field of observation must be wide enough to give some confidence that what is being observed is not just a detail within a much bigger picture. Therefore, a fundamental concept in modelling, especially in empirical modelling, is the definition of a 'range of applicability'. This is the range within which there is a high degree of confidence that the model will yield useful results.

In an empirical model, the range of applicability is the most important concept to consider. Generally, interpolating is safer than extrapolating. When interpolating, two data points are inside the range of applicability and a new one is fit in between the two existing data points, thus staying *within* the range of applicability. Conversely, when extrapolating, two or more data points are inside the range of applicability and the position of a point *outside* of that range is guessed. If data on dives to 30 m and 40 m are available, they can be used to make an educated guess for what happens at 35 m, but the same cannot be said for dives to 80 m.

1.4. Decompression models

Physical events governed by laws of physics can be complex to model, but in most cases experiments can be set up to yield reproducible data with which to determine the validity of the model. A decompression model, however, adds physiology into the mix, and this carries a lot of complications with it. One first has to develop a model of the human body, and then model decompression and decompression illness on top of that.

A mathematical representation of the human body is probably possible, but incredibly difficult if everything is to be taken into account. Aside from physical phenomena such as blood flow, gas diffusion, bubble formation and growth, there are a plethora of chemical processes taking place as well. On top of this baseline complexity, physiology varies not only from individual to individual, but also for the same individual from one day to the next. Sleep, hydration and nutrition are just a few aspects that influence how a person will react to external stimuli. Wanting to put all this into a set of mathematical formulae is quite a daunting task.

At present, there are essentially two types of decompression models†: dissolved gas models and bubble models. For simplicity's sake, this paper restricts itself to binary mixes as breathing gas (oxygen and an inert gas, such as nitrogen or helium). Conceptually, it applies to trimix as well, although there are some other factors that may be

† In addition, there are probabilistic decompression models, in which parameters of known statistical models are fitted to a set of empirical data concerning decompression illness incidences in subjects exposed to various decompression profiles. These are not commonly found in dive computers and therefore not covered in this paper.

important with regard to trimix such as isobaric counter diffusion.

A dissolved gas model describes the human body as a number of tissues or compartments, each of which is defined by two parameters. One parameter defines how quickly the tissue absorbs and off-gases the inert gas in the breathing mix (tissue half-time), and the other defines how much overpressure of this gas the tissue can tolerate before a controlling criterion is broken (maximum tolerated supersaturation, also known as *M*-value). In a bubble model, one or more bubbles are tracked as they grow or shrink during the dive as a result of gas migrating in or out of it, caused by changes in ambient pressure and breathing gas. In such models, the controlling criterion is the size of the bubble(s).

The dissolved gas model essentially dates back to 1908, when John Scott Haldane and his team published a paper on experiments carried out on goats (Boycott et al., 1908). This established the foundation of what is still very much in use today, and is generally referred to as the Haldanian model. The Haldanian model is brilliant for its simplicity and its flexibility in adapting to additional conservatism. Over the years, numerous studies have been carried out by the US Navy, Dr Bühlmann in Zürich and others, all aimed at better correlating the empirical data. They have mostly focused on redefining the number of tissues with which to represent the body; the tissues' respective half-times and *M*-values; and the difference in speed between absorbing and releasing the inert gas, e.g. the Exponential-Linear model in the V-VAL 18 (Thalmann, 1983). Since development of the Haldanian model, two world wars took place, astronauts landed on the moon and the internet was invented. Yet the most widely accepted decompression model still stands as it did 110 years ago.

This model has its limitations and certainly cannot be used to extrapolate results outside of its range of applicability. Still, when comparing the staggering difference between the simplicity of the Haldanian model and the complexity of the human body, it is impressive that it still provides useful results as the historical records on diving safety demonstrate. Implementing this model in a dive computer means that, for each tissue, every few seconds a simple equation is calculated and the results are compared with the maximum overpressure tolerated by the tissue itself. This is easily done by just about any microprocessor.

Bubble models started with the research of David Yount at the University of Hawaii (Yount et al., 2000). As technology advanced and Doppler recorders or ultrasound imaging became available, it became obvious that in many, if not all, dives (even those with no symptoms of decompression illness), a portion of the inert gas absorbed during the dive is released in the form of bubbles in the tissues or blood stream. The idea behind the model was to track a hypothetical bubble in its evolution during a dive as a function of the exposure to changing ambient pressure and partial pressures of inert gas.

The research of Dr Yount eventually led to the variable permeability model (VPM). The reduced gradient bubble model (RGBM), by Dr Bruce Wienke of the Los Alamos National Lab (Weinke, 2001), shares its beginnings with the VPM but then diverges. Both are significantly more complex than a straight Haldanian model and require very powerful processors to solve the nonlinear differential equations pertaining to bubble dynamics. And both have been adjusted, at least to some extent, against dive profiles with known outcome, i.e. data fitted, because they lack a comprehensive physiologically correct model of the human body.

