Deep decompression stops

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Key words

Decompression, deep diving, technical diving, models, trimix, review article

Abstract

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Technical divers have adopted widely the practice of either adding deep decompression stops to their decompression profiles or using decompression models that incorporate deep stops in the belief that these techniques will reduce the incidence of decompression sickness. However, new evidence suggests that the gas kinetic model on which this practice is based is flawed. This paper reviews the historical precedence, controlled studies and theoretical background for and against deep stops.

Introduction

The last 25 years have seen a rapid development of recreational diving activities. Whereas previously recreational diving had been confined to 'no stop' limits, the development of new techniques and equipment has seen recreational 'technical' divers adopt decompression and mixed-gas strategies to access depths not often previously explored, even by bounce commercial or Navy divers. These depths are in many cases outside the well-established areas of decompression theory and practice. However, access to 'new' decompression models via the internet and computers has encouraged technical divers that such dives are not only possible but also can be conducted safely. Many of these new decompression models include so-called 'deep' stops. Despite the lack of evidence to support their efficacy, deep stops have been incorporated into many of the newer diving computer algorithms, notably those from Uwatec™, Suunto™ and Delta P™ (VR3 technical dive computer), and have been enthusiastically embraced by the recreational diving community. This paper will review the theoretical and practical evidence for deep decompression stops.

The introduction of deep decompression stops has been popularly ascribed to the American ichthyologist Richard Pyle.[1] Pyle's work often required him to collect specimens from considerable depth (> 300 feet sea water (fsw)). After successful forays, Pyle was forced to perform deep stops during his ascent to decompress the swim bladders of the specimens he had collected. Pyle noticed that he felt better after dives where he had made these additional deep stops than after dives where he had not collected any specimens and had made stops according to the normally prescribed decompression profile. Several internet articles, such as those by Baker,[2,3] have promoted the insertion of decompression stops deeper than those predicted by the Buhlmann or Workman tables. However, while some methods of deriving these stops may have some theoretical logic to back them up, others have merely resulted from some empirical rule.[4,5]

For the purposes of this paper, a deep stop will be defined as a decompression stop that is performed deeper than the initial decompression stop that would be predicted by the Buhlmann ZHL-16C decompression model.

Deep-stop profiles conducted by technical divers are usually produced by one of three methods:

1 Pyle stops: the first new stop is conducted for two to three minutes halfway between the maximum bottom depth and the first prescribed stop. The schedule is then recalculated and if the distance to the next stop is greater than 10 metres' sea water (msw) another stop is generated halfway between the first new stop and the next prescribed stop. The schedule is then recalculated and the process repeated. From a decompression modelling point of view, the first of the deep stops produced by this method is usually too deep, in that the calculated inert gas tensions are not sufficiently greater than ambient pressure to optimise decompression.

2 Proportional M-Value Reduction Method (PMVRM, popularly known as the Gradient Factor Method): the diver decides what proportion of the Buhlmann supersaturation gradients are to be allowed both at depth and in the shallows.[3] For example, a diver might select a maximum allowed gradient of 20% of the Buhlmann value at the maximum depth and perhaps 80% for surfacing (compared with the 90% of each value described by Buhlmann). A computer programme then proportionally alters the maximum allowed gradients between these two values depending on the depth. This results in deeper initial stops and generally longer decompression schedules than those of the native Buhlmann models. The depth of the initial stop will be controlled by the deep gradient factor value selected by the diver, i.e., the lower the value the deeper the initial stop. While there are no formal guidelines on how to select the gradients, the general method seems to be that the greater the depth/time profile, the lower the deep gradient value that is selected.

3 'Dual phase' or 'bubble' models: the most popular of these are the Variable Permeability Model (VPM) and Reduced Gradient Bubble Model (RGBM) and are

readily available as PC-based software. The programmes produce similar decompression schedules incorporating decompression stops deeper than those predicted by the Buhlmann model. The majority of these stops are of short duration (one minute or less). They generally produce longer decompression times within the recreational diving depth range but substantially shorter profiles for deep decompression type dives.

