Venous gas embolism after an open-water air dive and identical repetitive dive

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ABSTRACT

Decompression tables indicate that a repetitive dive to the same depth as a first dive should be shortened to obtain the same probability of occurrence of decompression sickness (pDCS). Repetition protocols are based on small numbers, a reason for re-examination. Since venous gas embolism (VGE) and pDCS are related, one would expect a higher bubble grade (BG) of VGE after the repetitive dive without reducing bottom time. BGs were determined in 28 divers after a first and an identical repetitive air dive of 40 minutes to 20 meters of sea water. Doppler BG scores were transformed to log number of bubbles/cm^2 (logB) to allow numerical analysis. With a previously published model (Model2), pDCS was calculated for the first dive and for both dives together. From pDCS, theoretical logBs were estimated with a pDCS-to-logB model constructed from literature data. However, pDCS the second dive was provided using conditional probability. This was achieved in Model2 and indirectly via tissue saturations. The combination of both models shows a significant increase of logB after the second dive, whereas the measurements showed an unexpected lower logB. These differences between measurements and model expectations are significant (p-values <0.01). A reason for this discrepancy is uncertain. The most likely speculation would be that the divers, who were relatively old, did not perform physical activity for some days before the first dive. Our data suggest that, wisely, the first dive after a period of no exercise should be performed conservatively, particularly for older divers.

INTRODUCTION

In recreational diving, a repetitive dive performed on the same day as the initial dive is a common practice. Multiday repetitive diving has become especially popular during dive holidays or long weekends. Despite this, studies of the risk of decompression sickness (pDCS) and the occurrence of venous gas embolism (VGE) following repetitive dives are scarce.

Decompression tables and algorithms as used in dive computers provide strategies for repetitive diving. However, the underlying research of pDCS (and VGE) is generally based on small numbers, mostly three or four subjects [1,2], due to the many possible combinations of profiles for the first (dive1) and second dive (dive2).

Decompression tables such as those of DCIEM or the U.S. Navy consistently show that a repetitive dive (with a short surface interval) to the same depth as the previous dive should have a shorter bottom time, because of the residual nitrogen load, to present the same risk for decompression sickness. The reduction of bottom time is needed, as there is a residual nitrogen load in the tissues at the start of dive2.

This research investigates whether a moderately deep repetitive dive near the no-stop limit and identical to the initial dive, produces more VGE bubbles as would be expected from decompression theory.

To be able to conclude whether the difference between the measured bubble grades (BGs) of dive1 and dive2 is in accordance with decompression theory, it is necessary to estimate the theoretically expected BGs from the dive profile. Unfortunately, a direct and practical procedure to predict BGs from a dive profile does not exist (but see [3]). In the literature, several models, mostly based on a probabilistic approach, have been published to predict pDCS from the dive profile (see [4] and [5] for references). An easily applicable model to calculate pDCSs has been described as Model2 by Weathersby *et al.* [6], based on 920 air dives. In the same study Model1 has been described, but this model is inappropriate for our purposes. In Model2, a momentary risk factor (the risk to obtain DCS in an infinite small time period) is calculated from the nitrogen tissue tension of a slow and a fast tissue. After adding the risks of the slow and the fast tissue, the cumulative DCS risk (the risk after the start of the ascent until some time later) is obtained. The Methods section gives a more detailed description of Model2.

This model holds for any dive profile for which the time of ascent is well-defined and monotonous. We adopted this well-established Model2 [5] to estimate pDCS.

The next step is to estimate the BG from the calculated pDCS obtained with Model2. In the literature, only a few studies present DCS prevalence with known BGs. However, none of these studies were usable due to deviating conditions (measurements during rest, echocardiographically estimated BGs, non-air breathing gas, or extreme dives), except for the study of Nishi *et al.* [7]. Their Table 10.3.9 presents precordial Doppler-derived BGs, graded according to the Kisman-Masurel (KM) scale (in integer units) after a deep knee bend for 1,726 dives, with pDCS for any KM value. Since there seems to be no model describing a one-to-one relation between pDCS and bubble grade, we constructed a simple model from tabulated literature data, relating pDCS and BG. We used Nishi's *et al.* data to construct this pDCS-to-BG model.

