Ceiling-controlled versus staged decompression: comparison between decompression duration and tissue tensions

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Abstract
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Introduction: In dissolved gas decompression algorithms, the ceiling is the depth at which the dissolved gas pressure in at least one tissue equals the maximum tolerated value defined by the algorithm. Staged decompression prescribes stationary stops in three-metre intervals so as to never exceed this maximum tolerated value. This keeps the diver deeper than the ceiling until the ceiling itself decreases to coincide with the next, three-metre shallower stage. Ceiling-controlled decompression follows the ceiling in a continuous ascent.
Methods: Mathematical simulations using the ZH-L16C decompression algorithm and gradient factors were carried out for several dive profiles to compare patterns of tissue gas supersaturation and overall decompression times for decompressions based on these approaches.
Results: During a stationary staged decompression stop the available pressure gradient for inert gas washout diminished as inert gas is washed out while inhaled inert gas partial pressure remained unchanged. Ceiling-controlled decompression, on the other hand, maintained the available pressure gradient for inert gas washout at its maximum tolerated level. Decompressions were 4–12% shorter using ceiling-controlled approaches but at the cost of exposing tissues with faster half times to higher levels of supersaturation than they would experience during staged decompression.
Conclusions: Ceiling controlled approaches accelerate decompression but the effect of this on the risk of decompression sickness is unknown.

Introduction

A compressed gas dive causes accumulation of inert gas (usually nitrogen and/or helium) in the body through diffusion driven by the difference between inhaled inert gas partial pressure and inert gas pressure (also called tension) in the blood and tissues. The higher this inert gas pressure gradient, the faster the accumulation of inert gas into tissues. The process is reversed and inert gas is eliminated ('washed out') during ascent when the partial pressure of the inhaled gas falls below the pressure of that same gas in the blood and tissues. If during an ascent the ambient pressure drops below the sum of gas partial pressures in a tissue (supersaturation), bubbles can form. The presence of bubbles can lead to decompression sickness with manifestations ranging from mild discomfort to paralysis and even death.

Managing inert gas washout with the goal of minimising the probability of undesired consequences is the goal of 'decompression' procedures. Decompression usually involves an ascent with stops near the surface to allow for the controlled release of excess inert gas. The prescription of this ascent is the task of decompression algorithms, which are mathematical representations solvable by a computer of the physical and physiological processes involved in decompression sickness. The ideal decompression not only brings the diver back to the surface without consequences, but does so in a time-efficient manner.

This paper considers the dissolved gas algorithm, first proposed by Haldane in 1908,[1] and, in particular, the ZH-L16C algorithm developed by Bühlmann.[2] This algorithm is based on the assumption that there is a direct relationship between maximum tolerated inert gas pressure in a tissue and ambient pressure. The algorithm represents the human body with 16 tissues, each of which takes up and washes out inert gas at a different rate, and each having a different tolerance to inert gas supersaturation. Specifically, each tissue is identified by three parameters:

The half time, which defines the rate at which gas is taken up and washed out (it is the time in minutes a tissue at a certain pressure needs to reach 50% of a different pressure that it is exposed to). Typically, tissues with short half times

('fast tissues') have higher tolerance to supersaturation while tissues with long half times (slow tissues) have low tolerance to supersaturation.

The a and b values, which define the maximum tolerated inert gas pressure $P_{t.tol}$ as a function of ambient pressure P_{amb}:

$$P_{t.tol} = \left(\frac{P_{amb}}{b}\right) + a$$

This is also referred to as M-value. From this we can derive the minimum tolerated ambient pressure $P_{amb.tol}$ for a given inert gas tissue pressure $P_{t.inert}$:

$$P_{amb.tol} = (P_{t.inert} - a) * b$$

The highest value of $P_{amb.tol}$ among the 16 tissues defines the minimum depth (decompression 'ceiling') to which a diver can ascend without violating the algorithm, and the corresponding tissue is called the 'leading' or 'controlling' tissue. As ascending beyond the ceiling would violate the decompression algorithm, this determines the depth of the first (deepest) decompression stop, which by convention is a multiple of 3 m. The diver advances from one decompression stop to the next when the inert gas in the leading tissue drops sufficiently to be compatible with the ambient pressure at the next stop, 3 m shallower; in other words, when the ceiling coincides with the next, 3 m shallower stop.

The choice of the 3 m increment dates back to 1908 and the pioneering work of Haldane who advocated that a first ascent to half of the absolute pressure could be done safely, and that "*the remainder of the decompression would evidently need to be conducted in such a way that the maximum partial pressure of nitrogen in any part of the body should diminish at double the rate of the fall in absolute pressure of the air. The ascent of a diver can be conveniently regulated from the surface by signalling to him to stop or come on* ***at every ten feet as indicated on the pressure gauge*** *attached to the pump*."[1] A different unit system may have led to different increments, but the 10 feet of sea water or three metres of sea water (msw) steps established themselves as a standard also because many experiments were carried out in hyperbaric chambers, where fixed decompression stop depths allow for easier control and repeatability of dive profiles. Given that all validation efforts to date are of empirical nature, a different choice of decompression stop depth increments would have yielded different decompression durations but would probably have been as effective. Others have performed a purely mathematical exercise applying optimisation theory to ZH-L16C to show that staged decompression stop depths other than in standard 3-msw increments can lead to shortened decompression time between 8 and 15%.[3]