Decompression practices: historical perspective

Modern decompression practice is largely based on the work of JS Haldane.[6] Haldane's strategy for successful decompression was based on the concept that tissues could tolerate a finite level of supersaturation during decompression. If the ratio of ambient pressure to tissue pressure was kept below this level at all times during the decompression, no decompression sickness (DCS) should result. Haldane produced a gas kinetic model with five compartments and a single 'gradient' line, which limited the allowed over-pressure in all the compartments. This approach was combined with a stepped or staged decompression and resulted in the diver initially being brought as close to the surface as possible without exceeding the prescribed limit so as to minimise on-gassing at depth and to maximise the gradient for off-gassing inert gas from the tissues. While the development of Haldane's method was a vast improvement over previous practice, it was soon found that the schedules produced in this way were too conservative for shallow dives

and too aggressive for deep dives. The Royal Navy dealt with the problematic profiles by (usually) adding time to the final stop. Over the subsequent years this resulted in a series of modified tables, which became progressively more empirical in derivation.

Buhlmann and Workman further developed the Haldanean model during the 1960s.[4,7] Buhlmann and Workman both conducted extensive manned experiments to find the maximum tolerated supersaturations for the various assumed tissue compartments (Figure 1). In contrast to Haldane's original model, each compartment was given its own unique gradient line with the slow compartments having very low allowed supersaturation limits and the faster compartments progressively higher limits (Figure 2).

The gradients in the various compartments in both Buhlmann and Workman's models resulted from the manned experiments and the need to fit their models to the known no decompression limits (NDLs). Both Workman and Buhlmann independently ended up with similar maximum allowed gradients for compartments of similar half-times with air dives. However, Workman found that for the deeper dives where heliox was being used as the breathing gas, a reduced gradient was required, producing deeper initial stops than for an air dive of equivalent depth.[5] This finding had some historical precedence, being consistent with the early studies on helium diving dating back to the 1930s.[8] In the Buhlmann tables, as the helium content of the breathing

Figure 1
Typical Buhlmann type tissue inert gas tensions versus time; 16 compartments with half-times from 2 min to 635 min; 30 min bottom time, dive to 70 msw utilising trimix 18:35 and nitrox decompression
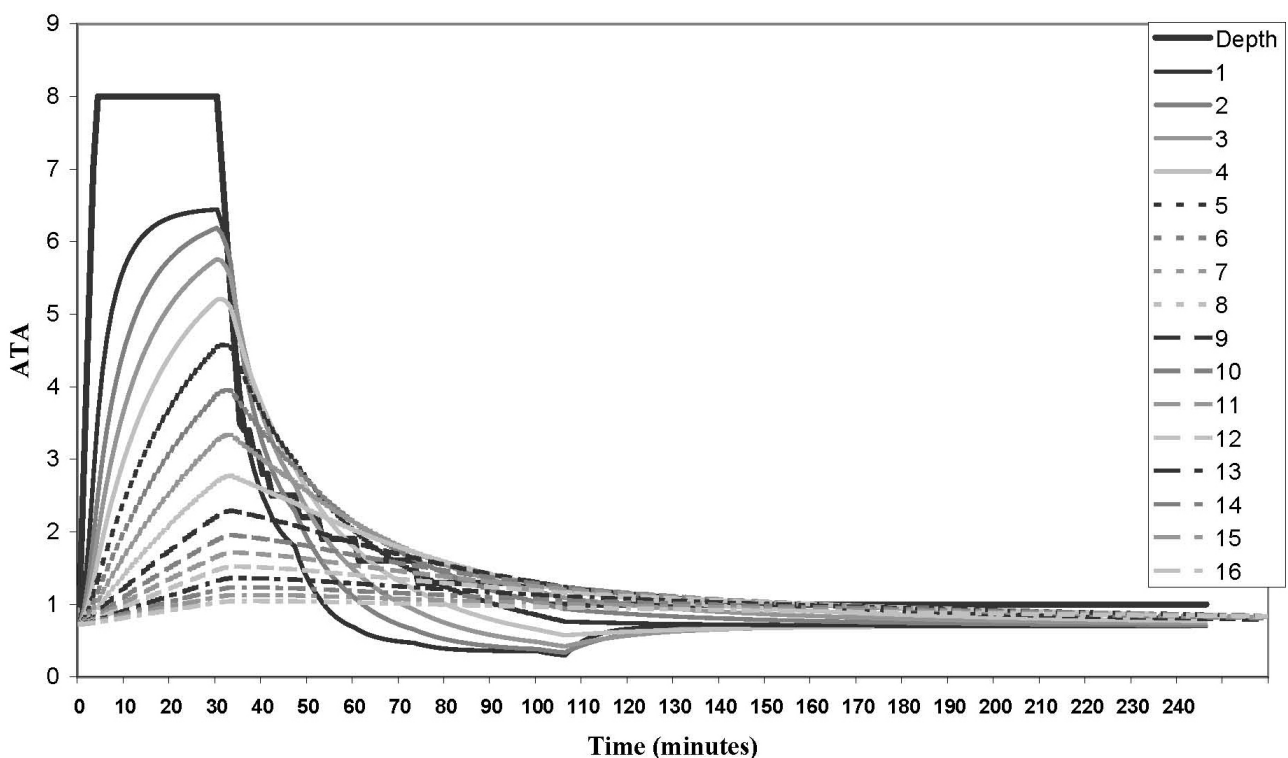
gas increases, the allowed gradients are actually increased, though this is offset by the faster exchange of helium in this model and results in similar overall profiles.