For dive1 the pDCS-to-BG model can be applied directly to the outcome of Model2, but for a repetitive dive Model2 needs a modification to apply this relationship. The model of Weathersby *et al.* [6] appears to have been mainly developed and validated for a first dive. With a surface interval of 2.5 hours, the tissue with a half-time of 26 minutes is irrelevant, whereas the 433-minute tissue was hardly loaded by the first dive with a bottom time of 40 minutes. This model is therefore not very appropriate for our two dives. Present knowledge about the evolution of nitrogen tensions and bubble dynamics suggests that the underlying mechanisms of bubble and DCS risk for repetitive dives are quantitatively not the same as for a first dive due to a change of the dynamics of the resolved and free gas This insight is based on empirical data suggesting that the parameters of two phase models are changed, such that risk is more enhanced than the classical approach suggests. Therefore, several modern algorithms (as, for instance, used in dive computers, such as Suunto and UWATEC) adapt half-times and M-values during the surface interval and beyond. To overcome the noticed drawback of the model we modified the model, making it suitable for our two dives, with their neither short nor long, surface interval. This modification will be explained further in the Methods section.

The difference between the measured BGs of the two dives can now be compared to the estimated difference between the theoretical BGs of dive1 and dive2.

METHODS

Subjects and dive profile

Twenty-eight recreational divers volunteered to participate in the study. Since performing the two dives was demanding, fitness to dive and experience were established by submitting a medical certificate and an additional questionnaire about age, sex, dive experience (number of years diving, total number of open-water dives and maximal depth). Subjects were selected on the basis of fitness to dive, no relevant medical history and sufficient experience to perform the dive profile.

This study, performed as a part of a diving medicine course of the Dutch Society of Dive Medicine on the (patho)physiology of decompression phenomena, did not require an official approval, as decided by the Internal Review Board of the University of Amsterdam. Despite this, the 28 course members who volunteered as subjects signed an informed consent.

The divers performed two 40-minute air dives to 20 msw (meters sea water) with descents of 20 msw/minute and ascents of 10 msw/minute and with a surface interval of two hours, 30 minutes. Ascent times to the stops (made at a buoyancy line) are included in the stop times.

There were two dive profiles with a minor difference: One group made a dive with a single stop at 4 msw for seven minutes (1Sdive); the other group performed the 40-minute 20-msw dive with two stops (2Sdive), a four-minute stop at 10 msw and a three-minute stop at 4 msw. The reason for having two identical dive profiles with a slightly different decompression profile (but the same decompression time) was to perform another study with the same BG data comparing both profiles, see [8].

The dives were performed on a wreck close to the shore of Mahé, Seychelles. Current was nil to rather weak. The dive profiles were recorded with Uwatec Smart Pro (Uwatec, Zurich, Switzerland) or Mares M1 (Mares S.p.A., Rapallo, Italy) dive computers. Subjects were instructed to use the dive computer solely as a watch and depth meter. For the Smart Pro, calibrated in meters of fresh water, depth was calculated in msw. After the dive, the dive profiles were retrieved and inspected for validity.

Bubble measurements

In several recent studies VGE measurements have been made with 30-minute intervals. For practical reasons, some studies were confined to one measurement (for instance [9]). In our study, the extent of VGE was measured twice; 40 and 100 minutes after surfacing. The time points of 40 and 100 minutes were dictated by the duration of a Doppler examination of a single subject, the number of subjects, the availability of two examiners and the transfer time by boat from the dive site to the examination room. The VGE measurements were performed precordially at the left third intercostal space with a continuous-wave Doppler DBM9008 and array probe (Techno Scientific, Toronto, Canada). All measurements were done by the same two experienced Doppler examiners.

One individual session consisted of four measurements with one-minute intervals. The first measurement was made while the subject was standing at rest and the other three immediately after a deep knee bend (flex). The Doppler sounds were digitally recorded on an MP3-recorder and scored blinded, with BG expressed in KM units (Kisman-Masurel units, see [7]). The highest value of the three deep knee bends was used for analysis in this study. This yielded one score for the 40-minute post-dive measurement and one for the 100-minute post-dive measurement.

Analysis of measurements

Since BGs could be measured only at two time points after surfacing, the maximum BG value is unknown. To approximate this maximum as well as possible, the largest of the 40- and 100-minute scores were used, a method applied previously [7,8].

BGs scatter enormously among subjects, whereas scatter within a subject is much smaller (in our study, two times smaller). Since we compare the measured VGE of dive1 and dive2, the logical approach is to use the subjects as their own reference. In other words, the VGE of dive2 is compared with that of dive1. Hence, we applied statistically paired testing. This more fruitful method needs far fewer subjects than the unpaired approach.

To examine the intra-individual difference between VGE grade (KM scale) of dive1 and dive2, the ordinal KM scores cannot be used directly. Therefore, the scores were transformed to a numerical scale, the number of bubbles/cm^2 (according to Table 10.3.8 of [7]).

However, direct calculation of the bubble count difference by subtraction is inappropriate since bubble counts deviate enormously between subjects, and large counts severely dominate in the statistics (the out-layer problem). Therefore, we used the logarithm of the bubble count (logB). Hence, after taking the logB-difference, we examined the actual bubble ratio of dive1 and dive2. In this way, the high bubblers did not dominate the analysis, presenting a more conservative way to analyze differences.

