VIA MEDICA

ORIGINAL PAPER

Theoretical tissue compartment inert gas pressures during a deep dive with and without deep decompression stops: a case analysis

Peter Buzzacott[1,2], Virginie Papadopoulou[3,4], Adrian Baddeley[5,6], Nadan M. Petri[7], Folke Lind[8,9]

[1]Université de Bretagne Occidentale, Brest, France
[2]School of Sports Science, Exercise and Health, University of Western Australia, Perth, Australia
[3]Department of Bioengineering, Imperial College London, London, United Kingdom
[4]Haute Ecole Paul Henri Spaak, Brussels, Belgium
[5]School of Earth and Environment, University of Western Australia
[5]University of Aarhus, Denmark
[6]Science Fellow at CSIRO Computational Informatics, Perth, Australia
[7]University of Split School of Medicine, Split, Croatia
[8]Hyperbaric Medicine at the Department of Anaesthesiology, Surgical Services and Intensive Care,
Karolinska University Hospital, Stockholm, Sweden
[9]Environmental and Respiratory Physiology at the Department of Physiology
at the Karolinska Institutet, Stockholm, Sweden

ABSTRACT

Background: Deep decompression stops are increasingly common in recreational technical diving. Concerns exist that they shift decompression stress back into slower tissues. A diver recorded an exceptional exposure dive, with deeps stops, on a commercially available dive computer.

Material and methods: Using the R package SCUBA tissue inert gas pressures in 17 Bühlmann (ZH-L16A) compartments were estimated from the dive computer recorded profile. The RGBM dive plan generated by the diver's software was similarly interrogated, as was a third profile with reduced deep stops generated using the VPM-B/E model.

Results: In this dive the combination of 5 gas switches appeared to ameliorate the effect of deep stops from 76 m depth.
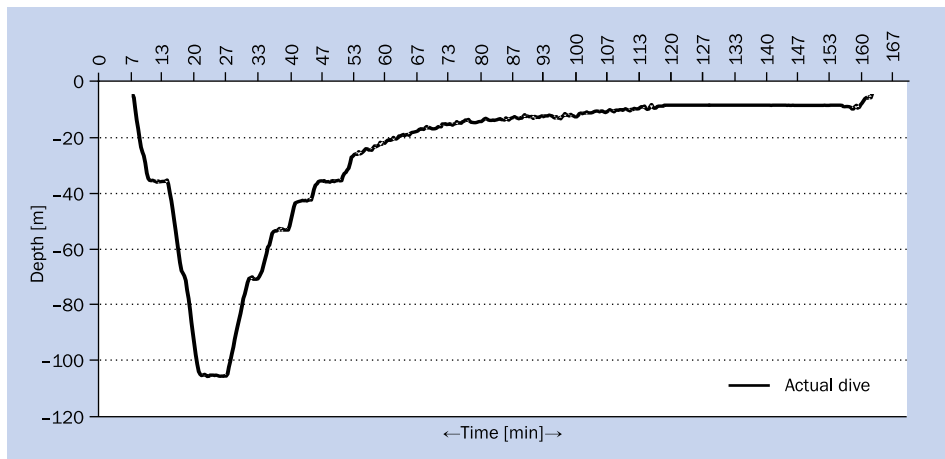
Conclusions: A higher-than-anticipated inert gas content in a decompression mixture, coupled with climbing 200 stairs post-decompression, appear possible risk factors for decompression sickness. Nonetheless, the physiological effect of deep decompression stops during exceptional exposure, even when diving with gas switches, remains urgently to be determined to improve safe decompression following exceptional exposures. Until algorithms utilising deep decompression stops are validated with human data, dive profiles incorporating deep decompression stops should be considered experimental.

(Int Marit Health 2015; 66, 1: 1–7)

Key words: diving computer, decompression, deep diving, gas solubility, models, technical diving

"Diving in general is fraught with risk, and decompression diving adds significantly more risk. Deep diving utilizing multiple gasses, including Helium, is about as risky as it gets."