The result of this approach from both Buhlmann and Workman is that profiles produced using their methodology have a characteristic long initial ascent towards the surface and long periods in the shallow to complete the decompression. In general, in the air range, the Buhlmann method produces deeper initial stops than the USN (Workman). However, this difference is relatively small compared with the more recently invoked 'deep stop' type profiles.

Buhlmann's ZHL-12 and later ZHL-16 models have proven very successful and have been widely applied in electronic diving computers, becoming the de-facto standard against which other models are compared in recreational diving. Their rate of DCS, when used in the recreational range, is quoted as somewhere between 1:1,000 and 1:10,000. One feature of the Buhlmann model that was different to earlier models was the adoption of a 10 m.min^{-1} ascent rate. Marroni

et al have demonstrated that this ascent rate has a lower decompression stress as measured by venous bubble scores than either faster or slower ascent rates.[9]

Historical precedent

Deep decompression stops have been practised empirically for probably close to 80 years. In the 1960s, Le Messurier and Hills studied the decompression practices of the pearl divers off the Torres Straits in Northern Australia.[10] These divers had developed their diving practice without any knowledge of decompression theory over some 80 years and at the cost of some 2,000 lives. The profiles they had developed had a similar rate of DCS to the USN tables then in use, about 5–7%, but featured deeper initial stops, a final stop at 6 msw (versus 3 msw for the USN) and generally an overall reduction in decompression time to about two-thirds of that for similar USN profiles. Interestingly, other groups of native divers in other parts of the world (e.g., Hawaii) had also empirically ended up with similar deep-stop dive profiles. However, the likelihood of a considerable 'healthy

