Selecting optimal air diving gradient factors for Belgian military divers: more conservative settings are not necessarily safer

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Abstract
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Introduction: In 2018, the Belgian Defence introduced a commercial off-the-shelf dive computer (Shearwater Perdix™) for use by its military divers. There were operational constraints when using its default gradient factors (GF). We aimed to provide guidelines for optimal GF selection.

Methods: The Defence and Civil Institute of Environmental Medicine (DCIEM) dive tables and the United States Navy (USN) air decompression tables are considered acceptably safe by the Belgian Navy Diving Unit. The decompression model used in the Shearwater Perdix (Bühlmann ZH-L16C algorithm with GF) was programmed in Python. Using a sequential search of the parameter space, the GF settings were optimised to produce decompression schedules as close as possible to those prescribed by the USN and DCIEM tables.

Results: All reference profiles are approached when GF_{LO} is kept equal to 100 and only GF_{HI} is reduced to a minimum of 75 to prolong shallower stop times. Using the Perdix default settings (GF_{LO} = 30 and GF_{HI} = 70) yields deeper initial stops, leading to increased supersaturation of the 'slower' tissues, which potentially leads to an increased DCS risk. However, Perdix software does not currently allow for the selection of our calculated optimal settings (by convention $GF_{LO} < GF_{HI}$). A sub-optimal solution would be a symmetrical GF setting between 75/75 and 95/95.

Conclusions: For non-repetitive air dives, the optimal GF setting is GF_{LO} 100, with only the GF_{HI} parameter lowered to increase safety. No evidence was found that using the default GF setting (30/70) would lead to a safer decompression for air dives as deep as 60 metres of seawater; rather the opposite. Belgian Navy divers have been advised against using the default GF settings of the Shearwater Perdix dive computer and instead adopt symmetrical GF settings which is currently the optimal achievable approach considering the software constraints.

Introduction

Breathing compressed air at depth during a dive leads to the diffusion of the inert gas in the breathing gas, nitrogen, into the different tissues of the body. This process is driven by the 'inert gas pressure gradient'; the difference between the pressure of the inspired inert gas in the lungs and the inert gas tension in blood and tissues. The process is reversed when the diver ascends; inert gas will be washed out from the tissues as the inert gas tension in the tissues and blood now exceeds the inert gas pressure in the lungs. When the ambient pressure is reduced, the sum of all metabolic and inert gas tensions in the tissues can be larger than the ambient pressure and the tissues become supersaturated. This supersaturation is relieved either by inert gas elimination through diffusion from the tissues into the blood and subsequently to the alveoli to be expired, or, if the decompression is sufficiently large and rapid, by the formation and growth of inert gas bubbles in tissues and/or blood, which may lead to decompression Sickness (DCS).[1] The reduction in ambient pressure, and the resulting inert gas supersaturation, must be carefully controlled to allow sufficient washout of inert gas and to minimise the formation of bubbles. Computing a safe reduction in ambient pressure and a safe ascent level is the main purpose of a dive computer.

In 2018, the Belgian Defence introduced a commercial dive computer, the Shearwater Perdix™, for use by its military divers, replacing the end-of-life Cochran EMC-20H™ dive computer. Initial experience indicated several operational constraints. Using the Perdix dive computer with its default gradient factors (GFs) resulted in a significant reduction of the no-decompression limits (NDL) compared to earlier practice using the Cochran computer, yielding either shorter usable work time underwater, or the introduction of mandatory decompression stops. For 'decompression dives', substantial longer required decompression times were observed. Therefore, the main purpose of this research was to provide recommendations to increase usable work time under water while maintaining safety, and to provide guidelines for GF selection during both no-decompression and decompression diving.

Methods

The basic decompression algorithm used in the Shearwater Perdix™ dive computer is a gas content model, the Bühlmann ZH-L16C model, with the use of GF[2] to modify the original equations.[3] The 'C' version of the ZH-L16 model was developed specifically for use in computer algorithms and dive computers. In this model, the human body is represented by 16 theoretical tissue compartments and the model assumes that inert gas exchange occurs at an exponential rate, both during inert gas uptake and elimination.[4] If the inspired inert gas pressure and the exposure time are known, the equalisation of pressure is calculated by means of different half-time values for different tissue compartment. Each tissue is considered to have a different maximum permissible inert gas tension, the 'M-value', as a function of the ambient pressure, which is defined by two parameters *a* and *b*:

$$P_{T,N2,tol} = \left(\frac{P_{amb}}{b}\right) + a \qquad (1)$$

Inversely, it is possible to calculate the maximum tolerated ambient pressure, or safe ascent depth, for each of the 16 tissue compartments based on the prevailing inert gas tension:

$$P_{amb,tol} = \left(P_{T,N2} - a\right) \times b \qquad (2)$$

The highest tolerated ambient pressure, or safe ascent depth, defines the shallowest depth to which a diver can ascend, and determines the depth of the decompression stop (a multiple of 3 m by convention). Ascending beyond this decompression 'ceiling' would violate the maximum permissible inert gas tension limit. The diver then waits at this decompression stop while inert gas is progressively eliminated from the body until the inert gas tension in all tissue compartments has decreased sufficiently to allow ascent to the next decompression stop.