It should be noted that the numerical scale of log bubble counts roughly matches the ordinal KM scale. The KM scale gives a subjective severity scale of VGE. Another profit of using logB-differences is that their distribution was normal, allowing parametric statistics. The measured logB-differences found were compared to the expected differences estimated with our model.

From decompression theory the difference between logB of dive1 and dive2 is supposed to be practically the same for the two nearly identical profiles (1S and 2S). Moreover, Model2 showed a difference in pDCS of less than 0.017% risk. This allowed pooling of the measured difference-logB data of the 1S and 2S profiles in order to reduce data noise, resulting in more reliable statistics. This is confirmed by the logB-difference data of both profiles of Table 2 ($p = 0.32$).

Estimation of theoretical BG from the dive profile

Background of Model2

In Model2 of Weathersby *et al.* [6], the nitrogen tissue tension as a function of time Pti(t) of a fast tissue (half-time, $T_{HALF} = 26$ minutes) and a slow tissue (T_{HALF} = 433 minutes) is calculated for the dive profiles *(Figure 1, Page 580)*.

Figure 1 gives Pti for the fast tissue. For both tissues, a momentary risk factor is calculated by:

1) taking the difference Pti(t) − P ambient, relative to P ambient (hence (Pti(t) − P ambient)/P ambient), depicted in Figure 1; and
2) by integrating this fraction over time t (from the start of the ascent) and multiplying the outcome with a constant.

Adding the risk factors of the two tissues yields the final risk factor r2, which can be seen as instantaneous risk. It sharply increases from zero during the ascent, peaks and then diminishes to zero.

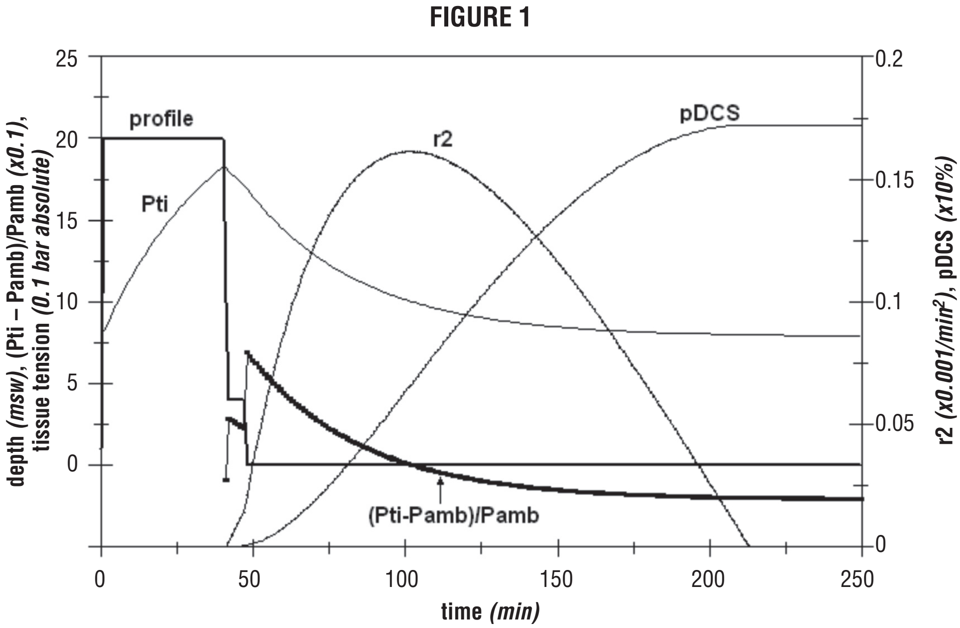

FIGURE 1. Visualization of Model2 with temporary (Pti, (Pti-Pamb)/Pamb and r2) and final (pDCS(t)) outcomes of Model2 (6) for the 20msw/40minute dive profile with the 4msw/7minute stop. Notice that the diagram has two vertical scales: the left one for the dive profile (Pti/Pamb)/Pamb and the nitrogen tissue tension (Pti), and the right one for r2 and pDCS. All outcomes for the 20-msw/40-minute dive profile with the two stops (10/4 and 4/3) deviate at most 2% from those of the former dive. Since the slow tissue does not contribute to this particular profile, the outcomes are based on the outcomes of the fast tissue (T_{HALF} = 26 minutes).

As shown in Figure 1, r2 behaves roughly as an inverted truncated parabola. This "parabola" is integrated over time, and the outcome is used as the exponent in a saturating exponential function, which gives pDCS as a function of time (t). This function pDCS(t) is the cumulative DCS probability, which reaches its maximum as soon as the r2-"parabola" is diminished to zero, as is also shown in Figure 1.