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Figure 2
70 msw dive as per Figure 1, but looking at inert gas tensions in each compartment versus ambient pressure; as each tissue nears its gradient line, a decompression stop is forced. Typically high supersaturation levels are allowed early in the dive, progressively reducing as the longer half-time tissues control the dive. Note the allowed higher gradients for the short half-time tissues and the increased gradients when helium is present in the breathing mix.
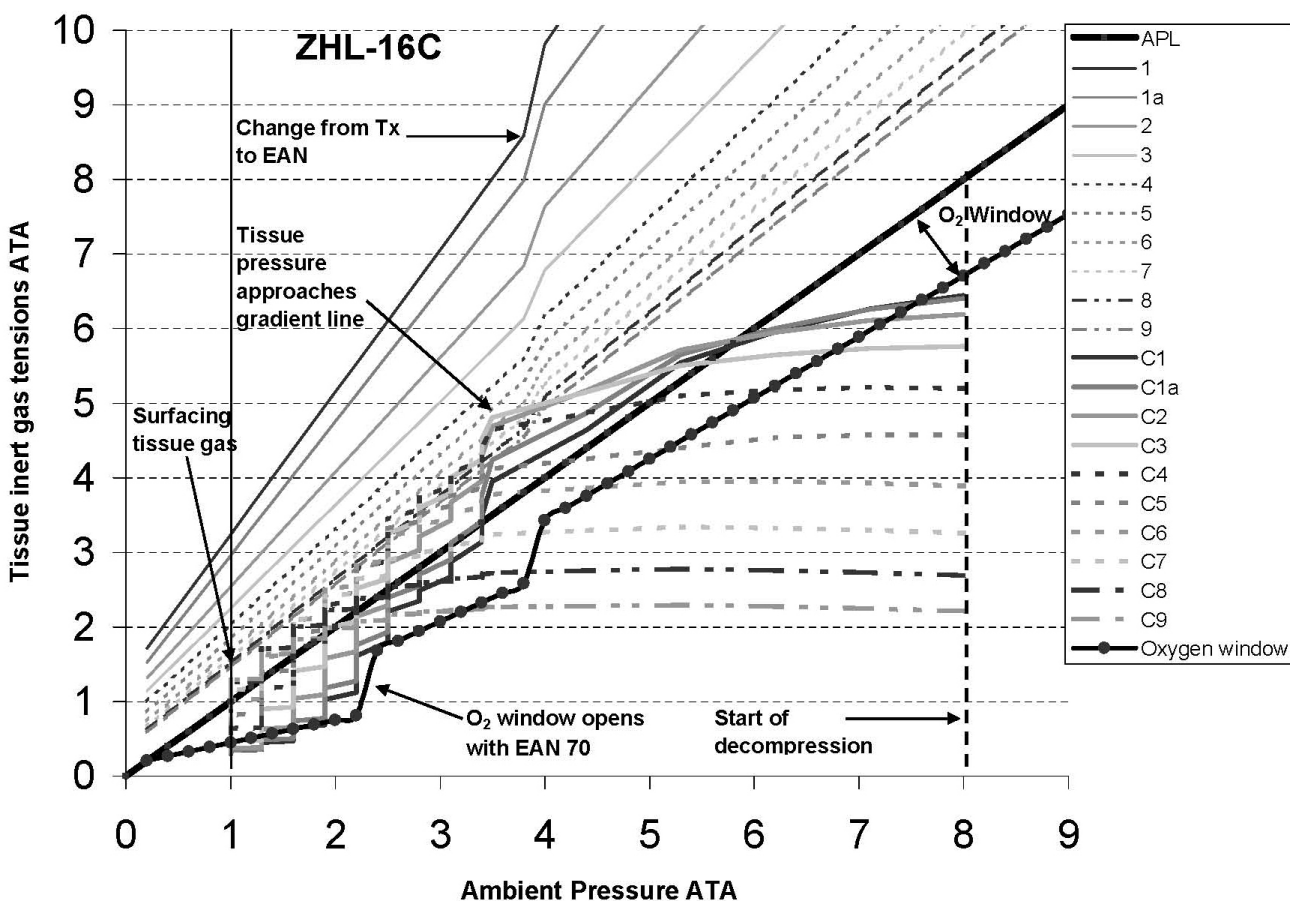
worker' effect associated with these native divers (given the harsh selection process) may significantly limit the applicability of these types of profiles to the wider diving community.

Hills' investigations into the practices of the Torres Strait pearl divers led him to believe that the USN type profiles were causing bubble formation to occur during the long initial ascent to the surface, the time in the shallow being prolonged to allow for bubble reabsorption before surfacing. This was in contrast to the popular view that no DCS meant no bubbles. Hills tested his hypothesis with a series of experiments on goats and demonstrated that by performing the final stop at 6 msw rather than 3 msw, the total decompression time could be reduced for the same incidence of DCS.[11]

Hills theorised that this reduction in decompression time was possible because the bubbles that had formed would have a smaller radius at the deeper final stop, hence their internal pressure would be higher, favouring reabsorption and gas elimination. He described traditional models as "bend then mend" and theorised that by avoiding the formation of free gas, by performing deeper initial stops, decompression could be both faster and safer. Hills went on to develop the Thermodynamic Decompression Model, a diffusion-based tissue model in which gas was prevented from coming out of solution by utilising a decompression profile conducted within the oxygen window or inherent unsaturation of tissues.[12–14] A feature of the Hills profiles, compared with the Buhlmann or USN profiles, is that the initial stops are much deeper. The mathematical complexity of his model limited its further development and implementation.