A different approach to decompression, embodied in bubble decompression algorithms, suggest that decompression safety might be improved by adding stops at greater depths than those calculated with the gas content models. In essence, this principle can be mimicked by modifying the original M-values and thus forcing a gas content model to impose deeper stops. Baker proposed the use of GFs in the Bühlmann ZH-L16C model to add a margin of safety by lowering the allowed tissue compartment overpressure.[2] Gradient factors are expressed as a decimal fraction or a percentage of the difference between the ambient pressure and the original M-value. They modify the decompression profiles by deviating from the original, experimentally validated M-values of the Bühlmann ZH-L16 model:

$$P_{T,N2,tol,GF} = P_{T,N2,tol} \times GF + (1 - GF) \times P_{amb} \qquad (3)$$

As presented in Figure 1, the GF setting consists of a set of two parameters, the 'low' setting (GF_{LO}) and the 'high' setting (GF_{HI}). Although different notations for GFs can be used (e.g., 0.3/0.7, 30%/70% or 30/70), the most common notation is GF_{LO}/GF_{HI}, e.g., 30/70, which will be used here. The actual applicable GF at a specific stop depth ($D_{stop,current}$) depends on the ambient pressure and a linear change from GF_{LO} at the first stop depth ($D_{stop,first}$) to GF_{HI} when surfacing ($D_{stop,final}$ = 0 msw):

$$GF = \left[\frac{GF_{HI} - GF_{LO}}{D_{stop,final} - D_{stop,first}}\right] * D_{stop,current} + GF_{HI} \qquad (4)$$

Changing the GF results in a modified decompression profile; GF_{LO} mainly controls the depth of the first decompression stop, while lowering GF_{HI} results in longer decompression times at shallower stops. In the Shearwater Perdix™, the default GF is 30/70, with three pre-set alternatives (Firmware v84/BT 10: 45/95, 40/85, and 35/75), or the user may set custom GF with the constraint that $GF_{LO} < GF_{HI}$.[3]

In contrast to the original ZH-L16 model, the use of GF in itself is not directly linked to experimentally validated decompression profiles. In order to develop such a relation, a method was developed to map experimentally validated profiles onto the ZH-L16C deterministic gas content model. Both the air decompression tables in the US Navy Diving Manual (Version 6) and the Defence and Civil Institute of Environmental Medicine (DCIEM) dive tables are extensively experimentally validated and considered by the Belgian Navy as an acceptable standard for safe decompression in terms of no-decompression limits, stop depths and stop times. Hence, these tables were used in the current study as the reference decompression profiles. The parameters of our deterministic overpressure model consist of the half-time values, the original M-values and the GF which modify these limits. The half-time values and the two parameters *a* and *b* defining the original M-values were kept fixed in the current study and only the GF were modified. The objective was then to find the values of the GF that enables the deterministic ZH-L16C model to produce decompression schedules that are as close as possible to those prescribed by the US Navy and the DCIEM tables.

This study considered air dives up to a depth of 60 metres of seawater (msw), and no-decompression diving and decompression diving were considered separately. The decompression diving segment was divided into two sections, i.e., the normal air diving limit and the 'exceptional exposure' dives.[5] Gradient factor selection guidelines were

Figure 1

Left panel: the blue line presents the combined inert gas tension curve and the dive profile (ambient pressure) for a single tissue compartment during a hypothetical dive to 30 msw (4 bar). Because of the maximum permissible tissue tension (M-value line), a decompression stop is included at 3 msw (1.3 bar ambient pressure). Right panel: a gradient factor (GF) is a fraction of the difference between the ambient pressure lines and the M-value line. The two parameters, GF_{LO} and GF_{HI}, modify the original M-value line, thereby changing the decompression profile