1.5. Extending the range of applicability

Over the years, researchers have limited their work to a certain depth range, a certain dive time, and to one repetitive dive (at most), in order to keep testing manageable. For example, 3000 dives would be necessary for the following test parameters:

- Five depth values – say 20 m, 30 m, 40 m, 50 m and 60 m;
- Five values of bottom time – say 10 mins, 15 mins, 20 mins, 25 mins, 30 mins,
- Four profile shapes – square, multilevel forward, multilevel reverse, triangular; and
- Ten testers to perform the dive three times to ensure some kind of statistical significance.

Apply the same parameters for one repetitive dive, with surface intervals of, say 30 mins, 60 mins, 90 mins, 120 mins and 180 mins, and 45 million dives are required.

It is generally accepted that the model works when calibrated against data collated by many researchers throughout the years (notably Workman, 1965; Bühlmann, 1995). Contributions of organisations like Divers Alert Network (DAN) and even training agencies contributing their databases help to extrapolate to a range *outside* of the tested range. After all, several million dives are performed every year and it all adds up to some pretty impressive statistics. We convince ourselves that we can trust our dive computer when we go for the fifth dive of the day on the fourth day of a live-aboard trip. Rarely, decompression illness appears, though the dive computer had given a green light, and we call it an 'undeserved hit.'

Lately, a growing number of divers have been performing long, deep dives, such as exploring cave systems in 24 hr submersions. These dives are outside of the range of any testing (except for research regarding saturation dives, but that's the opposite end of the spectrum), and these pioneering divers have found that the dissolved gas model does not work anymore, at least not in the standard implementation. Making it more conservative is done simply by lowering the tolerated supersaturation, which implies longer and deeper decompression stops for a given exposure. These divers did not go from recreational dives to deep 24 hr dives overnight, but gradually increased the exposure. Incrementally, they found what worked and what did not, and they started providing data points that had been missing until then, conceptually extending the range of the database and allowing modellers to account for these exposures by tweaking their parameters, both in dissolved gas models and in bubble models.

On the dissolved gas side, a prominent contribution is that of Baker (1998). With the introduction of the concept of gradient factors, Baker provided the ultimate transparency in adapting a model. On the bubble model side, RGBM provides some predefined levels of conservatism, while in VPM, the parameters that can be tweaked are available, yet are all but intuitive. But what is interesting is that whether simple or complex, these models owe their functioning not so much to an underlying theory, but to data fitting.

Other aspects concerning the range of applicability are multiday repetitive dives, as well as physiology of the individual. Research by Ljubkovic et al. (2012) points to two main characteristics defining each diver: the propensity to produce bubbles, and the propensity to pass these bubbles from the venous side to the arterial side, whether by patent foramen ovale (PFO[‡]) or pulmonary shunt. Both aspects are unrelated to overall fitness: for example, a fit US Navy diver does not, by default, have less propensity to decompression illness than a desk-bound employee. People fortunate enough not to produce bubbles or not to pass them from the venous to the arterial side, can tolerate dive profiles which would have dire consequences for people that produce bubbles and also pass them easily.

Extending the range of applicability is thus a matter of compensating for the simplifications in the original models, which did not capture all of the essential physics and physiology. Mars does not revolve around the Earth after all. In the absence of a physiologically complete and correct decompression model, such compensation is possible and can be obtained by increasing the conservatism of the model itself.

[‡] A hole in the wall of tissue between the left and right upper chambers of the heart, which allows venous blood to leak into arterial blood before the latter is circulated through the body.

2. *M*-values and pressure gradients

Fig 2 shows the maximum tolerated supersaturation values of nitrogen (*M*-values) for all 16 tissues in the unmodified ZH-L16C model (Bühlmann, 1990) in comparison with the nitrogen partial pressure in the saturated tissues before a dive[§]. The tissues are lined up along the horizontal axis, with half-times increasing (from left to right) from 4 mins (tissue 1) to 635 mins (tissue 16). The vertical axis represents nitrogen partial pressure expressed in bar. The dots represent the partial pressure of nitrogen in each tissue (also called tissue tension) before the dive. As the dive progresses and the diver breathes gas at higher than atmospheric partial pressure, nitrogen will diffuse into the tissues thereby increasing their partial pressure, causing the dots to travel upwards. The triangles represent the values for each tissue which are not to be exceeded upon returning to the surface (*M*-values). A safe dive is defined as one in which either the dots are kept below the triangles or staged decompression stops** are introduced at the end of the dive to bring the dots below the triangles prior to reaching the surface. In essence, for each tissue a limit is imposed on the amount of nitrogen that can be accumulated during the dive and brought back to the surface. And this is at the heart of the Haldane and Bühlmann approach: controlling the amount of nitrogen in each tissue.

This graph represents a significant portion of Bühlmann's work. Haldane had defined the maximum allowed supersaturation as being double the tension tolerated on the surface, and this applied equally to all tissues (his model utilised five tissues, from 5 to 75 mins). Bühlmann's work, and that of others before him, showed that fast tissues can tolerate much more, while slow ones actually tolerate less.

Fast tissues, by definition, will take on nitrogen quickly but because of this they will also start releasing it early on during the ascent. Fig 3 depicts a hypothetical distribution of tissue tensions halfway through a dive profile in which the maximum depth

[§] The value used here is 0.79 bar, i.e. 1 bar atmospheric pressure multiplied by 79 % of nitrogen fraction in the air. In reality one should deduct 5 mbar of water vapor pressure, but this detail is neglected as it does not change the essence of this discussion.