Conversion of pDCS to logB (pDCS-logBmodel)

The data of Nishi *et al.* [7] (Table 10.3.9) present precordial KM data (in integer units) of 1,726 dives obtained after a deep knee bend. This table gives pDCS for KM values from 0 to IV. These KM scores, transformed to logB, were used to model the pDCS-BG relationship under the assumption that for a given pDCS the distribution of KM-values for a sample of dives is close to normal. This will hold for pDCS > 0.5%. Now, the relation between BG and pDCS (based on mean values) is a one-to-one recursive relation, allowing classical modeling with least squares curve fitting. This yielded:

$$pDCS = 5.97 \times 10^{0.334 logB} \qquad [1]$$

where pDCS is in %. The resulting model of logB (pDCS -logBmodel) is visualized in Figure 2 *(facing page)*. With pDCS calculated from Model2, logB can be found by rewriting equation [1] that gives logB = 2.99logpDCS-2.32.

Notice that in equation [1] logB and pDCS are not functions of time. LogB is the maximum value found after surfacing, and pDCS obtains the value of the cumulative pDCS(t) of Model2 [6], with t being very large (formally infinite). The extension of Model2 with the logB calculation (pDCS-logBmodel) will be referred to as Model2-logB.

Modification of Model2 for dive2 (Model2modified)

Risks, like DCS risks, are cumulative and consequently do not diminish – *e.g.*, [6]. Bubble counts of dive1 and dive2 are transient phenomena. Bubble counts, first increasing after the ascent and reaching a maximum, decay after a few hours [7]. This will also happen in the last part of our surface interval. The maximum bubble count measured over time is assumed to be proportional with the instantaneous risk r2. This gives the risk that DCS symptoms become noticeable in a (very) short period of time. Consequently, when one wants to relate pDCS of a repetitive dive – a conditional probability – to the maximal bubble count after this dive, pDCS obtained with Model2 needs a downward correction before the start of the repetitive dive.

FIGURE 2

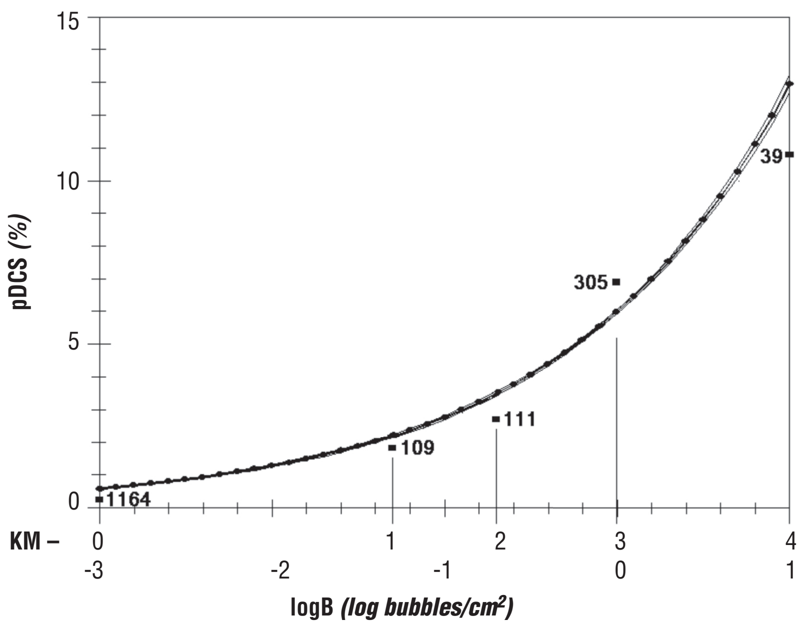

FIGURE 2. Exponential fit of empirical logB versus pDCS data of reference [7]. The fit, being pDCS = 5.97 x 10 $^{0.334 \log B}$ is given by the inner black line with the small dots. The residual is 3.2%, and the 95% confidence limits of the coefficient are 5.94 and 6.04. Those of the constant in the exponent are 0.329 and 0.340. (However, for the calculation of a difference between the two logB values of the model, the constant is irrelevant). The 95% confidence lines are indicated and hardly show deviations from the least square fit. The 5 data points (squares) were weighted by the numbers given in Table 10.3.9 of reference [7]. The numbers next to the squares give the number of dives.