Staged decompression however is fundamentally less than ideal in terms of inert gas washout, since a stay at constant depth implies that the inert gas pressure gradient is maximised only at the beginning of the stay and decreases from there as the tissue releases gas, and therefore the inert gas tension in the tissue decreases, while the inhaled partial pressure of inert gas remains constant. The fastest decompression would aim at maintaining the inert gas pressure gradient as high as possible throughout the ascent. The maximum available inert gas pressure gradient is achieved at the shallowest tolerated depth (the 'ceiling'). As inert gas washout leads to continuously decreasing inert gas tension, the ceiling moves continuously upwards. A decompression that follows the ceiling is thus a decompression with a continuously changing depth.

The effect of decompressing following the ceiling in comparison with standard staged decompression in 3 msw steps is quantified here via computer simulations of various dive profiles.

Methods

Computer simulations were carried out using ZH-L16C with gradient factors. Gradient factors[4] were defined as the ratio between inert gas pressure in tissue minus ambient pressure and maximum tolerated inert gas pressure minus ambient pressure. Using Bühlmann's terminology we get:

$$GF = \frac{P_{t.inert} - P_{amb}}{P_{t.tol} - P_{amb}} x100$$

Baker[5] used the concept of gradient factors to introduce additional conservatism in the decompression algorithm originally devised by Bühlmann. Gradient factors define a value not to be exceeded at the surface at the end of the dive (GF HIGH) and a value not to be exceeded early in the ascent (GF LOW), using the annotation GF LOW/HIGH (for example GF 30/85). Thus, GF LOW determines the depth of the first (deepest) decompression stop, while GF HIGH defines the duration of the last stop (typically at 3 m), so as to surface without exceeding GF HIGH. The stops between the deepest and the shallowest stop are calculated based on a linear interpolation between GF LOW and GF HIGH. We introduce the term GF TARGET to define the values corresponding to the various staged decompression stops resulting from this interpolation.

Note that the conservatism introduced with a given GF is not a straight percent reduction. We can rewrite the equation above as:

$$P_{t.inert} = \frac{\mathrm{GF}}{100} * P_{t.tol} + \frac{100 - GF}{100} * P_{amb}$$

Consequently, a GF HIGH of 85 would yield a reduction in tolerated inert gas pressure equal to:

$$P_{t.tol.red} = 0.85 * P_{t.tol} + 0.15 * P_{amb}$$

Gradient factors are, in essence, a normalisation of the pressures otherwise expressed in millibars in reference to maximum tolerated values also in millibars, and they are

used here to describe inert gas load in the tissues during the dive for ease of data interpretation.

The GF terminology is now commonplace and used in many modern dive computers (e.g., Shearwater, Heinrichs-Weikamp). For this discussion, in addition to GF TARGET, the following terms are defined:

GF NOW represents the instantaneous inert gas tension in the leading tissue (or in a specific tissue if so specified), calculated with the current inert gas tension, the ambient pressure corresponding to the current depth, and Bühlmann's $P_{t.tol}$ at that depth.

GF @SURF represents the result of applying the current inert gas tension in the leading tissue to surface conditions, i.e., it is calculated with the current inert gas tension, the ambient pressure at the surface, and Bühlmann's $P_{t.tol}$ at the surface.

Based on this terminology, the ceiling can be defined as the depth at which GF NOW reaches GF TARGET. It is the shallowest point the diver can reach while respecting the constraint imposed by the choice of GF LOW and GF HIGH and it maximises the inert gas pressure gradient available for washout.

All dive profiles presented here are the result of computer simulations and have been carried out for the sake of comparisons. For pressures we assumed salt water density of 1.025 kg·L^{-1} (1 msw = 10.055 kPa). When following the ceiling, we have chosen to do so only for depths deeper than 6 msw, as in practical terms it would be unwise to extend the continuous ascent due to the increased difficulty in maintaining a good buoyancy control close to the surface (for instance because of influence of surface wave action and the exaggerated effect of small changes in depth on changes in buoyancy).

Results

Results of our simulations are interpreted in terms of gradient factors during the ascent. Based on the terminology defined earlier, one of three situations can arise during ascent:

- GF NOW > GF TARGET: Diver is above the ceiling, the limiting criterion is violated
- GF NOW = GF TARGET: Diver is at the ceiling, inert gas washout is optimised (maximum pressure gradient exploited)
- GF NOW < GF TARGET: Diver is below the ceiling, inert gas washout is inefficient.

When performing staged decompression in 3 msw steps GF NOW = GF TARGET is achieved only upon reaching the next stop. As inert gas is washed out during the stationary staged decompression stop, GF NOW decreases. When it has decreased to the level corresponding to GF TARGET at the next, 3 msw shallower, staged decompression stop depth, the diver can ascend to that level. Throughout the stay at constant depth the pressure gradient available for inert gas washout is continuously diminishing.