** The term 'staged decompression stop' is used to differentiate a pause during the ascent to offgas excess inert gas as opposed to the decompression a diver undergoes as he or she offgasses nitrogen during the final part of any dive, also a dive within the no decompression limits. In the remainder, when a decompression stop is mentioned, the word 'staged' is implied.

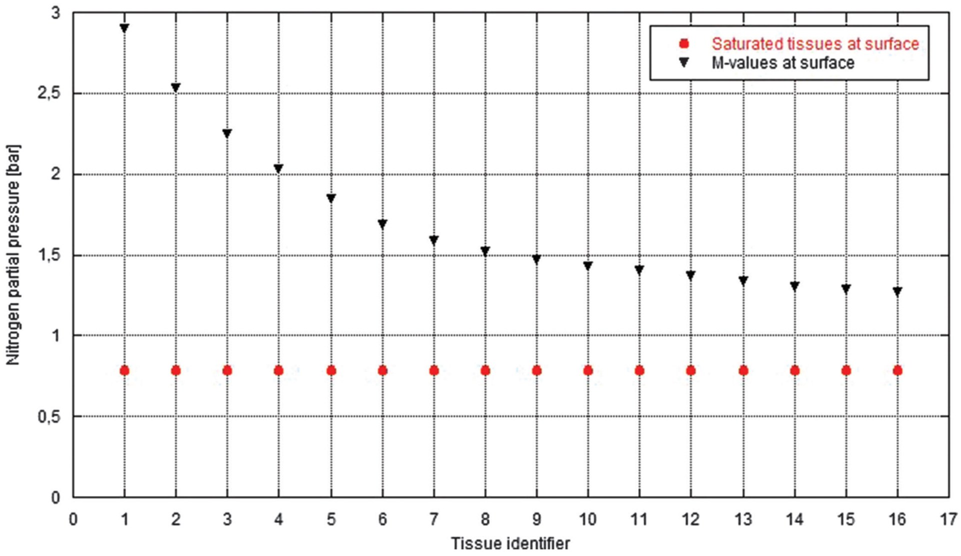

Fig 2: *M*-values in ZH-L16C

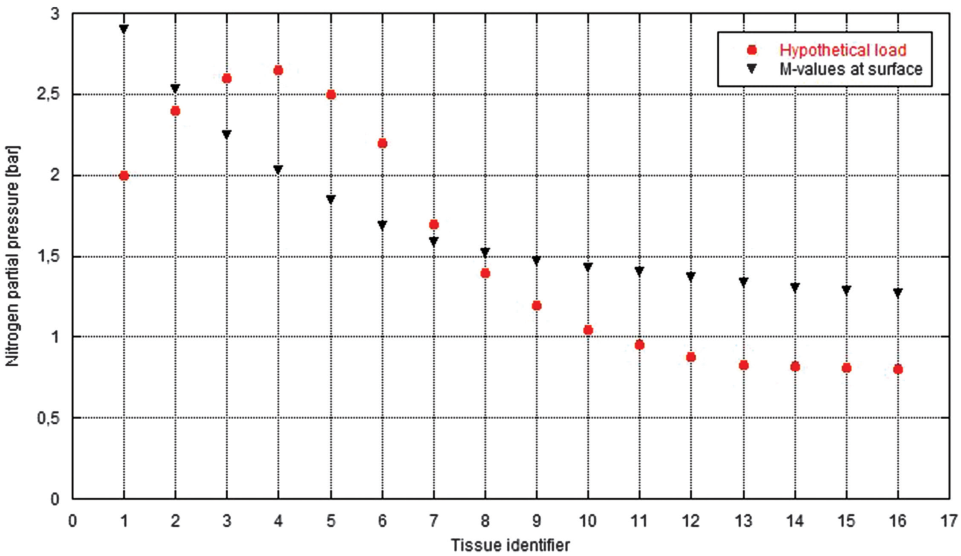

Fig 3: Hypothetical tissue tension distribution

is reached at the beginning and is followed by a slow and gradual ascent. In this particular example, we see that tissues 3 to 7 have tensions above the maximum tolerated value, so these tissues will require one or more decompression stops prior to reaching the surface. In the Haldanian approach, decompression stops are defined in 3 m (10 ft) increments[††], and at each there are corresponding maximum tolerated tissue tensions, relating to the surface value augmented by the increase in ambient pressure.

Fig 4 uses the same hypothetical dive as Fig 3 except the *M*-value triangles are replaced with a line and the *M*-value lines at 3, 6 and 9 m have been added. When a dot is above one of the lines, it means that it has to be brought below that line by stopping at the next deepest stop (e.g. a tissue tension higher than the maximum tolerated supersaturation at 3 m results in a 6 m stop). Fig 4 shows that tissues 3 and 7 only require a 3 m stop, but tissues 4, 5 and 6 also require a 6 m stop. Once these tissues have tensions below the green line, the diver can move up to 3 m and stay there until all dots have fallen below the black line. The diver moves up to the next permissible depth as soon as the next deepest obligation is absolved, in order to maximise the

[††] In the so-called Hills approach (Hills, 1978), there are no predefined decompression stop depths, but rather a continuously evolving ceiling that represents the minimum reachable depth for the current nitrogen load. As tissues offgas this ceiling keeps decreasing. Ideally this method allows for more effective offgassing since one always has the maximum pressure gradient available. In practical terms, there are two disadvantages: one has to constantly track the ceiling and move accordingly in order to take advantage of this effectiveness; and one loses the ability to plan gas consumption based on predefined depths for a certain amount of time.