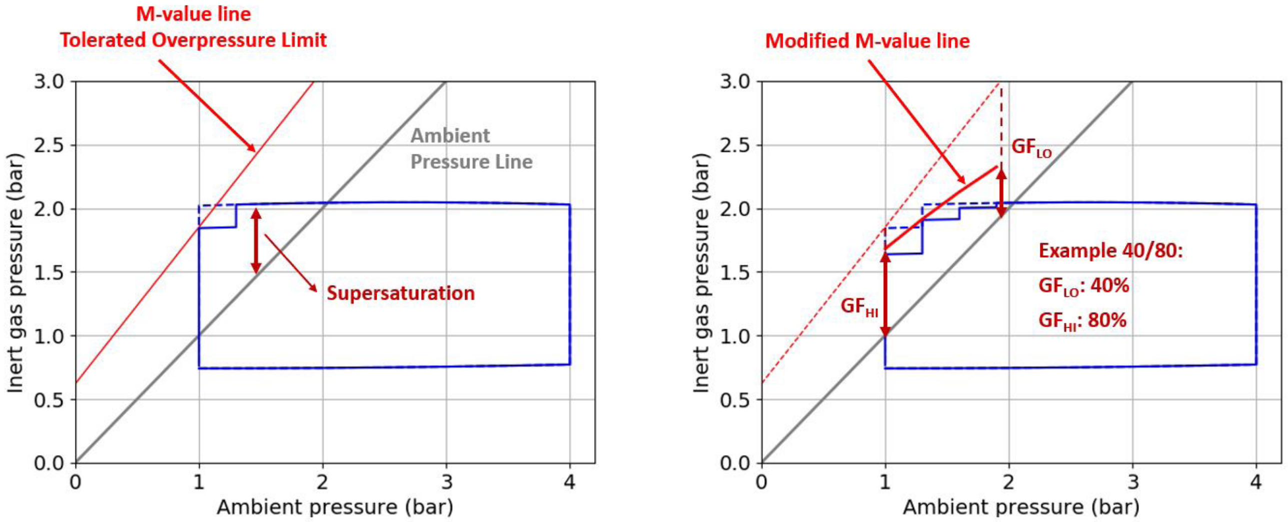


Figure 2

Sequential search of the gradient factor (GF) parameter space; the optimal solution is the GF setting which results in the minimum integrated difference between the reference profile, e.g., a Thalmann or DCIEM profile, and the decompression profile for a particular GF setting