Advice that followed the alternate dive plan generated by V-planner
(HHS Software Corp., Kingston, ON, Canada)

✉ Peter Buzzacott, MPH, PhD, School of Sports Science, Exercise, and Health, The University of Western Australia, e-mail: peter.buzzacott@uwa.edu.au

Figure 1. The dive profile from the diver's personal dive computer

INTRODUCTION

Recreational diving beyond traditional "no stop" time and depth limits (recreational technical diving), has undergone explosive growth in recent years [1, 2]. Empirically-derived "Haldanean" decompression models such as those developed by Bühlmann are being replaced in personal dive computers and in desktop decompression planning software by a new generation of "bubble models" [3]. To our knowledge, the algorithms these models use have not been validated either with human trials or probabilistically through fitting to existing human trials data. A characteristic of bubble models is that an ascending diver's first prescribed decompression stop is usually considerably deeper than if the same dive were planned with a Haldanean model [3, 4]. During exceptionally deep dives deeper stops may shift decompression stress towards slower theoretical compartments and result in surfacing with higher compartment pressures than Haldanean models allow [2, 4]. Doolette and Mitchell [4] noted that gas switching to elevated partial pressures of oxygen may ameliorate this potential hazard. Limited available evidence appears to support a more cautious approach than some current dive computer manufacturers may be observing. A study using a swine model found that, compared with a classical Bühlmann profile, deep stops after shallow decompression dives (30 msw for 70 min) reduced vascular bubbles but after diving to 65 msw for 20 min dramatically increased vascular bubbles [5]. After diving to 51 msw for 30 min, United States Navy divers suffered both higher incidence of decompression sickness (DCS) and higher grade of observed venous gas emboli when making deep stops during decompression (n = 198 dives) compared with only shallower stops (n = 192 dives) [6]. Following an exceptional exposure, a diver known to the lead author asked for the analysis of his recorded dive profile to identify if there were any obvious likely contributing factors.

The aim of this study was to assess to what degree, if any, the inclusion of deep stops generated by bubble-model software re-distributed estimated tissue inert gas pressures between faster and slower compartments in this single exceptional exposure. Using compartment pressure estimation software, this study compares estimated tissue pressures from the actual dive with estimates from two dive plans generated using desktop software; the diver's original Reduced Gradient Bubble Model (RGBM) plan with deep stops and a second bubble-model derived plan with reduced deep stops.

MATERIALS AND METHODS

A 33-year-old, experienced, fit, male technical diver with no previous history of DCS undertook a deep cave dive in 4°C water for the purpose of exploration. Five years prior to this dive he had been screened for atrial septal defect with colour flow Doppler echocardiography but found to have only a small high muscular ventricular septum defect with a pure left to right shunt and a pressure fall of 80 mm Hg that had been considered neither of clinical significance nor of increased diving-related risk. He dived in a dry suit using open circuit SCUBA to 110 metres' fresh water (mfw) for 7 min (total descent and time at maximum depth 23 min) with a bottom gas mixture containing 8% oxygen and 70% helium, followed by 147 min of decompression on 4 different gas mixtures (trimix 16/49, 30/28, 39/14 and 100% lastly). The oxygen was breathed in a dry habitat at 4.5 mfw (Fig. 1), with wooden benches for supine decompression inside a dry, rock air bell. The dive was planned with Dive Manager 4 dive planning software (Suunto Oy, Vantaa, Finland) with "0" conservatism setting. Actual gas

Table 1. Planned and actual gas blends (% N$_2$, **He**, O_2) with time [min] of use and depth [m] range