FIGURE 3

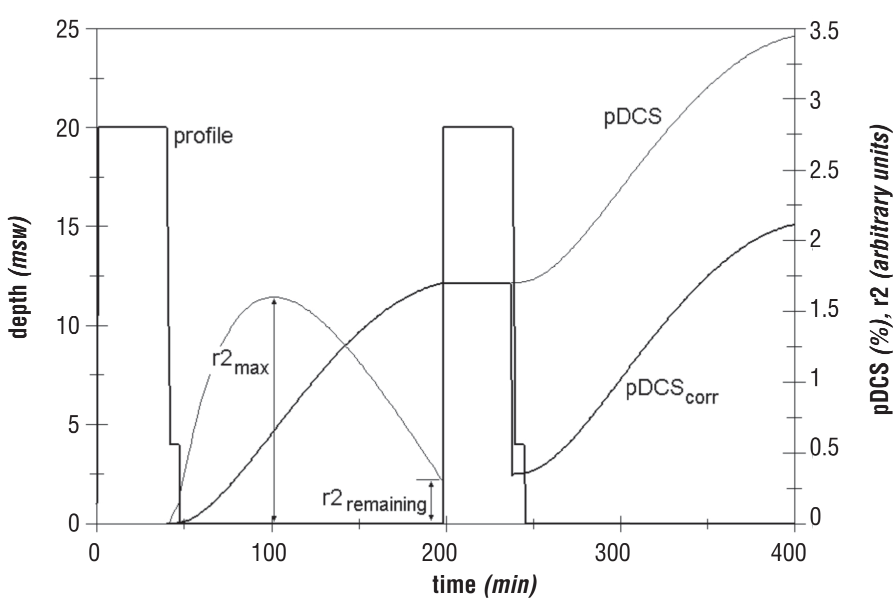

FIGURE 3. pDCS curves calculated for the whole profile and for dive2 after correcting pDCS at the time of ascent of dive2.

TABLE 1

1Sdive			2Sdive		
dive1	dive2	logB diff	dive1	dive2	logB diff
1	0	-1.58	2	3-	0.43
2	0	-2.34	1	1	0.00
2	2	0.00	1-	0	-1.01
0	0	0.00	2	2-	-0.12
0	0	0.00	3-	3	0.33
1	2	0.76	0	0	0.00
2	3-	0.43	2	1	-0.76
2	1	-0.76	2	2+	0.16
3-	3-	0.00	3	1	-1.52
1	1	0.00	1	2	0.76
0	0	0.00	0	0	0.00
3-	2	-0.43	2	3-	0.43
0	0	0.00	2	3	0.76
			2	1	-0.76
			2	4-	1.33

TABLE 1. Bubble grades (KM) of all subjects and logB difference of dive1 and dive2

Two values of r2 are relevant: the maximum and the value just before the start of the second dive *(Figure 3, Page 581)*. Now, pDCS at the start of the second dive ($pDCS_{start,2}$) was corrected by multiplication with the ratio $R = r2_{remaining}/r2_{max}$. This corrected value, $pDCS_{start,2,corr}$ was used in Model2 as the start value at the start of dive2 to calculate the pDCS after this dive, $pDCS_{corr}$. The latter value was used to calculate logB of dive2. The modified Model2 will be referred to as Model2modified.

Estimation of pDCS for dive2 with Model2 by using tissue saturations

The above method of correction can be avoided by applying Model2 for dive1 as well as for a hypothetical first dive which has approximately the same tissue saturations as dive2 and hence is assumed to have the same bubble stress. Such a hypothetical dive at 20 msw will have a larger bottom time. The two resulting pDCS values will finally yield the difference in logB.

For the evolution of the partial N_2 tension (pN_2), the ZH-L16C Bühlmann model with eight compartments was used, with half-times from five to 635 minutes [2]. However, the exact choice of the set of half-times is rather irrelevant, provided there are fast, moderate and slow compartments included.

TABLE 2

	logB 2nd – 1st		
	1Sdive	2Sdive	both
Mean	-0.30	-0.00	-0.139
SE	0.23	0.19	0.149
n	13	15	28
***p*-value 1S-2S dives**	0.32		
***p*-value, rel 0**			0.36
p*-value, rel 0.29			0.0078
p*-value, rel 0.25*			0.015

TABLE 2. Differences between measured logB of dive1 and dive2

* Estimate of the difference of logB between dive1 and dive2 of Model2-logB.

** The same but now for the lower 95% confidence limit of the model estimate of logB-difference.

Statistics

Statistics were performed with two-sided Student's T-tests, since none of the distributions deviated substantially from normal (Golmogorov-Smirnov normality test, *http://www.physics.csbsju.edu/stats/KS-test.n.plot_form.html*). Confidence limits of the parameters of equation [1] were calculated with SPSS 16.0 (non-linear regression).

RESULTS

The subjects

Thirteen divers (including one female) performed the first as well as the second 1Sdive, and 15 divers (including three females) performed the first as well as the second 2Sdive. Mean age was 53 ± 11 ($m \pm SD$); see reference [8] for further details about the subjects. The performed profiles of dive1 and dive2, averaged for subjects and time, show a negligible difference of 0.07 ± 0.08 msw ($m \pm SE$) for the intended 20-msw dive. At the bottom, the divers were swimming very slowly.