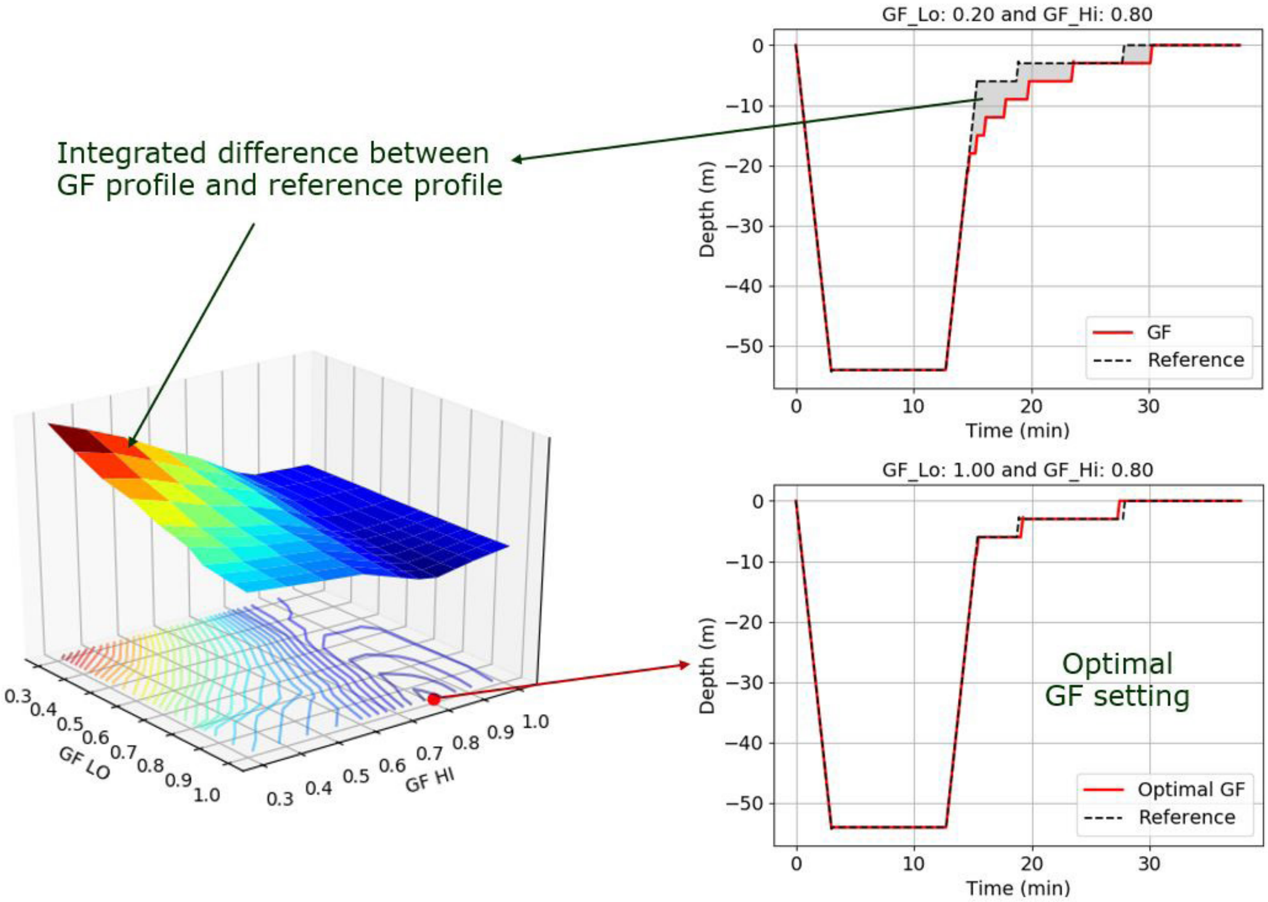
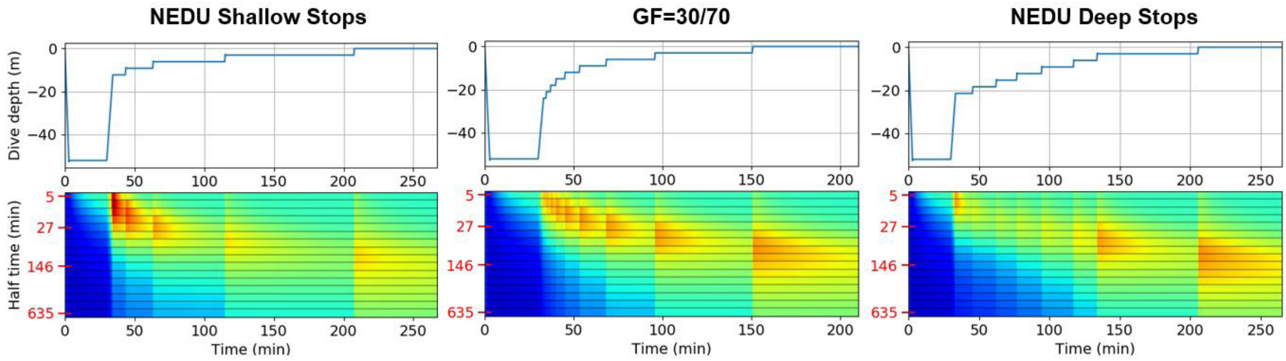


Figure 3

Comparison of three different decompressions for an air dive of 30 min to a depth of 52 msw: the NEDU shallow-stops schedule, the deep-stops schedule and a schedule using gradient factors (GF) 30/70. The upper panel presents the resulting dive profiles. The lower panel presents the evolution of the tissue ratio ($P_{T,N2}/P_{amb}$) for each of the 16 compartments of the Bühlmann ZH-L16C model (yellow-orange-red indicates a supersaturation, with red being the highest encountered supersaturation).



provided both for maximising work time under water without any decompression obligation, and for longer and deeper decompression dives, with the aim of approaching the familiar US Navy and DCIEM decompression procedures.

NO DECOMPRESSION LIMITS

The no-decompression limits (NDLs) were calculated using a two-step approach routine, based on an algorithm from the Thalmann algorithm decompression table generation software.[6] The reported NDLs included the descent time to the dive depth and were computed to the nearest second and assumed an ascent rate of 10 msw·min^{-1}.

DECOMPRESSION DIVING

The Bühlmann ZH-L16C algorithm was programmed in Python and implemented as a real-time algorithm, similar to the real-time algorithm as described by Thalmann.[7] The algorithm updates the inert gas tension in the 16 tissue compartments every two seconds and all calculations are based on the current depth and breathing gas. The algorithm then compares these tissue tensions with the ascent criteria, which are the maximum permissible tissue (inert gas) tensions at each of the 3 msw incremental stops depths, as calculated using Equations 1, 3 and 4. The algorithm determines the shallowest stop depth at which none of the current tissue tensions will be greater than their respective M-value. This depth is the safe ascent depth. The dive profile ascends to this decompression stop depth and waits for the safe ascent depth to decrement to the next 3 msw shallower stop until surfacing.[7] By using such a real-time algorithm, the inert gas dynamics during ascent (either continuing uptake or release of inert gas) is taken into account, in contrast to assuming an instantaneous ascent to the stop depth. The output of this real-time algorithm, i.e., the stop times and depths, was compared with and validated against publicly available data, including Bühlmann (2002)[4] and Thalmann (1984),[7] and the commercial available MultiDeco V4.19 software.