Profile	Descent	Bottom	Deco1	Deco2	Deco3	Deco 4
Planned dive[a]	40, **30**, 30	22, **70**, 8	34, **50**, 16	40, **30**, 30	40, **10**, 50	0, **0**, 100
From–to [min]	0–5	5–30	30–46	46–55	55–104	104–145
Depth range [m]	0–34	34–73	73–35	35–21	61–6	6–0
Actual dive[a]	42, **28**, 30	18, **74**, 8	35, **49**, 16	42, **28**, 30	47, **14**, 39	0, **0**, 100
From–to [min]	0–6	6–29	29–46	46–50	50–113	113–170
Depth range [m]	0–34	34–71	71–34	34–29	29–5	5–0

[a]% N$_2$, **He**, O_2

mixtures on the day were measured with a Vandagraph Mixchek Portable Helium and Oxygen Analyser (St Ives, Cambridgeshire) and then entered into his personal dive computer (HelO$_2$, Suunto Oy, Vantaa, Finland) immediately before the dive. During the dive the diver followed the decompression information displayed by his personal dive computer, which recalculated the diver's decompression obligation in real-time. This was a stand-alone dive with no diving for at least the previous week and no previous dives accounted for in the dive planning. Planned and actual gas blend switches are presented in Table 1. The surface of the entry lake, reached by 400 stairs over an 80 m descent, was at an altitude of 195 m. Altitude is known to affect both estimation of depth by the measurement of pressure by dive computers and also the physiological susceptibility to decompression sickness by divers (the higher the lake then the easier it is to suffer decompression sickness, due to the reduced ambient surface pressure). When decompression planning, in practice altitudes < 200 m are considered equivalent to sea-level. When climbing the stairs 2 h after the dive he became exhausted halfway, with dizziness and dyspnoea, and had to lie down, from where he was carried up to ground level on a trolley on rails normally reserved for dive equipment. He then experienced leg weakness, knee pain and was noted to have a "staggering gait". This was followed by bilateral leg muscle fatigue and knee pain which increased in both thighs until he received further oxygen breathing after which the pain changed character somewhat towards severe muscle soreness. He was evacuated by car to the nearest recompression facility where he arrived 3 h later. Apart from a slight difficulty with left sided finger-nose testing there were no focal neurological symptoms on arrival to the hospital. A diagnosis of chokes, DCS (and possibly in-part neurological DCS), was made and recompression to 2.8 ATA according to the United States Navy treatment table 6 commenced 6–7 h after surfacing, in a Sechrist 3200 monoplace chamber. About 15 min after pressurisation the patient experienced noticeable relief in symptoms. No extensions were added to the 5-h treatment. As the symptoms did not regress completely, within the next 24 h he received two additional regular hyperbaric oxygen treatments at 2.8 ATA, each lasting 100 min. The residual symptoms from knees and surrounding muscles gradually disappeared within 3 days and at 2½ years follow up he had made a full recovery and returned to diving.