Vann et al were able to demonstrate in goats that profiles from thermodynamic models did not produce detectable venous bubbles until the final ascent from the last stop to the surface.[15] Similar depth/time profiles decompressed using the USN table produced detectable bubbles from 40 fsw. Hills' profiles also had some success in the commercial oil industry.[16] Hills found that the addition of a few minutes' 'deep' often prevented DCS symptoms without the need to add time in the shallow (personal communication, BA Hills, 2005). Krasberg claimed considerable success using Hills type profiles for deep diving in the North Sea; however, precise data on these profiles and the implementation of Hills' model have remained elusive.[16]

1970s bounce diving experience

During the 1970s, prior to the development of safe saturation techniques, there was much interest in deep bounce diving. Despite deep stops being advocated by some researchers, others were equally (or more) successful with more traditional types of profiles. Whereas Cabarrou et al were able to produce workable profiles with traditional Haldanean type supersaturation limits, Bennett et al had only limited

success for similar depth/time profiles despite drastic reductions in the deep supersaturation limits by adding deep stops.[17] Their initial approaches, which produced very similar profiles to the modern 'bubble' models, were unsuccessful, with a high incidence of vestibular and Type I DCS, and it was not until they adopted a mixed perfusion/diffusion-based gas kinetic model that they were able to produce successful profiles. However, these profiles were substantially longer than those of Cabarrou for the same depth/time exposure without deep stops.[18]

Bubble models

The development of ultrasonic bubble detection devices and their application to decompression practice demonstrated that despite the low observed incidence of DCS in traditional profiles, venous bubbles were present after most dives.[19–21] One explanation for the presence of these bubbles in the absence of symptoms is the 'critical volume hypothesis'.[11,22] This hypothesis states that the body can tolerate a certain amount of gas coming out of solution into one or more critical tissues. As long as the volume of evolved gas during a dive is kept below this amount, no symptoms of DCS should result. For the Buhlmann type gas model, the fast compartments control the ascent profile for shallow, short depth/time profiles. Since little gas has been taken up in the critical tissue(s) during such dives, relatively large apparent supersaturations can be justified for the same critical volume of gas to come out of solution.

Based on the observed behaviour of bubbles in gelatine,[23] Kunkle and Yount applied the critical volume hypothesis in an attempt to marry the empirically derived Buhlmann type supersaturation limits with some basic theories on bubble mechanics.[24,25] The resultant VPM model predicted deeper initial decompression stops than the Buhlmann model with similar decompression times within the recreational range.[25] The model amortises the calculated evolution of gas over the dive such that calculated evolved volume of gas is restricted to less than a critical volume as defined by the model. This produces supersaturation restraints that are then overlaid to the Buhlmann gas model. The effect of this is to substantially lower allowed compartment supersaturations at depth (and hence deeper stops) but paradoxically may produce shorter overall decompression times and higher predicted compartment surfacing gas tensions in the mid to slow compartments. In dives of greater than 70 msw, these surfacing compartment tensions commonly exceed the limits derived experimentally by Hempleman and Buhlmann, which were shown to produce clinical symptoms.[26]

Wienke has developed a model (RGBM) similar to the VPM model.[27] This has been enthusiastically adopted by both the dive computer manufacturers and the technical diving community despite limited field validation. Like the VPM, the RGBM predicts deeper initial stops than the Buhlmann or Workman type profiles.