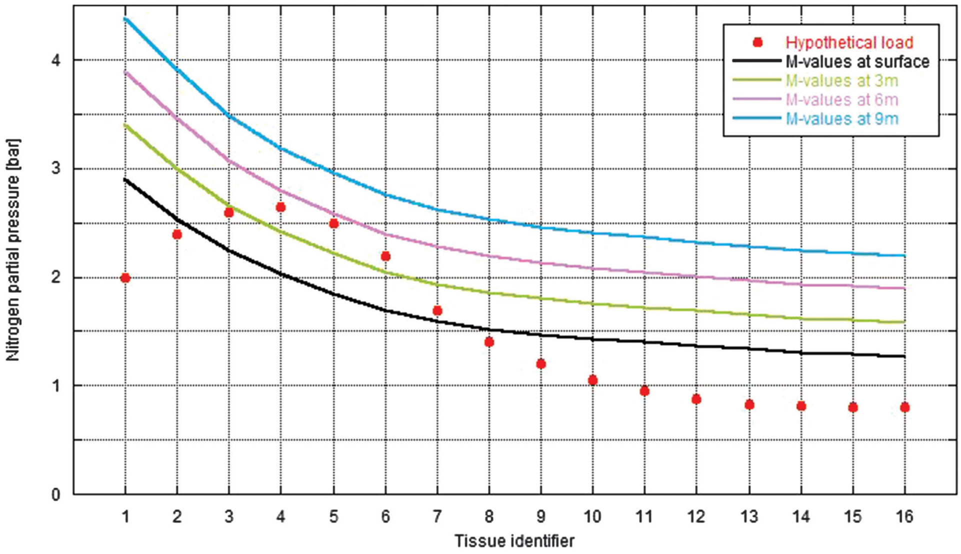

Fig 4: Hypothetical tissue tension and *M*-values for several depths

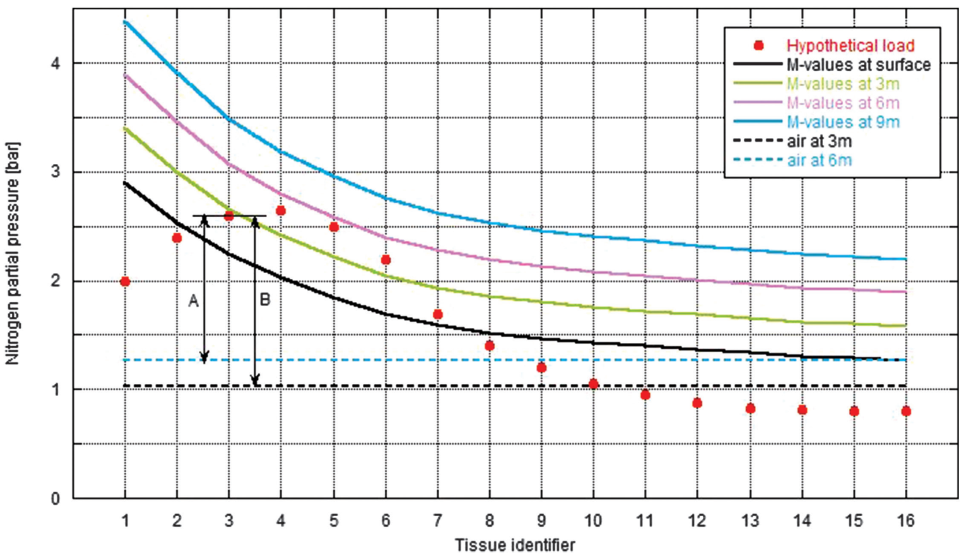

Fig 5: Impact of stop depth on offgassing gradients

pressure gradient available for offgassing. This is given by the difference in the partial pressure in the tissue and the partial pressure in the inhaled gas, the latter of course diminishing as the depth decreases.

Fig 5 shows the same hypothetical profile as Fig 4 but with the addition of a line corresponding to the partial pressure of air at 3 m and 6 m. It shows that at 6 m the pressure gradient available for offgassing ('A') is smaller than that at 3 m ('B'). So if the computer says 3 mins at 3 m but the diver stays at 6 m, then the offgassing will take longer. The computer simply states what the decompression time would be if a diver were at 3 m, but staying deeper means that there is less pressure difference and hence the release of nitrogen is slowed down. This in turn results in a longer time to reach the desired reduction.

Fig 6 compares a dive to 40 m using air and nitrox EAN32[‡‡]. For the sake of illustrating a concept, the hypothetical load is always the same. While at 40 m, on air the diver is constantly submitted to a higher partial pressure ('A'), which leads to a quicker rise of tissue tensions during the dive and slower offgassing during decompression ('C'). Conversely with EAN32, slower rise of tissue tensions occur during the dive ('B') and quicker offgassing during decompression ('D'). Thus, for the same dive profile, using Nitrox implies slower ongassing and more efficient offgassing of nitrogen. It may not seem much on the graph, but the difference is substantial and can

‡‡ EAN stands for Enriched Air Nitrox, 32 represents the concentration of oxygen in the mix, the balance being nitrogen. Similarly EAN80 is 80 % oxygen and 20 % nitrogen.