This becomes evident in Figure 1, showing the results for a dive to 60 msw for 20 minutes performing staged decompression using air and GF 85/85 (constant GF TARGET = 85). The dashed black line represents the depth profile. During the ascent a first stop occurs at 15 msw, followed by stops at 12 msw, 9 msw, 6 msw and 3 msw. The dashed green line represents GF NOW. A red line is drawn at GF TARGET = 85. By definition, GF NOW is not to exceed this value at any time during the dive and in particular at the end of the dive when GF NOW usually reaches its maximum value. Figure 1 also shows GF @SURF (dashed blue line), which coincides with GF NOW at the end of the dive: it is an indication of the accumulation of inert gas produced by this dive. What is most evident in Figure 1 however is the sawtooth profile of GF NOW during ascent. As intended by the algorithm, the value of 85 is reached at the beginning of each staged stop, but decreases as inert gas is washed out and the tissue tension decreases, while the ambient pressure is constant. The algorithm computes the end of the staged stop so that, as the diver reaches the next staged stop, the GF increases to 85 again due to the decrease in ambient pressure. Discontinuities visible in the GF NOW line are due to the fact that GF NOW is referenced to the leading tissue, which changes as the dive progresses from the fastest to the next fastest and so on, and such a switch leads to a sudden change in tissue tension ($P_{t.inert}$) and in maximum tolerated inert gas pressure ($P_{t.tol}$), both of which are contained in the definition of gradient factor. The progression in leading tissue during the dive is discussed later.

Figure 2 illustrates the same staged decompression dive as in Figure 1 (dashed lines) but in addition shows the corresponding ceiling-controlled decompression (up to 6 msw) (solid lines). GF NOW stays equal to or very close to GF TARGET over the relevant part of the ascent. Following the ceiling also implies that the ascent profile is continuous and always a bit shallower. As a result of this shallower profile with maximised inert gas gradient, GF @SURF decreases faster and the dive is shorter because GF @SURF reaches the value of 85 sooner. The area between the solid green GF NOW curve (ceiling-controlled decompression) and the dashed green GF NOW curve (staged decompression) is proportional to the lost efficiency of decompressing according to the standard 3 msw stops.

Figure 3 shows a dive to the same depth and bottom time but with an ascent calculated according to GF 30/85. The red line represents GF TARGET, which is the interpolation between GF LOW (30) and GF HIGH (85). The interpolation is carried out as defined for staged decompression, resulting in the sequence of steps shown. On the ceiling decompression GF NOW closely follows GF TARGET. Since the lowering of GF LOW from 85 to 30 introduces stops deeper than in the previous case, the reduction of decompression duration

Figure 1

GF NOW and GF @SURF profiles in a simulated dive to 60 msw for 20 minutes breathing air and using GF 85/85 to calculate a staged decompression

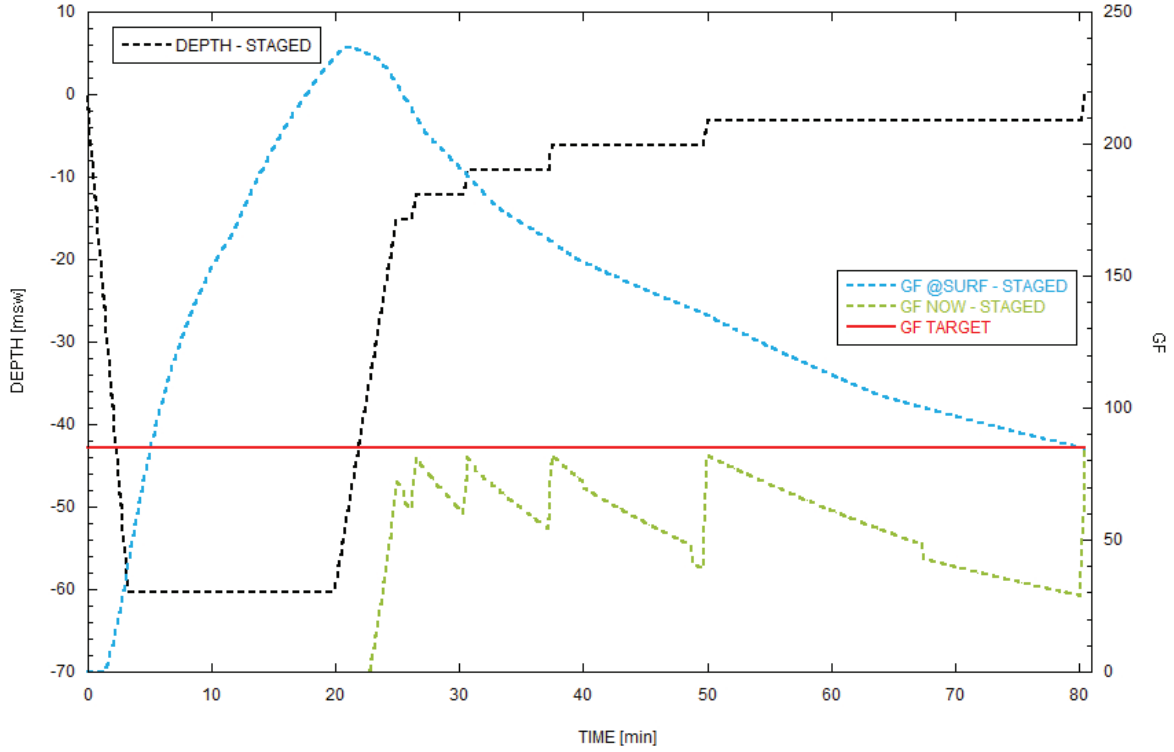

Figure 2

GF NOW and GF @SURF profiles in a simulated dive to 60 msw for 20 minutes breathing air and using GF 85/85 to calculate and compare staged decompression and ceiling-controlled decompression until reaching the 6-msw stop