In the next step, this validated algorithm was used to determine which GF result in a schedule that approaches the reference decompression profiles. The GF optimisation was done using a sequential search of the parameter space, with the cost function being the integrated difference between the decompression profile for a particular GF setting and the reference decompression profile (Figure 2). The integrated difference was calculated starting at the beginning of the ascent and ended when surfacing. The time increment was identical to the two second time step of the algorithm. No additional constraints, e.g., the first stop depth, were incorporated. All possible combinations of GF_{LO} and GF_{HI} between 0.3 and 1.0, with increments of 0.05, were tested, and the GF setting which resulted in the minimal integrated difference between the resulting decompression profile and the reference profile was selected as the optimal solution. Afterwards, all optimal solutions were visually inspected to confirm the goodness-of-fit, and no manual corrections were required.

First, the GF settings were investigated for a single dive of 30 minutes to a depth of 52 msw. Two decompression schedules for this particular dive have been extensively tested.[8] These schedules both had 174 minutes of decompression time but differed by having either traditional shallow stops (resulting in 3 DCS in 192 man dives) or deep stops (11 DCS in 198 man dives and higher VGE grades) (Figure 3 left and right panels). The large size and clear outcome of this trial was considered a strong reference case for optimisation. Figure 3 (lower panels) presents the calculated tissue ratio, i.e., $P_{T,N2}/P_{amb}$, for the 16 compartments of the Bühlmann model for both decompression schedules. An increased (calculated) supersaturation of the slower tissues is currently the most plausible theoretical cause for the increased DCS incidence observed using the deep-stops schedule.[8] In the current study, the optimal GF was calculated to approach the shallow-stops profile and the standard GF setting of the Shearwater Perdix™ (30/70) was investigated in terms of supersaturation and compared to the two decompression schedules (Figure 3 centre panel).

Finally, the GF settings for many other different air decompression dives up to a depth of 60 msw were investigated by using the DCIEM decompression tables as reference dives.[7]

SHEARWATER PERDIX™ SOFTWARE INPUT RESTRICTIONS

The current software inside the Shearwater Perdix™ does not allow the selection of just any GF_{LO} and GF_{HI} combination. The following three embedded rules in the Perdix software enforce input restrictions on the GF setting:[9]

1. GF_{LO} must be less than or equal to GF_{HI}
2. GF_{HI} must be greater than 30
3. GF_{LO} must be greater than 10

Therefore, the optimisation of GF to approach the reference decompression profiles was done twice: once with and once without using the Shearwater Perdix™ software constraints on GF selection.

SIMULATION PARAMETERS

All DCIEM dive profiles were calculated using 18 msw·min^{-1} as the descent and ascent speed. For dives from the US Navy Manual, the descent speed and ascent speed were set to 18 msw·min^{-1} and 9 msw·min^{-1} respectively. The last decompression stop was performed at 3 msw. A water density of 1,019 kg·m^3, a pressure increase of 1 bar per 10 msw, and an atmospheric pressure of 1.01325 bar at surface were used to calculate the ambient water pressure at depth.

Results

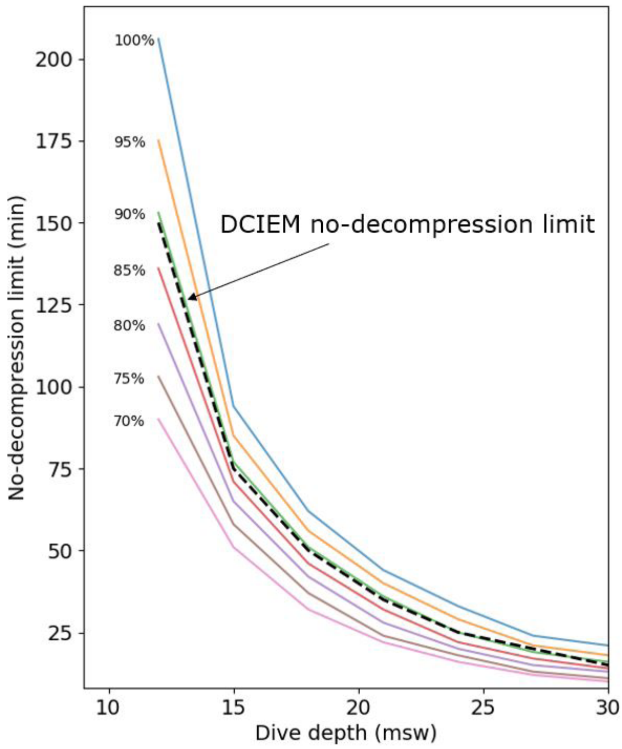
NO DECOMPRESSION LIMITS

The no-decompression limits are determined by the GF_{HI} setting. Figure 4 shows the NDL as a function of the dive depth and for different GF_{HI} settings, together with the DCIEM NDL for comparison. These DCIEM NDLs were approached by the Shearwater Perdix™ when the GF_{HI} was set to 90. As the default GF_{Hi} setting of the Perdix computer is 70, this reduces the NDL considerably, and can be seen to be responsible for the operational constraints reported by the Belgian Navy divers. Considering the DCIEM NDL as a safe standard, a GF_{HI} of 70 is too conservative.