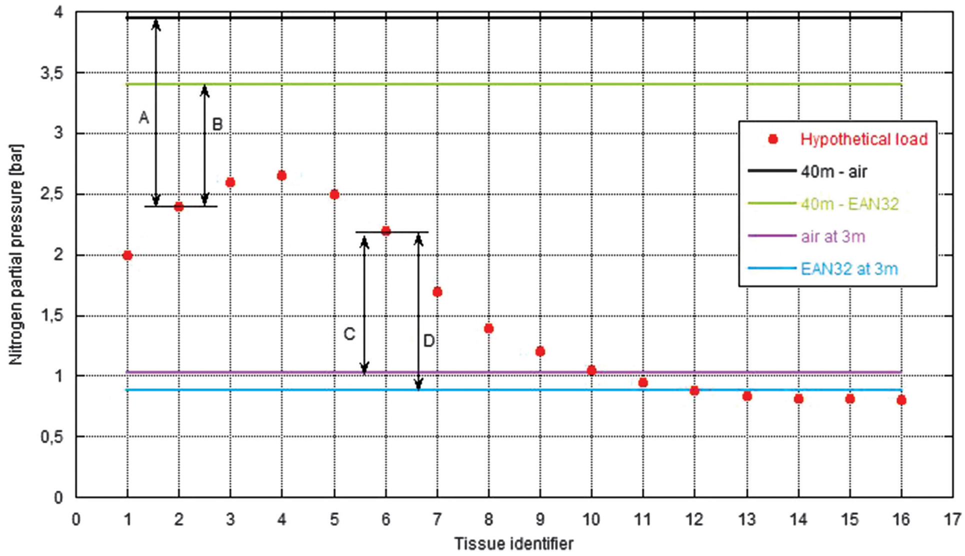

Fig 6: Comparison between air and EAN32 at depth and during decompression

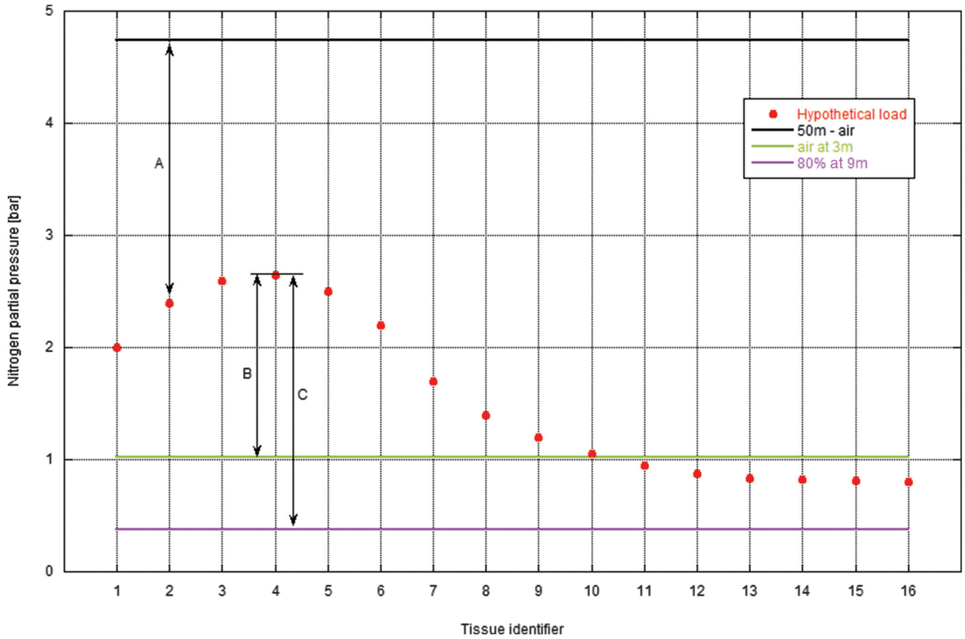

Fig 7: Comparison for a deep dive on air with and without EAN80 for decompression

be easily demonstrated by carrying two computers, one set to air and the other to EAN32.

Fig 7 shows the effect of adding a dedicated decompression gas for a dive to 50 m on air. Air allows a diver to reach this depth and the slow offgassing is compensated by switching to a gas with very low inert gas content in order to accelerate the offgassing. The pressure gradient driving nitrogen into the tissues is high in both cases ('A'), but decompression on EAN80, which in Fig 7 is used at 9 m, allows for much quicker offgassing ('C' instead of 'B'). There is another important factor to consider in favour of a high oxygen concentration decompression gas, which is exemplified in Fig 8.