Figure 3
Ultrasound-derived venous bubble scores versus DCS incidence from various institutions[33]
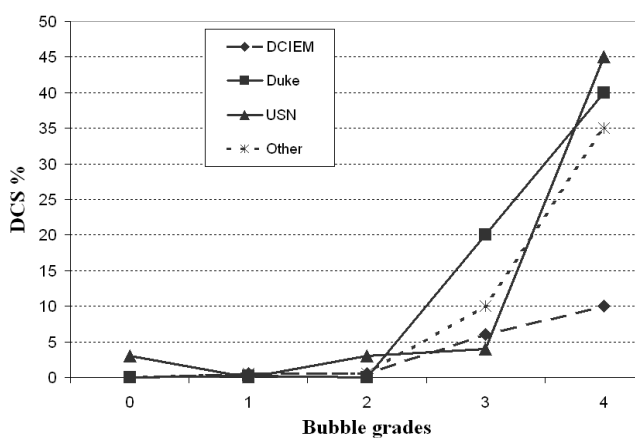
Limitations of gas kinetic models

The VPM, RGBM and Buhlmann models all share the same basic compartment model. A major feature of this base model that has made it popular with technical divers is its ability to deal with gas mixtures other than air. The model assumes that helium is on-and off-gassed 2.65 times faster than nitrogen.[4,28] The partial pressures for each inert gas in each compartment are calculated, and then added together and compared with the prescribed limit (which in the Buhlmann model is itself varied depending upon the fraction of each gas). Buhlmann derived the 1:2.65 ratio from a fairly weak data set of human experiments.

However, recent experiments actually measuring helium and nitrogen elimination at 1 ATA (101.3 kPa) would tend to indicate that the true ratio is probably closer to 1:1.2.[29,30] In these studies, helium kinetics were best described by a model incorporating perfusion, diffusion and an element of counter-diffusion between arterioles and venules. The proportional contribution of each component was dependent upon the blood flow and the inert gas involved. Doolette's experiments were carried out at 1 ATA. Extrapolation of this work to higher pressures involving tissue supersaturation and decompression must be performed with caution as the rate of inert-gas washout has been described to vary with decompression.[31]

To confuse matters further, the ability of venous bubbles to enhance inert-gas washout during decompression may also substantially alter the kinetics of gas exchange.[32] This may result in an acceleration of the elimination of helium when bubbles are present, as retention of gas in venous bubbles may significantly affect arterio-venous gas exchange. Thus, while there is evidence that helium kinetics may be slower than predicted in traditional models, a mechanism may exist whereby elimination may be accelerated in the presence of venous microbubbles.

Therefore, while it is unlikely that the Buhlmann model of gas exchange is physiologically accurate, it is quite plausible that it might still provide workable decompression solutions within certain ranges when used in conjunction with its original decompression rules. However, if the decompression ascent rules are altered, the relationship may not necessarily hold.

This may be particularly pertinent for technical recreational divers who often utilise inert-gas switching to accelerate decompression in association with the insertion of deep decompression stops. Such practices may actually reduce gas exchange as outlined previously, while the decompression model predicts a reduced decompression obligation. The result may well be an inadequate decompression solution. Recently, at least one of the technical diving training agencies has recommended the maintenance of a constant fraction of helium in decompression mixtures to minimise the risks of inner ear decompression sickness.

While the presence of venous gas emboli (VGE) in USN and Buhlmann profiles was taken as a marker of inadequate decompression (on the basis that no DCS should equal no bubbles), it should be noted that low-grade venous bubbles scores do not correlate with incidence of DCS (Figure 3). Even Spencer Grade IV bubbles correlate only approximately to a 45% risk of clinical DCS.[33] Thus, while the presence of venous bubbles might be a marker of inadequate decompression they may paradoxically also enhance tissue nitrogen elimination and decompression. If this were so, the presence of *low-grade* VGE may represent optimised decompression rather than indicate a *significant* level of decompression stress. This would bring into question the use of low-grade VGE scores as justification for the adoption of deep decompression stops and reduced decompression gradients, as happened in the 1980s.

Studies on deep decompression stops

To date, two papers have been published and two abstracts reported that have specifically addressed the issue of the value of deep initial decompression stops.