Depths were recorded and planned for in mfw therefore each depth was divided by 1.03 to equate to pressure in msw for the estimation of tissue pressures using the R package SCUBA (ver. 1.7-0, A Baddeley, Perth Western Australia). Stepwise inert gas pressures in 17 Bühlmann compartments (ZH-L16A) were estimated from the profile recorded by the HelO$_2$ dive computer worn by the diver (max depth 110 mfw, total time 170 min) [7, 8]. Both compartment 1 and its alternate 1a were included thus increasing the total number from 16 to 17. Compartment 1 has a half-time of 4 min and 1a a halftime of 5 min. While decompression planning software uses either one or the other, for the purpose of interrogating the profiles in this study both were included. Bühlmann compartments were selected because they are commonly used and there are more of them than in other popular Haldanian models. The RGBM dive plan generated *a priori* to the dive by the diver's desktop software (Dive Manager 4, Suunto Oy, Vantaa, Finland) with a personal setting of –2 was similarly interrogated (max depth 113 mfw, total time 145 min), as was a third profile with reduced deep stops (< 1 min at > 48 m, < 2 min at > 30 m, < 3 min at > 21 m) generated for comparison (V-Planner, HHS Software Corp., Kingston, ON, Canada) using the Varying Permeability Model (VPM) (max depth 113 mfw, total time 145 min) with conservatism set to +2. The VPM-B/E variation was used because it is advertised as a variation of the VPM for "...*the extreme or extra long dives and exposures*" [9]. Furthermore, the manufacturer advises "*It gives a more relaxed version of a profile for dives when extra safety is prudent*" [9]. Both dive plans were matched to the actual dive in descent rate, arrival time at maximum depth, time ascent commenced and gases breathed (Fig. 2). The two plans were also matched on maximum depth and total dive time (Fig. 2), only the ascent profiles differed (the RGBM plan had longer deep stops). Bühlmann ZH-L16A *a* and *b* values
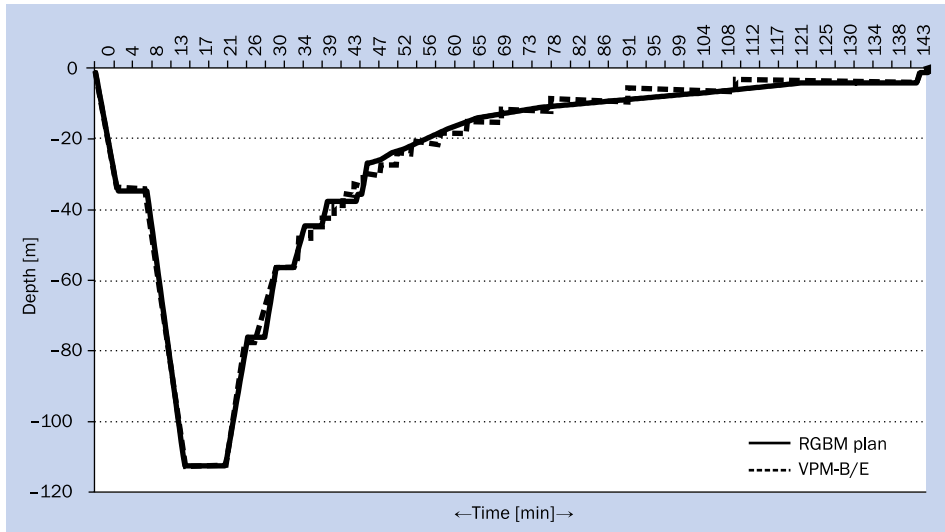
Figure 2. Planned dive profiles with deep stops (RGBM) and reduced deep stops (VPM-B/E)

were calculated for nitrogen and helium from published half-times using equations 1 and 2, where T_{half} is the half-time in min for the respective compartment [8, 10, 11]:

$$a = 2T_{half}^{-1/3} \tag{1}$$
$$b = 1.005 - T_{half}^{-1/2} \tag{2}$$

Intermediate combined inert gas a and b values for each compartment were calculated by linear interpolation of the values for nitrogen (N_2) and helium (He) using equations 3 and 4 [12].

$$a_{(He+N2)} = (a_{He}.P_{He} + a_{N2}.P_{N2}) / (P_{He} + P_{N2}) \tag{3}$$
$$b_{(He+N2)} = (b_{He}.P_{He} + b_{N2}.P_{N2}) / (P_{He} + P_{N2}) \tag{4}$$

P_{He} and P_{N2} are the dissolved partial pressures of He and N_2 respectively. At any time during the dive minimum tolerable ambient pressure for each compartment, (and, therefore, maximum allowed ascent to the next decompression stop), was estimated using equation 5, hereafter referred to as "$P_{amb.tol}$".

$$P_{amb.tol} = (P_{comp.i} - a)b \tag{5}$$

where $P_{comp.i}$ is the inert gas pressure within compartment i. These pressures were divided by the respective ambient pressure at time (t) to give a percentage of the allowable pressure (according to the model) that each compartment was exposed to at each step. Maximum percentage of each $P_{amb.tol}$ are presented for each compartment in Table 2 as are percentage of allowable surfacing pressures which are merely the percentage of $_{Pamb.tol}$ but for depth = 0 m (intercept M_0 of the M-values) calculated using equations 6 and 7.

$$M_0 = a + 1/b \tag{6}$$
$$\% M_0 \text{ value} = 100\%*(p_{surfacing}/M_0) \tag{7}$$

The maximum difference (tension) ΔP between dissolved inert gas in each compartment and inspired inert gas are also

presented in Table 2. The respective times when theoretical off-gassing tension peaked are noted in parentheses.