Fig 8 shows the hypothetical nitrogen load of Fig 7 after the required decompression time has elapsed so that all dots are now below the *M*-values. Segment B represents the pressure gradient available for further offgassing when using air while staying at 3 m; segment C represents the pressure gradient available for further offgassing when breathing EAN80 while staying at 9 m; and segment D represents the pressure gradient available for offgassing upon ascending to the surface and breathing air. Staying underwater, even at 9 m, on EAN80 is much more efficient than starting the surface interval. Staying on air on the other hand results in losses in efficiency because of the small pressure gradient, which (slowly) becomes even smaller as any offgassing reduces the gradient further.

In light of this, is a safety stop more significant at the end of a no decompression dive or at the end of

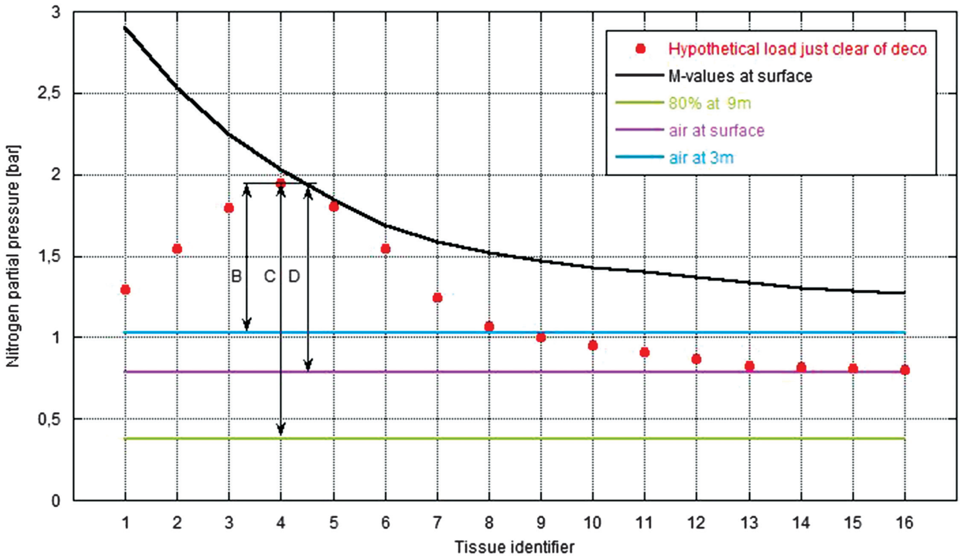

Fig 8: Pressure gradients at end of dive

a decompression dive? A common belief is that it would be more significant in the former scenario as in the latter a stop is already required. Without wishing to minimise the importance of doing a safety stop between 3 and 5 m after a no decompression dive, Fig 8 illustrates how doing a safety stop after a decompression dive is even more significant. After a no decompression dive, by definition none of the dots are on or above the black line, so there is an inherent margin between the tension in each tissue and the criterion for a safe ascent.

Clearing decompression, however, means at least one of the tissues barely clears the criterion for a safe ascent (the same is true of dives to the 'no decompression' limit, which have an appreciable risk of decompression illness). Performing a safety stop will move the dot below the line, which within the Bühlmann model is beneficial. The extent of the movement away from the black line is a function of time and available pressure gradient. Therefore, it is recommended to perform a safety stop after a decompression dive and after a dive to the 'no decompression' limit. Divers on EAN80 should extend this as much as possible. On air, as the dot descends and gets closer to the blue line (partial pressure of nitrogen in air at 3 m), the pressure gradient will become small enough that the diver should ascend to take advantage of the (slightly) higher pressure gradient available there.

3. Increasing conservatism by reducing inert gas load

The previous section outlined the basics of managing decompression using algorithms, which are model information coded for use in dive computers. An algorithm has a baseline conservatism, but in most dive computers it is possible to choose an alternate, more conservative setting (Smart et al., 2015). There can be many reasons why one may want to increase the conservatism, be it out of caution, or out of consideration for 'internal' (predisposition to bubble formation, fitness level, temporary lack of sleep or hydration, etc.) or 'external' factors (current, water temperature, etc.). The conservatism settings are often referred to as P0, P1, P2 or similar (Sayer et al., 2016).

In a Haldanian framework, increasing conservatism is easily achieved by lowering the *M*-values as shown in Fig 9. This is the same as Fig 4, but with a second set of *M*-value lines that represent a 15 % reduction of the original ones. The immediate effect is less nitrogen in the tissues at the end of the dive. But looking at Fig 9, we see also that:

- Tissue 2 does not require a decompression stop with the original *M*-values, but it does require one with the 15 % reduction.
- Tissue 3 requires a 3 m decompression stop and, after the 15 % reduction, requires a 6 m stop.
- Tissues 4 and 5 require a 6 m decompression stop and, after the reduction, require (barely) a 9 m stop.
- The overall effect is to lengthen the decompression, since all red dots have to reach a lower final value.