Marroni et al conducted a series of sea dives to 25 msw.[34] The durations of these dives were within the no decompression limits and the following profiles were followed:
- 3 m.min⁻¹ ascent rate without stops
- 3 m.min⁻¹ ascent rate with stops
  - stop for 5 min at 6 msw
  - stop for 5 min at 15 msw
  - stops for 5 min at both 6 msw and 15 msw
- 10 m.min⁻¹ ascent rate without stops
- 10 m.min⁻¹ ascent rate with stops
  - stop for 5 min at 6 msw
  - stop for 5 min at 15 msw
  - stops for 5 min at both 6 msw and 15 msw
- 18 m.min⁻¹ ascent rate without stops

Figure 4
French Navy experimental deep-stop profile n⁰1 versus
the standard MN 90 profile. In the repetitive series,
the n⁰1 profile produced higher bubble grades and
symptomatic DCS[35]
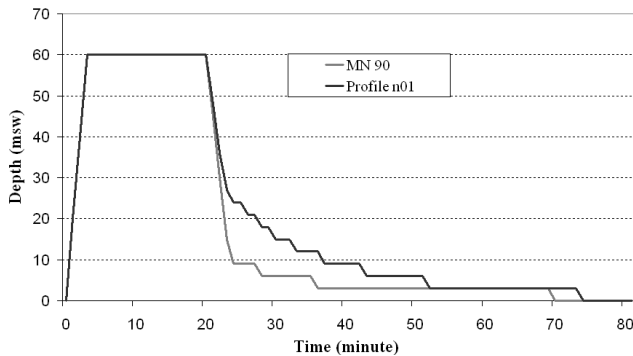
* 18 m.min⁻¹ ascent rate with stops
  * stop for 5 min at 6 msw
  * stop for 5 min at 15 msw
  * stops for 5 min at both 6 msw and 15 msw

Divers were monitored for venous bubbles post dive using a Doppler ultrasound device. Highest bubble scores were seen in dives that had a 3 m.min⁻¹ ascent rate with a 5 min stop at 6 msw even though the total decompression time was similar to that for the lowest scoring group (10 m.min⁻¹ ascent rate with stops at 6 msw and 15 msw). The addition of the deep stop at 15 msw seemed to substantially reduce the bubble scores in all profiles irrespective of ascent rate. This reduction in bubble scores was far larger than that seen with the addition of the 6 msw stop. However, statistical analysis of the results was not provided, thus their significance is unknown.

It is interesting to note that the longest decompression time (3 m.min⁻¹ ascent with stops at 6 msw and 15 msw) did not produce the lowest bubble scores. While the addition of the deep stop to a given ascent rate did seem to reduce the venous bubble scores, this generally occurred in the setting of an increased total decompression time. Unfortunately this paper failed to answer the more important question of whether the addition of a deep stop for a given total decompression time alters decompression stress.

Blatteau et al looked at the issue of deep stops in a way more relevant to technical decompression diving.[35] They compared the standard French Navy profile MN 90, for a dive to 60 msw for 20 min followed by a 50 msw dive for 13 min (3 hour surface interval), with a profile where they reduced the ascent rate to 12 m.min⁻¹ (as opposed to 15 m.min⁻¹ for the standard profile) and added deep stops beginning at half the maximum depth. The subsequent ascent rate was reduced to 3 m.min⁻¹ from 6 m.min⁻¹ for the standard table. This profile was designated n⁰1 (Figure 4).

A second profile was also tested where they used their standard ascent rates and added a single deep stop at

half the maximum depth for two minutes, n⁰2. This latter profile was tested only for a dive of 60 msw/15 min bottom time. Evaluation was conducted using Doppler ultrasonic monitoring and venous bubble grading. Peak bubble scores were seen 60 minutes after surfacing in all dives. Similar bubble scores were seen in both the deep-stop profiles and the standard profiles; however, in the multiple dive series, the deep-stop profile n⁰1 produced higher bubble grades (which persisted for more than three hours) and symptomatic DCS. The n⁰2 profile did not produce significantly different bubble scores to the native Haldanean type Navy schedule (MN90). This paper would appear to confirm the observation from Marroni's paper that prolonged decompression times *per se* do not necessarily reduce decompression stress.