RESULTS

Planned and actual gas-switches (Table 1) suggest total inert gas partial pressures were as predicted by the plan until the diver reached the decompression stop in the 50th min whereupon the depth was 29 mfw instead of 21 mfw and the actual blend of gas he switched to contained 61% inert gas (and 39% oxygen) instead of the planned 50% inert gas and 50% oxygen. The diver breathed this higher-than-anticipated inert gas combination for the next 49 min until he reached 6 mfw and switched to oxygen. Estimated resultant off-gassing peak inert gas differentials, maximum percentage $P_{amb.tol}$ during decompression and percentage M_0 upon surfacing are presented in Table 2.

Off-gassing is estimated to have peaked in each compartment at close to the planned times. Maximum ΔP between dissolved and inspired inert gas was always estimated to have been lower in the actual dive than in either plan for compartments 1–11. Compared with the reduced deep stops plan the RGBM plan with deep stops would have produced higher maximum percentage of $P_{amb.tol}$ pressures in compartments 1a–9, but lower values in compartments 10–14. At the end of the dive the estimated percentage of surfacing M_0 values for the actual dive were equal to, or lower than, those in either dive plan, likely due to the extended time decompressing on oxygen in the habitat.

DISCUSSION

The diver arrived at maximum depth one half-a-minute later than planned, reached only 110 mfw instead of the planned 113 mfw and then left the bottom 1 min

Table 2. Estimated maximum combined inert gas ΔP between dissolved and inspired inert gas (ATM) for Bühlmann ZHL-16A compartments, with respective half-times for N_2 and He, maximum % $P_{amb.tol}$ during decompression with times of occurrence in parentheses and % M_0 value upon surfacing

Compartment number		1	1a	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Half-time [min]	N_2	4.0	5.0	8.0	12.5	18.5	27.0	38.3	54.3	77.0	109	146	187	239	305	390	498	635
	He	**1.5**	**1.9**	**3.0**	**4.7**	**7.0**	**10.2**	**14.5**	**20.5**	**29.1**	**41.1**	**55.1**	**70.6**	**90.2**	**115.1**	**147.2**	**187.9**	**239.6**
Max Washout ΔP[a] Actual dive		1.35 (26)	1.47 (26)	1.63 (32)	1.94 (32)	1.98 (50)	2.29 (50)	2.36 (50)	2.17 (51)	1.88 (113)[d]	2.00 (113)[d]	2.01 (113)[d]	1.95 (113)[d]	1.86 (113)[d]	1.74 (113)[d]	1.61 (113)[d]	1.49 (113)[d]	1.37 (113)[d]
Dive plan[b]		1.59 (26)	1.77 (31)	2.23 (31)	2.36 (31)	2.23 (47)	2.44 (47)	2.55 (55)[e]	2.47 (55)[e]	2.16 (55)[e]	2.04 (104)[d]	2.03 (104)[d]	1.96 (104)[d]	1.85 (104)[d]	1.72 (104)[d]	1.59 (104)[d]	1.46 (104)[d]	1.34 (104)[d]
Reduced deep stops[c]		1.91 (27)	2.01 (27)	2.07 (27)	2.04 (40)	2.28 (40)	2.34 (54)	2.47 (54)[e]	2.37 (54)[e]	2.08 (96)[d]	2.15 (96)[d]	2.10 (96)[d]	2.00 (96)[d]	1.87 (96)[d]	1.73 (96)[d]	1.58 (96)[d]	1.45 (96)[d]	1.33 (96)[d]
Max % $P_{amb.tol}$[g] Actual dive		22 (26)	31 (26)	45 (27)	57 (32)	67 (43)	76 (51)	84 (51)	89 (68)	94 (68)	95 (77)	92 (120)	94 (120)	93 (120)	89 (120)	84 (120)	79 (120)	74 (120)
Dive plan[b]		24 (26)	32 (26)	48 (31)	61 (31)	72 (47)	84 (47)	89 (47)	91 (67)	95 (67)	93 (78)	90 (104)[d]	93 (123)[f]	94 (123)[f]	91 (123)[f]	87 (123)[f]	83 (123)[f]	78 (123)[f]
Reduced deep stops[c]		24 (26)	31 (26)	45 (30)	57 (33)	66 (36)	74 (44)	83 (54)	86 (54)	91 (70)	92 (96)	95 (114)[f]	97 (114)[f]	96 (114)[f]	92 (114)[f]	88 (114)[f]	83 (114)[f]	78 (114)[f]
Max % M_0 value[h] Actual dive		0	0	1	2	6	13	23	36	51	68	81	90	95	98	98	97	95
Dive plan[b]		0	1	1	4	10	20	31	47	64	82	94	100	100	100	103	100	97
Reduced deep stops[c]		0	0	1	3	9	18	29	44	62	79	91	97	101	102	101	98	95