No case of DCS was observed during the Doppler sessions or reported afterwards *(Table 1, above left)*.

Log bubble counts (logB) of measurements

For the subjects who performed the 1Sdive and the 2Sdive Table 1 gives the measured BGs (KM), being the highest after a deep knee bend at the 40- and 100-minute interval. The 1Sdive gives slightly smaller values, but for this study this is irrelevant, since only the difference between dive1 and dive2 is of importance. Since the two dive profiles (S1 and S2) were nearly identical, the pDCS

FIGURE 4

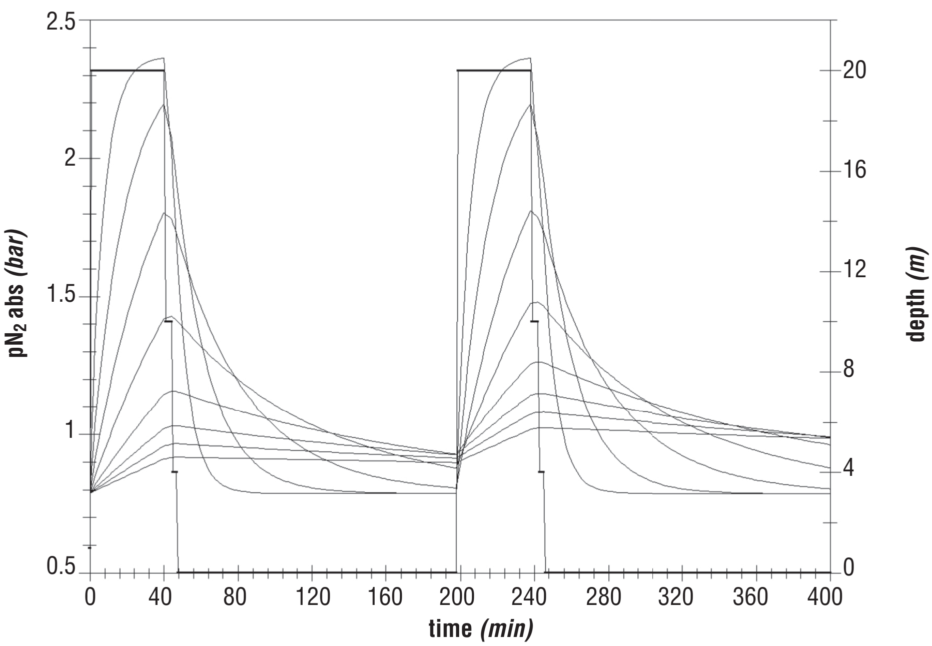

FIGURE 4. Saturation of the eight compartments of S2dive. The curves of S1dive (left hand scale) are indistinguishable from this set (except during the ascent phase). The scale of the dive profile is at the right.

values obtained with Model2 were the same (within 0.017% risk), and so were the logB values. Consequently, it may be supposed that the measured logB-difference between dive1 and dive2 are about the same for both profiles. Therefore, the measured logB-differences of both profiles were pooled. This reduces the data noise due to the small numbers for both profiles. Indeed, the logB-differences of 1Sdive and 2Sdive are not significantly different, as Table 2 *(facing page)* shows (p=0.32).

The second dive generated 0.14 log unit fewer bubbles than dive1, a difference not significant from 0 log unit (p=0.36).

logB calculated from Model2-logB

The first dive yielded a pDCS of 1.70% and after dive2 the uncorrected pDCS was 3.46%. According to equation [1] this risk yielded a logB of -1.63 and -0.72, respectively. However, according to Model2modified, with the ratio $R = r2_{remaining}/r2_{max}$ (=0.20) $pDCS_{start,2,corr}$ equaled 0.34% *(Figure 3, previous page)*. This corrected value resulted in a $pDCS_{corr}$ of 2.13% *(Figure 3, lower S-shaped curve)*, which yielded a logB of -1.34 LU. This gives a logB difference of 0.29 (= -1.34-1.63).

TABLE 3

1	2	3	4	5
comp	**comp**	**pN_2 dive1**	**pN_2 dive2**	**pN_2 50' dive**
halftime	**volume**	**start ascent**	**start ascent**	**start ascent**
5	6	2.364	2.364	2.369
12.5	1	2.198	2.198	2.271
27	1	1.804	1.811	1.932
54.3	24	1.423	1.476	1.535
109	12	1.150	1.259	1.223
187	20	1.027	1.146	1.075
305	4	0.966	1.079	0.999
635	12	0.919	1.024	0.942
sum		**11.850**	**12.356**	**12.346**

Table 3. pN_2 at times of ascent of dive1, dive2 and extended first dive

Halftimes in minutes, volumes in liters, tensions in bar absolute. Volumes after reference [2] and attributed to the theoretical compartments.