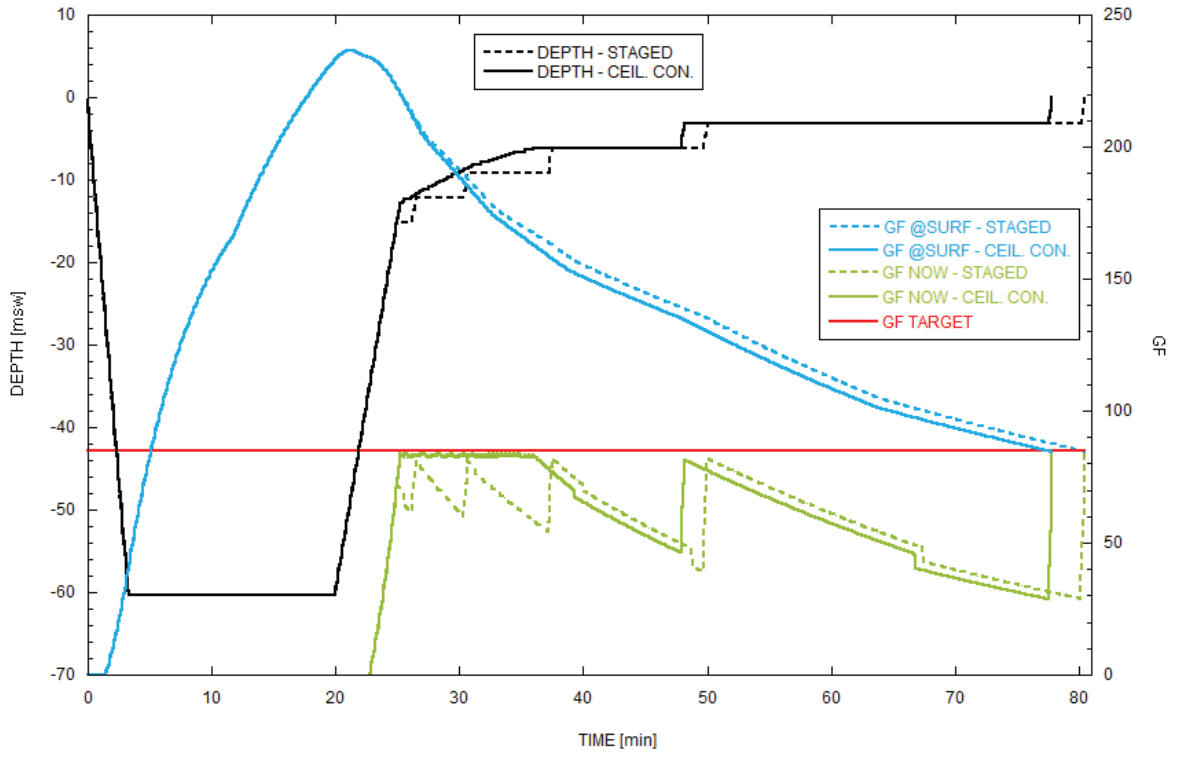

Figure 3

GF NOW and GF @SURF profiles in a simulated dive to 60 msw for 20 minutes breathing air and using GF 30/85 to calculate and compare staged decompression and ceiling-controlled decompression until reaching the 6-msw stop