[a] Estimated with R package "SCUBA"
[b] Planned with Suunto Dive Manager 4
[c] Planned with V-planner VPM-B/E
[d] Shallowest stop, switch to 100% oxygen
[e] 21 m, switch to third decompression gas
[f] 3 m stop on 100% oxygen
[g] During decompression
[h] On surfacing

ahead of schedule. During the ascent these small but more conservative deviations from the plan allowed the diver to commence decompression at a less saturated state than planned. Maximum ΔP (Table 2) was lower than planned, as was max%$P_{amb.tol}$, though %$P_{amb.tol}$ peaked in the 7 slowest compartments at 120 min just as the diver reported exerting himself climbing out of the water inside the habitat. This occurred after breathing 11% more inert gas than had been planned for (Table 1) during the ascent from 21 mfw to 6 mfw, (and switching to that gas 5 min ahead of schedule, at depth 29 mfw). It is possible that the diver's personal dive computer signalled that a gas-switch was desirable or permissible earlier than expected given the lower partial pressure of oxygen (0.38 ATA vs. 0.49 ATA; Table 1) but that is mere speculation at this time, long after the event. It appears as though the estimated surfacing M-values in the 8 fastest compartments were lower than planned for.

Concerns have been raised that during single-gas dives deep stops might reduce VGE at the expense of increased supersaturation in slower compartments [2, 4]. In this analysis the maximum ΔP between dissolved and inspired inert gas was higher in the fastest compartments (1 and 1a) for the reduced deep stops profile than for the plan with deep stops (1.91 and 2.01 ATA vs. 1.59 and 1.77 ATA, respectively) and lower in compartments 5–8 which, while not conclusive, is in keeping with this notion. In a 2007 review of deep decompression stops, Fock advised that decompression software-generated (VPM and RGBM) profiles utilising deep stops likely resulted in higher predicted inert gas tensions in the mid and slow compartments and that for dives greater than 70 msw these surfacing compartment tensions commonly exceed those shown experimentally to produce clinical symptoms [2]. Doolette echoed this concern but suggested that effective gas switching has the potential to ameliorate the shift [4]. In this study, using a simple exponential function to estimate inert gas uptake and washout over a range of compartment half-times, we concur that, when coupled with effective gas switching, deep stops did not in this case appear to shift decompression stress back towards slower compartments (when considering only the 3 parameters selected in this analysis). It nonetheless remains possible that estimates of other parameters associated with decompression stress may suggest a different effect upon decompression stress.