Correction of pDCS of Model2 with tissue saturations
Saturations were calculated for the whole profile, as illustrated in Figure 4 *(Page 583)*. It is clearly shown that at the start of dive2 only the two fastest compartments are unloaded. At this time, pN_2 values (in bar absolute) of the six remaining compartments are 0.81, 0.88, 0.93, 0.93, 0.92 and 0.92 respectively. As a consequence, at the start of the ascent of dive2 (t = 238 minutes) the four slowest compartments are much more loaded than at the start of the ascent of dive1 *(t = 40; columns 3 and 4 of Table 3, Page 583)*. The saturation curves clearly suggest that more bubbles after dive2 can be expected.

The pN_2 of the compartments from the start of the ascent and beyond were approximated by those of a virtual first dive with a bottom time longer than 40 minutes. The match will never be exact for all eight compartments with the same extension of the bottom time, but a minimal common deviation can be found for one unique extension. With a lengthening of 10 minutes of the hypothetical dive, the match between both sets of saturation curves was optimal, as Table 3 shows. Column 5 shows the start-ascent-tensions of the extended first dive (50 minutes). The sum of the tensions of the eight compartments matches the sum of the second dive. With Model2, this 20-msw/50-minute dive resulted in a pDCS of 2.40% and consequently a logB of -1.18. The resulting logB difference of 0.45 is significantly different from the measured logB-difference; $p = 0.00051$.

DISCUSSION

Relevance of outcomes
The predicted logB difference of 0.29 means that the repetitive dive is expected to produce twice as many bubbles. However, we measured that the repetitive dive actually produced about one-quarter fewer bubbles. The difference between the theoretical expectance (0.34 log unit) and the actual measurement (-0.14) is significant ($p = 0.0078$, Table 2). Also the lower confidence limit calculated with pDCS-logBmodel, being 0.25 log unit, yields a significant difference with the measurements ($p = 0.015$). Using the same procedure with tissue saturations yields a significance of $p < 0.001$.

Comparison with other studies
VGE studies of repetitive air dives are scarce, which makes it difficult to evaluate our results. Some studies of predicting pDCS or BG of single and repetitive dives have been performed, but here they are useless since primary data and statistics have not been described. Two more informative studies have been done with rather similar dive profiles that make a comparison fruitful [9, 10].

The first one, a VGE field study of 101 first dives and 180 repetitive dives with a large variability of profiles, showed that high Spencer scores (>2) occurred nearly twice as much after the repetitive dive than after dive1 (first day of diving trip) [9]. We calculated from this study a logB difference of 0.33. This difference is possibly an underestimate since the repetitive dive (maximum depth 80 feet, with a dive time of 45 minutes, all median values, was less severe than the first one (a maximum depth of 95 feet, with a dive time of 39 minutes).

The second VGE study with a first 25-msw/25-minute dive and a shorter repetitive dive of 25msw/20 minutes (*i.e.*, five minutes shorter) with eight different decompression schedules did not, on average, show a BG difference between the first and second dives [10].

The outcomes of these two experimental VGE studies are in line with the outcome of Model2-logB.

The KISS approach
Measurements: For the analysis the highest BG of the two time samples was used. Another approach is using the KISS method. The KISS value is a kind of combined bubble grade measure of two or more KM scores, with the individual scores raised to the third power [11]. According to the regular KISS procedure [11], the KISS outcomes are log transformed (with zeroes being equivalent to log 0.01). Next, the differences of the logarithms of the KISS outcomes of dive1 and dive2 were taken (so the log of the ratio KISSdive1/KISS-dive2). Averaged over the subjects a mean logKISS difference of -0.19 ± 0.20 (m±SE, n = 28) was obtained.

Modeling: Applying Model2 for dive1 and Model2-modified for dive2, pDCS values at 40 and 100 minutes were transformed to logB and then to KM values. Finally, KISS values of 0.23 and 0.57 were found for dive1 and dive2 respectively, yielding a log KISS-difference of 0.37. This is significantly different from the measured log KISS-ratio of −0.19; $p = 0.0093$.

The subject outcomes of the larger-of-the-two method are well correlated with those of the KISS method (r = 0.94).

Limitations and weaknesses of the modeling
Largest-of-the-two approach: A limitation of our study is the restriction to two measurement points. This decreases the accuracy of the analysis compared to a study with, for instance, four points. With four time points it cannot be ruled out that results would be less deviating

from the theoretically expected BG-difference between dive1 and dive2. However, the deviation will be small since the measured versus expected difference of logB of the KISS approach is nearly the same as that of the largest-of-the-two method (0.46 and 0.48 log unit respectively).