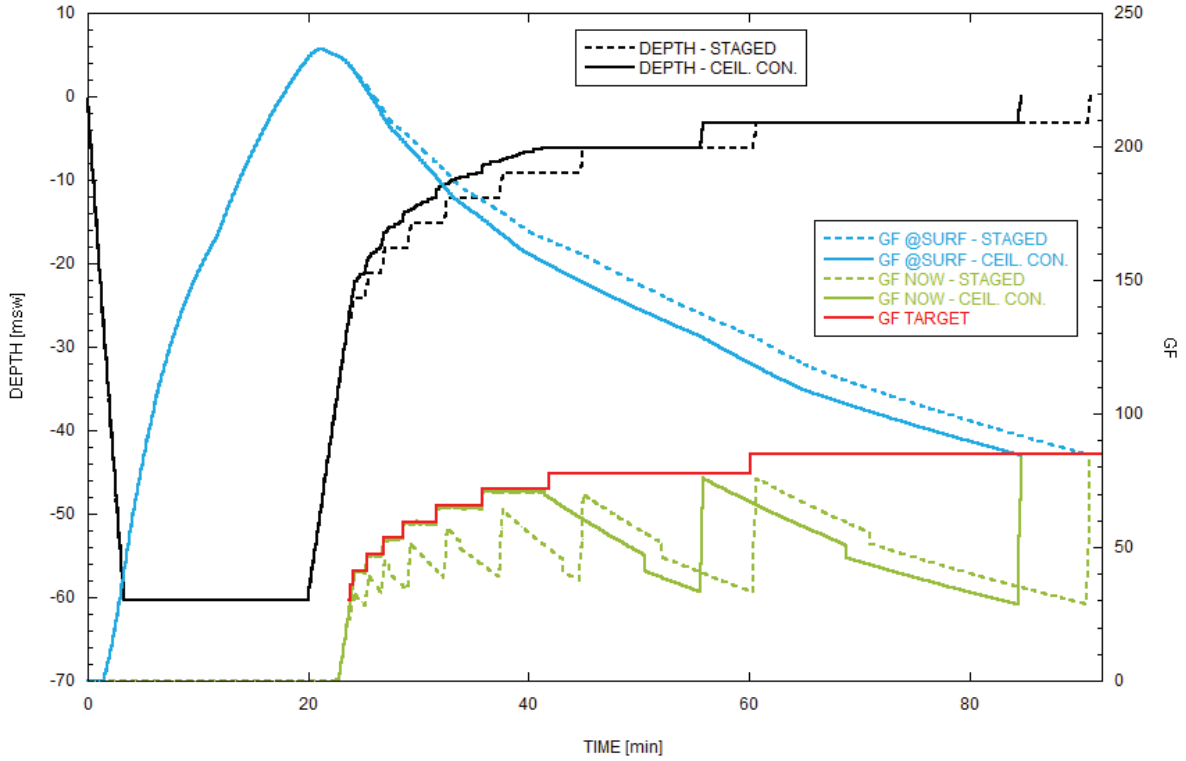

Table 1

Duration of decompression for various profiles conducted with staged or ceiling decompression, with the time advantage for ceiling-controlled decompression; EAN – enriched air nitrox (the subscript designates the oxygen fraction)

Gas(es), depth, bottom time, GF LOW/HIGH	Staged decompression (min)	Ceiling-controlled decompression (min)	Time advantage (% difference)
Air, 60 msw, 20 min, 85/85	55	53	5
Air, 60 msw, 20 min, 30/85	67	61	10
Air, EAN_{40} and EAN_{80}, 60 msw, 20 min 85/85	25	24	4
Air, EAN_{40} and EAN_{80}, 60 msw, 20 min 30/85	29	27	6
Air, EAN_{40} and EAN_{80}, 60 msw, 40 min 30/85	83	75	10
Trimix, 150 msw, 20 min, 30/85	282	249	12

achieved by following the ceiling increases. Simulations were also carried out with different bottom times, breathing gases and GF values, These results are summarised in Table 1.

Further detail of the behaviour of the individual tissues is now considered for the GF 85/85 dive. Figure 4 depicts GF NOW for the two decompression procedures previously depicted in Figure 2, but now with colours identifying which of the individual tissues (among the 16 ZH-L16C tissues) is the leading tissue. At the start of the ascent tissue T2 (half time = 8 minutes) is the leading tissue, and this role is soon passed on to tissue T3 (half time = 12.5 minutes), then T4 (half time = 18.5 minutes) and so on, and the dive ends with tissue T7 (half time = 54.3 minutes) controlling the final surfacing. This figure shows that although following the ceiling exposes the tissues to higher supersaturation, the time interval during which this higher supersaturation is at the limit of the M-value for one individual tissue is rather short, and in this particular choice of depth and bottom time only tissues T3 and T4 spend any significant time at GF = 85, and each only for 5–6 minutes. Figure 5 shows the detail

Figure 4

GF NOW profiles for tissues T2–7 (from the 16 tissues in Bühlmann's ZH-L16C algorithm) for a dive to 60 msw for 20 minutes breathing air and using GF 85/85 to calculate and compare staged decompression and ceiling-controlled decompression until reaching the 6-msw stop; the noise in the GF NOW traces is due to the choice of time and depth steps in the simulations