This, by and large, is what lies behind P0, P1, P2 or other monikers in dive computers. The *M*-value reduction may not be evenly distributed over all tissues. In addition, some introduce mathematical tricks to speed up ongassing and slow down offgassing. The concept, however, remains the same: each

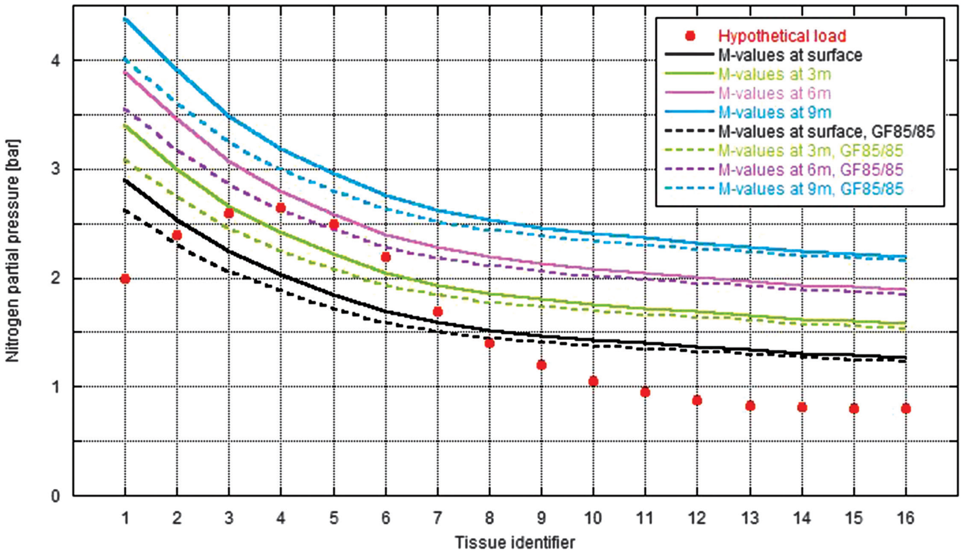

Fig 9: *M*-value reduction as a means to increase conservatism

tissue is viewed as a bucket that fills with inert gas during the dive and which must be emptied to a certain safe level before returning to the surface. Increasing the conservatism means lowering the safe level in the bucket, and this is accomplished by reducing 'no decompression' limits (less time available for inert gas to get in), or extending decompression times (more time available for inert gas to get out). Unfortunately, these monikers do not help the diver in appreciating the impact of the new conservatism level on the dive.

4. Gradient factors

The Bühlmann ZH-L16C algorithm has been used extensively by technical divers pushing the frontiers of diving. The original pushes divers as close to the surface as possible in order to maximise the pressure gradient available for offgassing. However, there is also evidence that in some particular dive profiles, a slower ascent with deeper stops may present benefits.

Fig 9 shows that this can be achieved by reducing the *M*-values until that same hypothetical load would generate a 21 m or 24 m stop. This, however, would imply a long stop at 3 m. Baker (1998) came up with a simple but ingenious idea. He defined two values: one that represented the percentage of the original Bühlmann values accepted at the surface (GF high); and one that represented the accepted reduction of Bühlmann's values to define the depth of the first stop during the ascent (GF low).

So revisiting Fig 9, where a 15 % reduction was applied to everything (and thus would be defined a GF85/85), Baker's approach would allow a diver to apply, say, a 15 % reduction at the surface (GF high of 85) and a 60 % reduction to define the first stop (GF low of 40), and then interpolate between those two values to define all the stops and their duration in between. This would be termed 'GF40/85' and the comparison between this and GF85/85 is shown in Fig 10, with the gradient factor of 40 applied at 9 m, and which, by interpolation, results in a gradient factor of 55 (45 % reduction) at 6 m and 70 (30 % reduction) at 3 m.

As a consequence of this mathematical manipulation, tissues 3, 4 and 5 now require a 12 m decompression stop, since they are placed above the *M*-values at 9 m, while decompression duration at 3 m is not increased. It could actually be slightly decreased if a decompression gas high in oxygen is used, since control may be passed from a faster tissue to a slower one during decompression, and the slower tissue may have benefited from the deeper stop already.

There are three aspects that make this approach very appealing:

1) The increase of conservatism introduced by the GF low does not kick in until there is sufficient inert gas uptake to require decompression. Then, it applies to the 6 m stop only (since the 3 m decompression stop is what allows the diver to reach the surface, and thus defined by GF high). As the inert gas uptake increases, the GF low value is gradually applied to 9 m, then to 12 m and so on, with corresponding interpolation of GF values for the stops in between. It's a dynamic application of *M*-value reduction that 'penalises' the diver more as the severity of the dive increases. This can be seen in Fig 11, calculated using the dive planner function on one of many commercially available dive computers. Fig 11 illustrates the total ascent time (i.e. the sum of all decompression stops and time required to travel the