Both of the papers discussed utilised Doppler venous bubble scoring as a marker of decompression stress.

ABSTRACTS

Two abstracts were reported at the 2007 Undersea and Hyperbaric Medicine Society meeting in Hawaii.[36,37]

In the first study, air dives to 51 msw for 30 min bottom time (including descent time) were conducted.[36] Decompression was then carried out according to either a deterministic gas content model or a probabilistic bubble model (BVM). In the former the first stop was at 40 fsw and the latter 70 fsw. In both cases the total dive time was 174 min. The trial was terminated at the mid-point interim analysis with 11 cases of DCS (including two CNS cases) in the deep-stop group and only three in the shallow group (198 and 192 dives in each group respectively). It should be pointed out that the profiles produced with the BVM model in this study correlate poorly with the profiles generated with the 'bubble' models used by the technical diving community.

The second study reported the results of a series of experiments on pigs.[37] In this study, the pigs received either a long shallow profile (30 msw/70 min) or a short deep profile (65 msw/20 min). Decompression was then carried out using either a Buhlmann model or a new 'bubble' model incorporating deep stops. The animals were monitored using ultrasound to detect the development of venous gas emboli (VGE). For the long shallow profile the addition of the deep stops reduced VGE scores; however, in the deep profile, the addition of the deep stops produced a dramatic increase in bubble formation and the experiment was aborted. A revised profile with the deep stops removed produced a significant reduction in vascular bubble formation.

Summary

The availability on the internet of decompression software for mixed-gas diving has seen an explosion of technical diving over the last 10 years. It is now common for recreational divers to conduct dives to over 50 msw, and dives to in excess of 100 msw are regularly reported in the popular

dive literature. Many of the divers conducting these dives have little formal training or education in decompression theory beyond the basics taught in their technical diving courses and yet may be extremely opinionated and vocal in internet forums on the subject, based solely on their diving experience. It is rather alarming to see the almost zealous way in which deep stops have been incorporated into the recreational market given the paucity of good evidence as to either the benefit of such stops or a validated method of incorporating them into diving practice.

While there is some theoretical reasoning behind the adoption of deep decompression stops and some empirical and historical evidence that they may be of value, the available studies do not support their introduction. Problems encountered with deep mixed-gas dives may be as much related to the inadequacies of the base compartment model to accurately describe inert-gas kinetics as to the presence or otherwise of deep stops. Finally, the lack of correlation between DCS and low bubble scores and the increased nitrogen elimination described with venous microbubbles makes the interpretation of Doppler ultrasound bubble scores (used to justify the adoption of deep stops) difficult.[20]

It would seem that, from the available evidence, decompression profiles where more time is spent deep do not always reduce decompression stress as might be expected. This may be especially true of dives involving mixed gases and inert-gas switching. While accepting that stops deeper than those prescribed by the Buhlmann model may be optimal for safe decompression from significant depth, several workers in the field are now questioning the validity of deep stops as generated by 'bubble' models.[36-9] Further studies are needed to better define the value of deep stops and the best method of optimising decompression schedules, before deep stops are routinely incorporated into dive profiles.

Recommendations

* Decompression diving to depths of less than 80 msw using the Buhlmann ZHL-16C model would appear to have a relatively low incidence of DCS.
* Conducting the final decompression stop at 6 msw may allow for reduced decompression requirements.
* The use of helium as a breathing gas may necessitate deeper initial stops than those predicated in the USN air diving tables for an equivalent depth.
* The inclusion of half maximum depth (Pyle) type empirical stops is not supported at present by the available literature or decompression modelling.
* The inclusion of deep stops in association with gas switches involving large changes in concentrations of inert gas may result in inadequate decompression.
* Newer 'bubble' models incorporating deep stops have not been formally validated. Recent evidence would suggest that this approach produces initial stops that are too deep and may result in an increased rate of DCS.

* Further formal studies looking at deep stops in mixed-gas decompression diving need to be conducted.

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