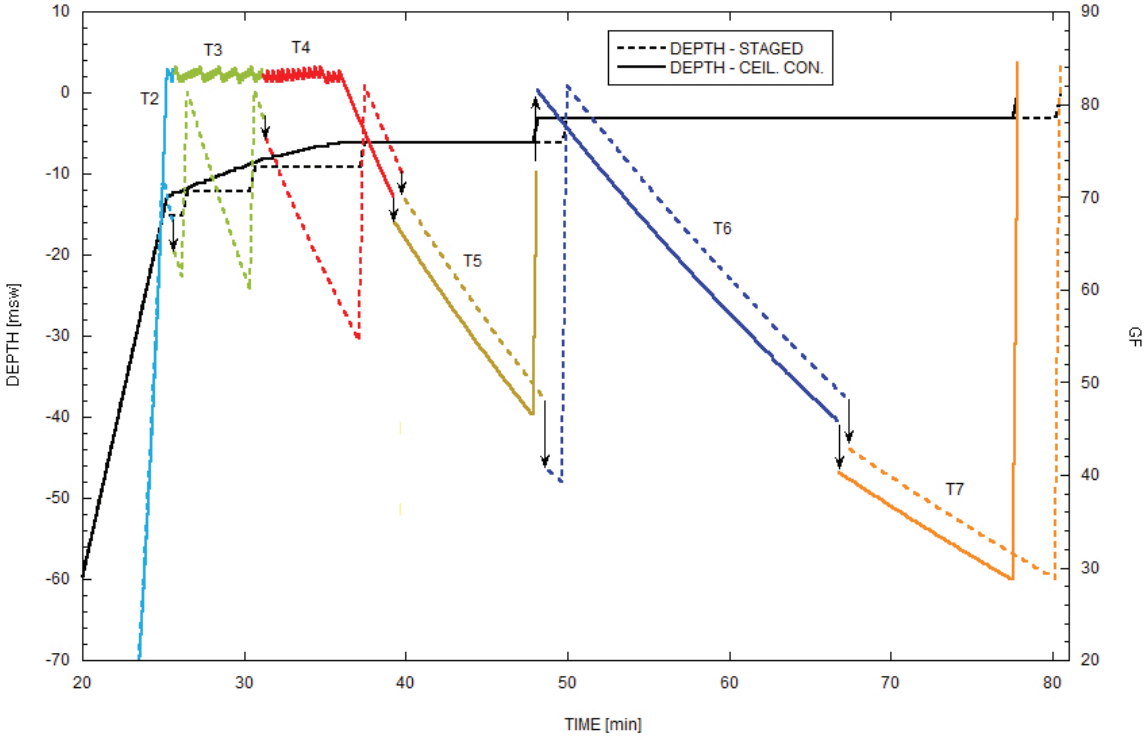

Figure 5

GF NOW profiles for tissues T3 and T4 (from the 16 tissues in Bühlmann's ZH-L16C algorithm) for a dive to 60 msw for 20 minutes breathing air and using GF 85/85 to calculate ceiling-controlled decompression until reaching the 6-msw stop; the noise in the GF NOW traces is due to the choice of time and depth steps in the simulations

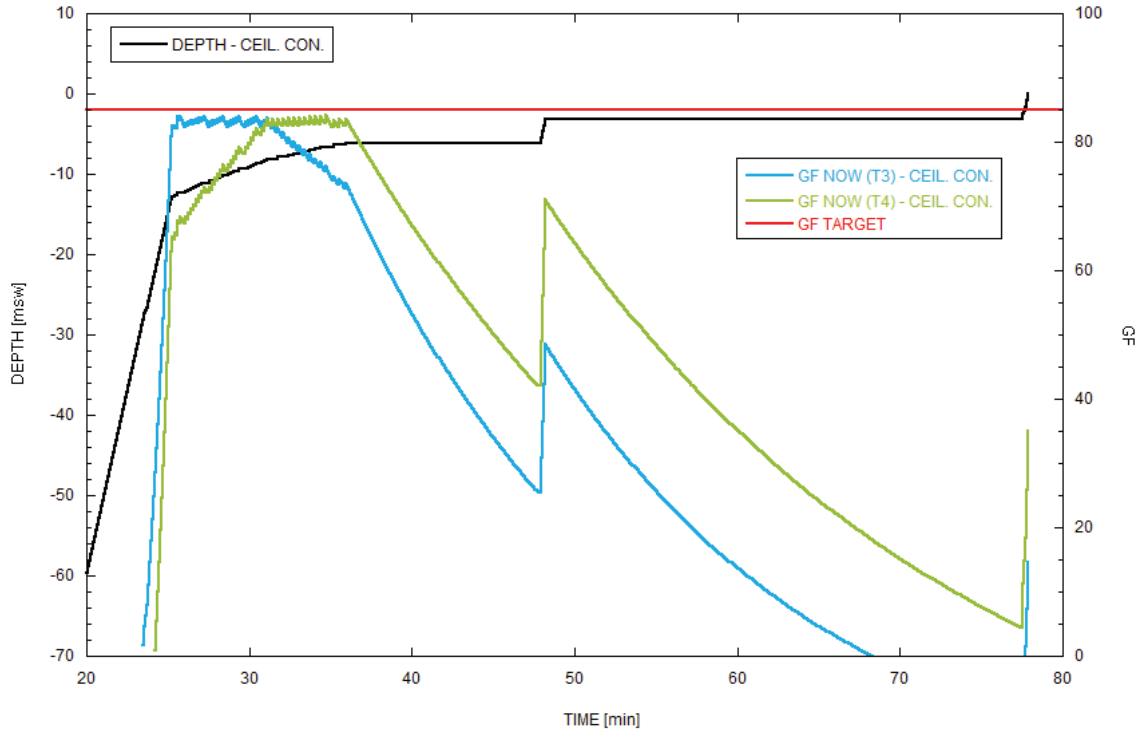

Figure 6

Tissue nitrogen tension profiles for tissues T6–9 (from the 16 tissues in Bühlmann's ZH-L16C algorithm) and inhaled nitrogen pressure for a dive to 60 msw for 20 minutes breathing air and using GF 85/85 to calculate and compare staged decompression and ceiling-controlled decompression until reaching the 6-msw stop