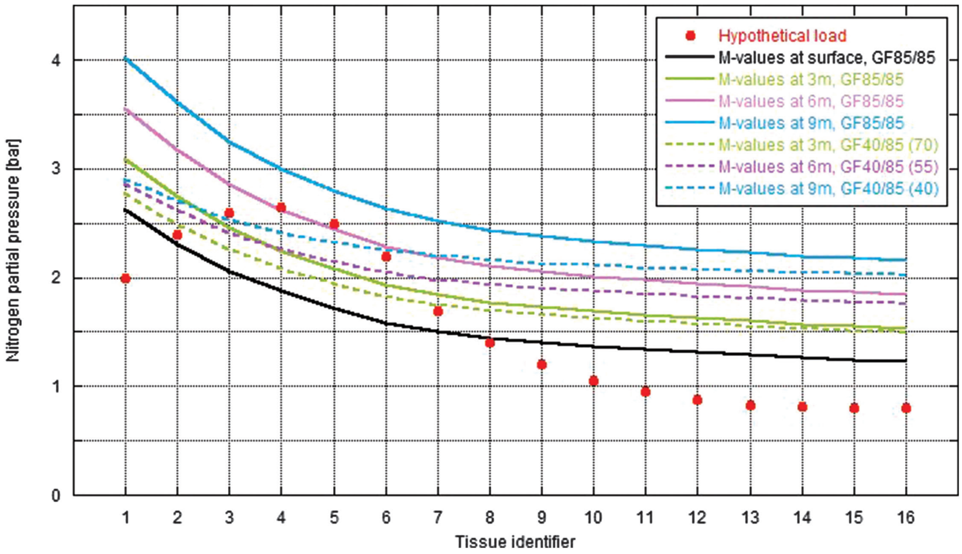

Fig 10: *M*-values at GF85/85 and GF40/85

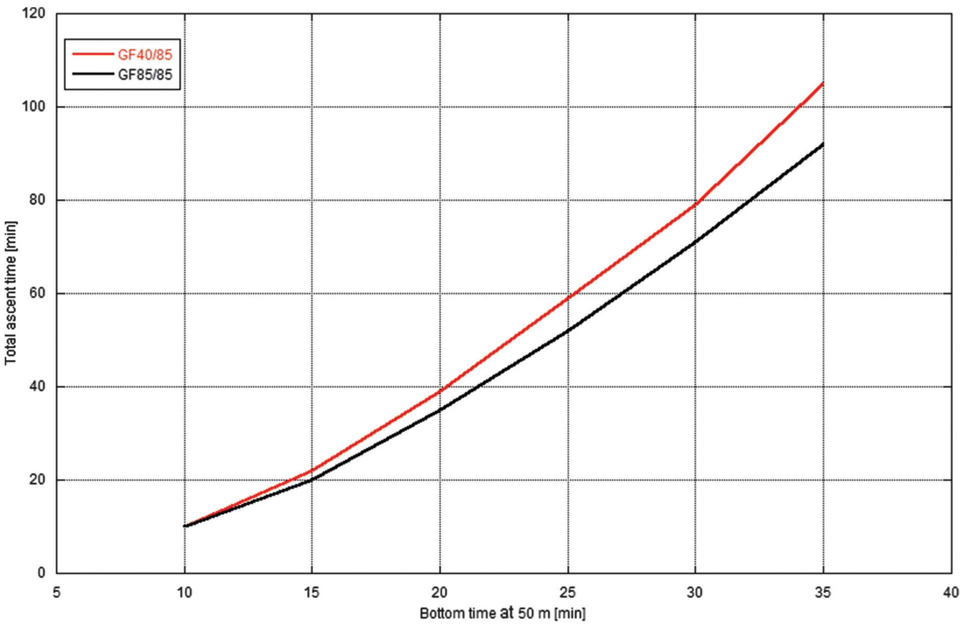

Fig 11: Effect of extending the bottom time on a 50 m dive

vertical distance to the surface at 9 m/min) for a dive to 50 m on air as a function of bottom time for GF85/85 (no dynamic adjustment) and GF40/85 (dynamic adjustment to determine deepest stop).

2) The definition of the two values, GF high and GF low, is simple and easy to understand, yet allows one to reproduce any ascent schedule that a bubble model may predict. Divers wishing for slightly longer or shorter overall decompression, can decrease or increase both values. If they want to start staged decompression deeper and spend less time at 3 m, they can decrease GF low and increase GF high. If they do not have a decompression gas that allows them to offgas at 20 m, then they can raise GF low and maybe reduce GF high. And for recreational divers wanting to add a bit of conservatism, they can take the standard values and reduce them in 5 % steps until they feel comfortable with the result.

3) This approach does not shift decompression time from shallow stops to deep stops. Current research carried out by the US Navy (Doolette et al., 2011) suggests that deep decompression stops may not be appropriate for all dive profiles, when such deep stops are introduced to partially replace a shallower stop. With the gradient factor approach, a deep decompression stop can be viewed as part of a multilevel dive with the GF high as the determining parameter defining the return to the surface.

5. Practical applications

Technical divers are comfortable with the use of gradient factors and know what works for them. A recreational diver might be more comfortable with the P0, P1 and P2 approach, though it would be helpful if dive computers combined these settings with a description of the increased conservatism. For example, this could be P0-85/85, P1-70/80, P2-60/70.[§§] Personal customisation to address an overall assessment of one's fitness to dive, or day-related deviations caused by internal or external factors could be defined on a scale from 1 to 3 which, when selected, would cause a deduction of 5, 10 or 15 percentage points from the starting values of the gradient factors.

Similarly, a GF reduction can be used to account for repetitive dives, for instance by subtracting 15 percentage points from the set GF values upon surfacing, and adding back 1 percentage point every 12 mins. Thus, for surface intervals shorter than 3 hrs there is an additional conservatism that decreases as the surface interval increases. A similar logic can be applied to multiday dives.

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[§§] No recreational dive computer manufacturer uses 100 % of the original Bühlmann values but rather the baseline conservatism that corresponds to approximately 85/85.