DECOMPRESSION DIVING

Figure 5 (left panel) presents the Bühlmann ZH-L16C decompression profile with the default Perdix GF selection, i.e., 30/70, for a single compressed-air dive of 30 min to a depth of 52 msw, compared to the NEDU study shallow-stops and deep-stops profiles. The total decompression was shorter by more than 50 min with respect to the NEDU profiles, and the decompression schedule included deeper stops during the initial phase of the ascent, similar to the

Figure 4
No decompression limit (NDL) as a function of the dive depth for different GF_{HI} settings in the range between 70 and 100; the black dashed line represents the Defence and Civil Institute of Environmental Medicine (DCIEM) NDL, which is approached when the GF_{HI} is set to 90



NEDU deep-stops profile. Figure 3 (lower panel) presents the evolution of the tissue ratio for each of the 16 Bühlmann compartments (with half-times ranging from 5 min to 635 min) using the 30/70 setting. As a result of the deeper stops during the initial phase of the ascent, the supersaturation was reduced for the faster tissue compartments at the beginning of the ascent but increased for slower tissue compartments later on in the decompression and after surfacing, similar to the NEDU deep stops profile.

Figure 5 (right panel) illustrates the GF with which a Bühlmann decompression schedule approaches best the NEDU shallow-stops schedule: GF_{LO} and GF_{HI} were set to 100 and 40, respectively. This GF_{LO} ensures that the first stop depth is as shallow as possible, while a lower GF_{HI} increases the stop times. Note that this setting is not possible with the software restrictions in the Perdix dive computer.

Figure 6 shows the GF settings that best approached the air decompression dives of the DCIEM table: GF_{LO} was kept equal to 100 and only GF_{HI} was decreased. This is in line with the previous optimization result for the NEDU reference profile. The minimum GF_{HI} of 75 was obtained near the NDL boundary. Again, the current software inside the Shearwater Perdix dive computer does not allow for the selection of these 'optimal' settings. Taking into account the constraints, 'sub-optimal settings' were

Figure 5

Left panel: The ZH-L16C GF 30/70 decompression profile, compared to the shallow-stops and deep-stops schedules used in the NEDU study; using gradient factors (GF) 30/70 results in a shorter total decompression time and in deeper decompression stops during the initial phase of the ascent. Right panel: The optimal ZH-L16C GF 100/40 decompression profile approaches the shallow-stops schedule. A GF_{LO} of 100 ensures that the first stop depth is as shallow as possible, and the reduced GF_{HI} prolongs the decompression time. N2 – nitrogen