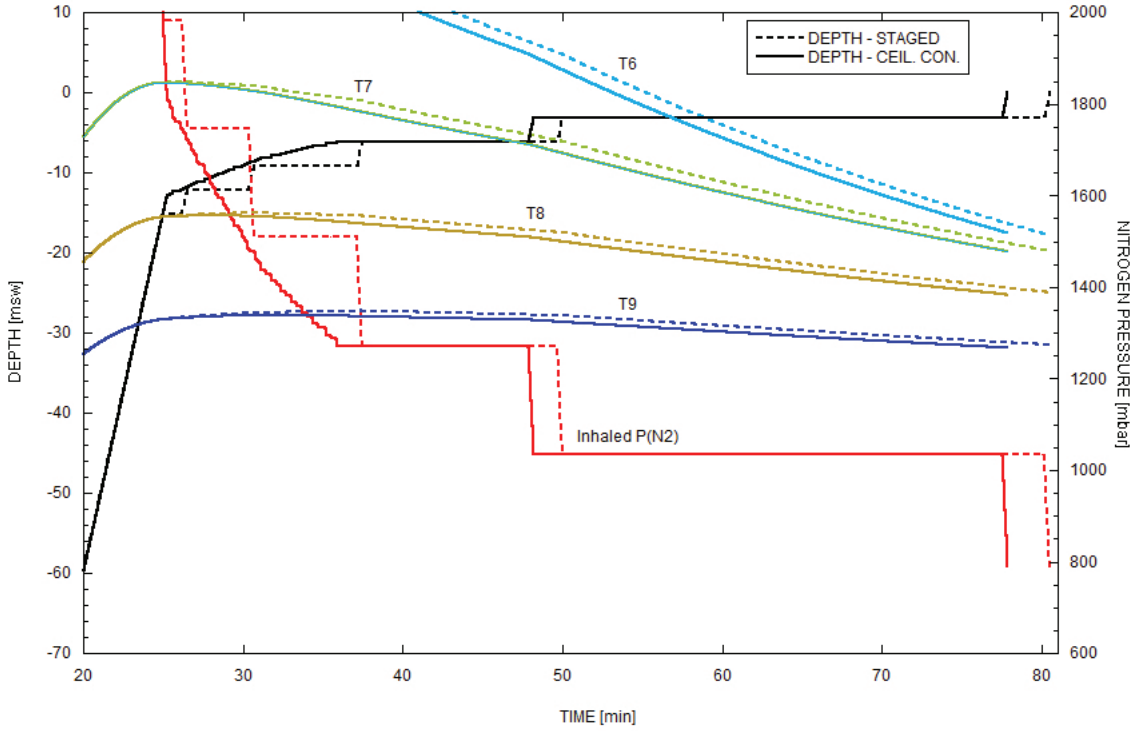

Table 2

Calculated values of tissue pressure (mbar) and maximum tolerated inert gas pressure for the 16 tissues in the Bühlmann ZH-L16C algorithm upon surfacing from a dive to 60 msw for 20 minutes breathing air and using GF 85/85 to calculate and compare staged decompression and ceiling-controlled decompression until reaching the 6-msw stop; deco – decompression

Tissue	Staged deco (mbar)	Ceiling deco (mbar)	$P_{t.tol}$ (mbar)
1	969	970	2,868
2	1,018	1,023	2,277
3	1,148	1,163	2,034
4	1,323	1,341	1,855
5	1,463	1,476	1,700
6	1,512	1,518	1,564
7	1,478	1,477	1,480
8	1,388	1,383	1,423
9	1,273	1,267	1,382
10	1,176	1,169	1,348
11	1,100	1,094	1,321
12	1,033	1,028	1,293
13	976	971	1,267
14	928	923	1,241
15	887	884	1,225
16	855	852	1,207

of inert gas pressure (expressed in terms of GF) for tissues T3 and T4 and it can be seen that when the tissue is not '*leading*', its tension is significantly lower than the M-Value (in this representation it means GF NOW << GF TARGET).

To this point the discussion has focused on fast tissues, up to and including that which is the leading tissue at surfacing (T7 in the case described in Figures 2, 4 and 5). During decompression these tissues become supersaturated and exhibit a pressure gradient in favour of inert gas wash out. It is also appropriate to discuss slow tissues, which switch from gas uptake to gas washout very late in the decompression profile, if at all. Figure 6 compares the inhaled pressure of nitrogen to the tension in tissues close to the leading tissue at the time of surfacing, specifically T6 (half time = 38.3 minutes), T7 (half time = 54.3 minutes), T8 (half time = 77 minutes) and T9 (half time = 109 minutes). Tissue 6 is, as expected, washing out nitrogen under a fairly substantial gradient all the way to the surface. Tissue 7 switches from taking up to washing out nitrogen at around 12 msw in both profiles. Tissue 8 switches at 9 msw in both profiles. Tissue 9 switches at the end of the 9 msw stop in staged decompression and at around 7 msw when following the ceiling. Tissues slower than T9 will take up nitrogen all the way to a depth of 3 msw or shallower. This means that slow tissues are undersaturated for most of the decompression, will take up less inert gas following a shallower profile, and thus can only benefit from following the ceiling.

Table 2 lists the nitrogen pressure in each tissue upon surfacing for the two ascent procedures. When following the ceiling, tissues T1 through T6 have higher ending nitrogen

pressure; tissue T7 shows no difference, as is expected since it is the leading tissue upon surfacing in both cases, while tissues T8 through T16 have lower ending nitrogen pressure when following the ceiling.