LIMITATIONS OF THE STUDY

The limitations of this report include that no physiological data were collected (gas consumption, thermal status, bubble detection, etc.). The exact cause of DCS in this case remains undetermined although climbing 200 stairs within 2 h of surfacing was likely not beneficial. Other factors may well have played a part, such as personal susceptibility (e.g. the ventricular septal defect), deviation from the planned profile and/or planned schedule of gases, etc., and our analysis neglects these to focus only on the potential effect of deep decompression stops upon inert gas supersaturation in various compartments. We do not intend to imply these are the sole cause of DCS. Deep-stop enabled trimix dive computers are widely available and more recreational technical divers than ever are diving deeper than 100 msw before conducting deep stops. While deep stops and bubble models remain to be validated with human data this issue urgently deserves further research to improve decompression safety following exceptional exposures. Until such formal validation is conducted we recommend all exceptional exposure dives planned with bubble models be considered experimental.

CONCLUSIONS

As an aside, we conducted the exact same analysis as for Table 2 except as though no gas switches had taken place and all dives (planned or actual) were completed on the starting gas, trimix 30/30. The data (not shown here) are available on request and we observed no difference in estimated surfacing supersaturation (M_0) in any compartment between the plan with deep stops and the plan with reduced deep stops but, compared with the reduced deep stops plan, we did find a shift in estimated greatest supersaturation stress during decompression (Max%$P_{amb.tol}$) towards slower compartments in the plan with deep stops. Concerning dives with deep stops, a parameter potentially worth exploring further may not be so much the surfacing value as in the maximum decompression stress (supersaturation) during ascent. In this study we selected 3 parameters that are commonly referred to in diving supersaturation, namely tissue supersaturation pressure, percentage $P_{.amb.tol}$ during the dive and percentage M-value at the end of the dive, but there are many more parameters that might be explored. Given this analysis is of a single case these three parameters were thought adequate but this remains a limitation.

CONFLICT OF INTEREST

In June 2012 Peter Buzzacott was unconditionally given a DG-05 dive computer by Hollis (San Leandro, CA, USA), a company that manufactures dive computers.

REFERENCES

1. Mitchell SJ, Doolette DJ. Recreational technical diving part 1: an introduction to technical diving methods and activities. Diving Hyperb Med 2013; 43: 86–93.
2. Fock A. Deep decompression stops. Diving Hyperb Med 2007; 37: 125–132.
3. Wienke B. Diving decompression models and bubble metrics: modern computer syntheses. Comput Biol Med 2009; 39: 309–331.
4. Doolette DJ, Mitchell S. Recreational technical diving part 2: decompression from deep technical dives. Diving Hyperb Med 2013; 43: 96–104.
5. Gutvik CR, Mollerlokken A, Brubakk AO. Difference in bubble formation using deep stops is dependent on bottom time; experimental findings and theoretical support. 33rd Annual Scientific Meeting of the EUBS; Sharm El Shiekh, Egypt: European Undersea and Baromedical Society; 2007: p. 146–49.
6. Doolette DJ, Gerth WA, Gault KA. Redistribution of decompression stop time from shallow to deep stops increases incidence of decompression sickness in air decompression dives. Panama City, FL: Navy Experimental Diving Unit. 2011. Report No.: 11-06.
7. Baddeley A. The scuba package for the R system. Available at cran.r-project.org/web/packages/scuba; Perth, WA 2011.
8. Bühlmann AA. Tauchmedizin. Springer-Verlag, Berlin 1995.
9. The VPM-B model. HHS Software Corp.; [cited 2013 12th November]; Available from: http://www.hhssoftware.com/v-planner/vpmdetail.html.
10. Powell M. Deco for Divers. Southend-on-Sea. ISBN 1-905492-07-3; 2008.
11. Schellart NAM, van Rees Vellinga TP, van Hulst RA. Body fat does not affect venous bubble formation after air dives of moderate severity: theory and experiment. J Appl Physiol 2013; 114: 602–610.
12. Baker EC. Understanding M-values. Immersed 1998; 3: 23–27.