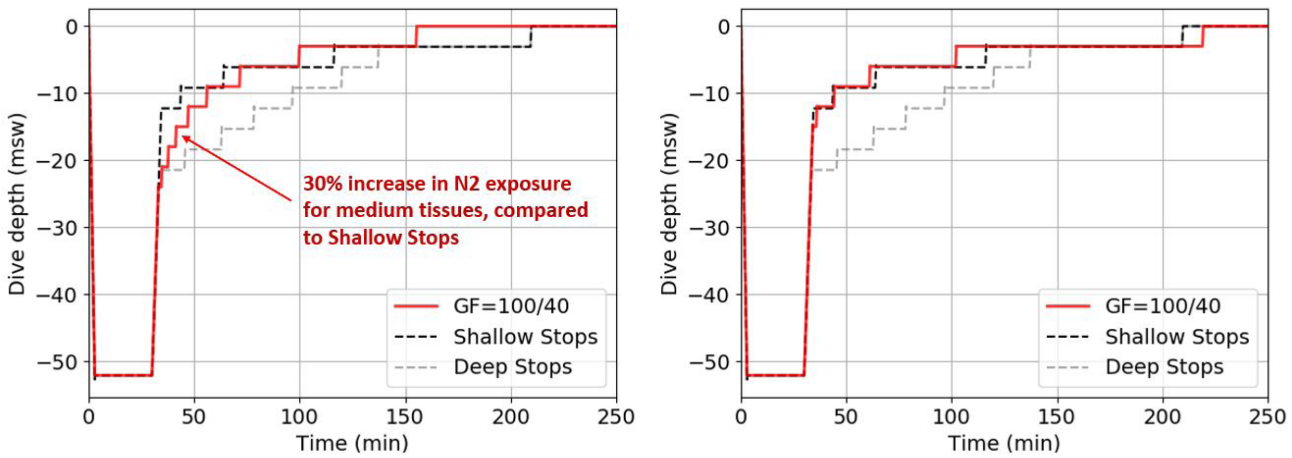


Figure 6

Optimal gradient factor (GF) settings to approach air decompression dives of the DCIEM table, for several selected dive depth/time combinations; the grey area represents the no-decompression dive range; the blue line divides the decompression dive segment into normal air dives and exceptional exposure dives. No air diving is allowed in the red area

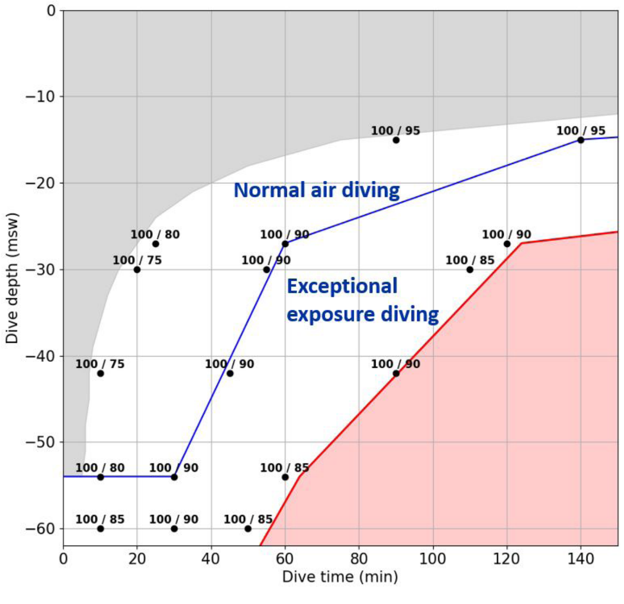
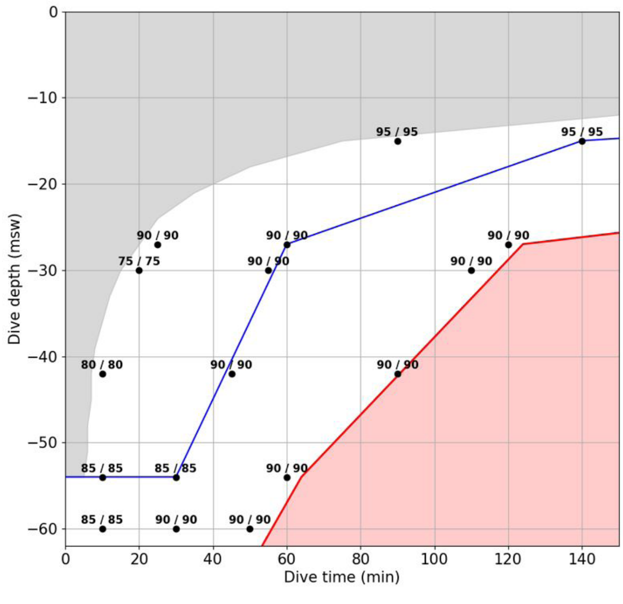


Figure 7

Sub-optimal GF settings, compliant with the GF input restriction in the Shearwater Perdix™ software, to approach air decompression dives of the Defence and Civil Institute of Environmental Medicine (DCIEM) table, for the same dive depth/time combinations as in Figure 6



calculated, compliant with the Perdix software constraints (Figure 7). For each of the dives, the sub-optimal solution was a symmetrical GF. Overall, a symmetric GF of 90/90 was the best suboptimal setting to approach the DCIEM tables, except for short bottom times where the lowest GF found amongst all the dives was 75/75. Using a symmetrical GF setting of 90/90 for all dives within the normal air dive boundary resulted in a maximum difference of five minutes of decompression time at a shallow stop depth, compared to the DCIEM tables.

Discussion

The efficacy of GFs is only supported by anecdotes[10] and to our knowledge, no large-scale experimental trial has ever been undertaken to examine the DCS incidence for decompression with and without the use of GFs. Modifying ZH-L16 with GFs represents an extrapolation beyond the original ZH-L16 experimental validation data that may not be reliable in all circumstances since the actual biophysical processes can be altered to an unknown extent, leading to a different probability of DCS. Therefore, in the current research, GFs are considered just as two mathematical parameters to modify the validated M-values and to change the resulting decompression profile, rather than in terms of adding conservatism per se: a 'deviation' factor instead of a 'conservatism' factor.