Discussion

The reduction in decompression duration when following the ceiling is a logical fact, and this reduction can vary from a few percent of the total staged decompression duration to about 12% for the dive profiles we have investigated. Deeper and longer profiles, lower GF LOW and a more tailored choice of breathing gases will likely have a greater effect. The deeper the first stop, the greater the advantage from following the ceiling. The inert gas pressure in each tissue at the end of the dive also follows a predictable outcome; tissues slower than the leading tissue at the end of the dive take up inert gas almost all the way to the surface and they benefit from the shallower and shorter depth profile. Faster tissues wash out inert gas during the decompression phase and benefit from the longer times involved in staged decompression. The difference is very small, since when following the ceiling the gradients for washout are higher and thus, albeit for a shorter time, the washout is more efficient. As Table 2 shows for the 60 msw dive on air and GF 85/85, the differences are not significant, especially in light of the tolerated values at the surface.

An immediate conclusion however cannot be drawn as to the relative safety between the two procedures. Whereas the decompression algorithm has a binary outcome (either it is violated or it isn't), the impact of a dive on a human can only be described in terms of risk of decompression sickness. Countless dives, both in dedicated experiments carried out in hyperbaric chambers and in the field, have provided the empirical data to establish a scale of such risk. The vast majority if not all of this data stems from staged decompression protocols and it cannot be extrapolated, *a priori*, to ceiling-controlled dives. Following the ceiling increases the duration of supersaturation in the fast tissues and reduces it for slow tissues. This might increase, not change, or decrease the risk of decompression sickness.

The risk of decompression sickness would increase if the high supersaturation over a prolonged time interval caused (more) bubble formation and the latter had a negative impact. This would be equivalent to saying that the M-values have a time limit; they are tolerated only because in staged decompression there is only a short exposure to the highest value. It would imply that the apparent inefficiency of the staged decompression is actually an intrinsically valuable component in the process itself.

The risk of decompression sickness would not change if the higher supersaturation over a prolonged time did not have a negative impact, possibly because as seen above it is not prolonged for very long, and later these fast tissues become undersaturated and any bubble that may have formed will shrink. This would be equivalent to saying that M-values did not have an immediate, short-term time limit. It would imply that the apparent inefficiency of the staged decompression is simply that, an inefficiency.

The risk of decompression sickness would decrease if in addition to the above being true the slow tissues, favoured by a ceiling ascent, played a dominant role in causing decompression sickness.

Workman[6] first suggested the concept of time-limited validity of M-values when discussing the higher tolerance of fast tissues with respect to slow tissues, by noting that in fast tissues the excess saturation time-course (at the surface but also in staged decompression) is brief, while in slow tissues the time-course is longer and consequently the need arises to start off at a lower M-value. Workman applied the same considerations to the difference between tolerated supersaturation during ascent (high excess saturation over a prolonged time span) and staged decompression ("*periodic excess saturation*"). Another "*important factor of difference in permissible tissue tension values for various half-time tissues may well be the greater molar concentration of inert gas for some slow tissues resulting from greater solubility of inert gas in these tissues. As molar concentration of inert gas increases in a tissue the probability of bubble formation would increase upon reduction of hydrostatic pressure as a greater number of gas molecuels are available in excess of that held in solution at saturation*."[6] This could be a mechanism to describe a decrease in risk of decompression sickness mentioned above. A study comparing decompression schedules with deep stops vs shallow stops discussed the likely importance of high gas supersaturation and consequent bubble formation in slow tissues.[7] Although conceptually quite different profiles were analysed from those proposed here, there is evidence that slow tissues do play a significant role in the risk of decompression sickness. Reducing their inert gas tension, as is implicit in ceiling-controlled decompression profiles, may be beneficial overall.

Figures 4 and 5 show that the increased tissue tension reaches values near or equal to the M-value in only a few tissues, and does so for only a short time interval. Longer bottom times would increase these intervals but also spread the role of leading tissue to slower tissues. In addition, following the ceiling eliminates the sudden surges in inert gas pressure in the tissues when advancing from one stage to the next (sawtooth profiles). These surges could represent a bubble excitation mechanism. Eliminating them could represent a counterbalancing influence to the higher supersaturation. There is therefore, in our opinion, reason to believe that following the ceiling might be as safe as staged decompression and that the decompression time advantage could be exploited. Following the ceiling can also be implemented in combination with lower GF LOW/

HIGH values, sacrificing the shortened decompression time in favor of lower supersaturation, while eliminating the sawtooth profiles.

Conclusions

Ceiling-controlled decompression shortens the decompression duration at the cost of higher supersaturation in the faster tissues. While this increase in supersaturation does not lead to a breach of the limits of the decompression algorithm, one cannot *a priori* state that it does not lead to an increase in risk of decompression sickness. Computer simulations comparing dives using staged decompression and ceiling-controlled decompression and subsequent analysis of the inert gas tensions suggest that the two procedures might be similarly acceptable and thus the matter should be investigated further.

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Dr Angelini is employed by a diving equipment manufacturer (Mares), who manufacture diving computers.

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