Essential in the current air decompression diving analysis is the unchanged GF_{LO} parameter and the decrease of the GF_{HI} parameter. Our optimisation analysis indicates that it is never required to use a GF_{LO} as low as the Perdix default setting of 30 to approach the reference decompression profiles. Also, using the Bühlmann ZH-L16C model with the Perdix default GF settings (30/70) the calculated tissue supersaturations closely resemble the NEDU deep-stops schedule, suggesting a potential increased DCS risk for these GF settings. Although no actual gas exchange measurements have been made, an increased supersaturation of the slower tissues is currently the most plausible cause for the increased DCS incidence when using the deep-stops schedule.[8] This would mean that the default GF settings do not only introduce operational constraints but can (according to this comparison) potentially lead to an increased DCS risk, which is the exact opposite of the desired effect.

In 2017, DAN Europe published an analysis of 320 dives included in the DAN Europe Diving Safety Laboratory database (DAN DSL), having resulted in DCS symptoms.[11] No information about the actual GF setting in the dive computers was available and instead, max GFs were calculated according to the Bühlmann ZH-L16C model: inert gas tensions were calculated for the 16 compartments and represented as a fraction of the M-value, which was then considered as the instantaneous GF along the ascent. Then, the maximum GF during the ascent was labelled as the corresponding max GF, i.e., the 'GF_{HI} value', for that particular dive. They concluded that 73.3% of all DCS cases had a GF_{HI} between 70 and 90, and that only 2.5% had a GF > 100. However, in the light of the current analysis, it is argued that this does not show the full picture for the DCS dives from the DAN DSL as no information is presented about the lowest GF along the ascent, i.e., a 30/70 setting appears as a 'GF_{HI} 70' value in the data, as does a 70/70 setting. Therefore, referring to Figure 3, the DAN analysis focusses on the overpressure in the fast tissues, and does not cover the critical overpressure in the slower tissues.

In 2018, Fraedrich evaluated several commercial dive computer algorithms, including the Bühlmann ZH-L16C algorithm. The ZH-L16C total decompression time (TDT) was compared to TDT from a model based on a large database of air decompression schedule validation dives, specifying the DCS incidence risk as a function of the bottom time and TDT.[12] However, this approach does not seem to be universally applicable: indeed, the NEDU study presents a clear example of two decompression profiles, with identical bottom time and TDT, but with vastly different DCS incidence. Moreover, another study showed that the use of multiple deep stops and longer ascents (increased TDT for an identical bottom time) increased bubble generation.[13] Therefore, we chose to use the complete decompression profile as a test for comparison, rather than the TDT alone.

Similar to our results, Fraedrich found a GF_{HI} equal or lower than 70 to be required to get a TDT comparable to the validated US Navy dive profiles.[12] We found that a GF_{HI} of 40 approaches the NEDU shallow-stops decompression profile, while GF_{HI} settings of 75–90 are required to approach the DCIEM air decompression dives (that used a different experimental dataset for validation). The NEDU shallow stops schedule, based on the Thalmann algorithm with the VVal-18 parameter set, had a 1.5% incidence of DCS, which is very low for an exceptional exposure dive. It has been acknowledged that the VVAL-18 parameter set may result in inordinately long decompressions,[14] and a modified version, the VVAL-18M parameter set, was used for the Air Decompression Tables as found in the US Navy Diving Manual (Version 6). This shorter (VVAL-18M) decompression for the NEDU reference dive depth and bottom time is approached with a GF_{HI} value of 80, which is in the same GF_{HI} range as for the DCIEM air decompression dives. Also, Fraedrich found a GF_{LO} equal or higher than 55 to be required to have the first stop shallower than the US Navy deep stops schedules.[12] We found that the optimal solution for the NEDU shallow stops schedule and all optimal solutions for DCIEM schedules keeps the GF_{LO} parameter fixed to 100 while only the GF_{HI} parameter is lowered to increase stop times at shallower stop depths.

Conclusions

No evidence was found that the default 30/70 setting, and the corresponding deeper stop depths, would lead to a safer decompression profile for non-repetitive air dives up to a depth of 60 msw during military training and operational dives. Our advice to the Belgian Navy divers has been, while using the GFs as they are currently implemented in the software, including the input constraints, to use a symmetric setting of 90/90 and to symmetrically decrease it when a higher safety margin is deemed appropriate. In any case, it is proposed to avoid decreasing GF below 75/75 to not induce deeper stops and keep the resulting decompression profiles not too far from the experimentally tested profiles, as that would induce unknown biophysiological changes not accounted for by the decompression model.

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