The choice of 40 minutes for the first Doppler measurement was determined by the conditions of this open-sea experiment. However, on the basis of literature data of similar dive profiles (>30 minutes of bottom time), a BG-maximum before 40 minutes is unlikely. Our data show no statistical difference in BGs between the 40- and 100-minute samples, suggesting that the maximum is in between. Recently, with a 21-msw/40-minute (3msw/five-minute stop, 50 divers) dry simulation, we (NS) measured that the maximum is close to 100 minutes. This suggests that the intervals of 40 and 100 minutes were well chosen.

The use of logB: Categorical BGs (KM) were converted to a continuous variable (logB) according to Table 10.3.8 of reference [7]. For experimental and modeling work this method has been adopted before (*e.g.*, ref. 3,8). Although this table was mainly based on pig data, this animal model is classical for DCS studies and more generally for cardiological research with known successful extrapolation to human heart fluid dynamics (*e.g.*, ref. 12). The right ventricle-pulmonary artery system of pig and human are anatomically, physiologically and biophysically (fluid dynamics) so similar that there was no theoretical difficulty with using this transformation for our purposes. If there is some bias or other inaccuracy, its influence will be strongly reduced since only *BG-differences* were considered.

It is possible to avoid the use of logB by modeling the pDCS-BG relation, for instance, with an exponential function. Directly applying the pDCS-BG data of Nishi *et al.* [7] yields $pDCS=0.69^{e0.73BG}$ (BG in KM and pDCS in %). With this equation the log of the ratio pDCSdive1/pDCSdive2 of the measurements was -0.027 ± 0.052 ($m \pm SE$). With Model2 and Model2modified this ratio was 0.098. The value of the measurements appeared to be significantly different from that of the modeling: $p = 0.023$, although less significant than the difference obtained with the Model2-logB approach. The probable reason for this is that the pDCS method uses an ordinal variable, the KM score. This is mathematically disputable. In contrast, transforming bubble grades to a numerical continuous variable (logB) allows simple and robust parametric statistics.

The instantaneous DCS risk: Both bubble count and instantaneous risk rise, peak and diminish. More/less bubbles means more/less instantaneous risk. Although the precise mathematical relation between both is not known, a linear one is to date the best choice. In the before-mentioned 21-msw/40-minute experiment, bubbling has been measured until 160 minutes after the ascent (lower 95% confidence limit is 55% of maximal bubble count). Possibly, the factor R ($r2_{remaining}/r2_{max}$) being 0.20 is an underestimation resulting in a too-low estimate of pDCS after dive2, and consequently, dive2 would have started with many remaining bubbles and would result in a higher logB than we calculated.

Calcuation of pDCS of dive2 via tissue saturations

The choice of the set of halftimes for N_2 tensions is not critical. Moreover, finally differences in tension were calculated that makes the approach even more robust. The same holds for a series model, such as DCIEM. The slow compartment of Model2 does contribute for only at most 10% in dive2. When the seventh and eighth compartment were completely removed in the calculations of Table 3, then a bottom time of 47 minutes was needed. This finally yielded a logB difference of 0.31 log unit ($p = 0.048$).

With the use of tissue saturations, only tissue tension was considered. However, nitrogen load is another important parameter. When tensions were multiplied by compartment volumes (column 2 in Table 3 with the fat-compartment counting five times more due to the fat/water solubility ratio), the optimal match yielded an extension of bottom time of 18 minutes.

Another point of view is considering M-values [4] calculated with ZH-L16C [2]. The first eight minutes after the dive2-ascent the third compartment is leading for bubble formation, then the fourth until about 25 minutes (five minutes earlier than with the first dive) and, next, the slow compartments take over. This suggests that the slow compartments are most relevant for bubble formation in the hours after the dives. After surfacing, the leading M-values of dive2 range from 91.5 (third compartment) to 80% (eighth compartment) of their critical values (*i.e.*, the transition between super- and hyper-saturation). For dive1 these values are 90% and 72%, respectively, suggesting that dive2 generates more bubbles.

The above discussion about N_2 tensions, N_2 loads and leading M-values indicate that dive2 can certainly not be considered as a dive without history. It is a dive with high supersaturations in nearly all tissues after the ascent and a considerably higher bubble stress than dive1.

Discrepancy of measurements and expectations

By directly applying Model2 for dive1 and Model2-modified for dive2, and by applying Model2 for the 50-minute dive after calculating tissue saturations *(Table 3)*, dive2 must produce significantly more bubbles. A similar procedure, but now with application of the KISS method (40- and 100-minute scores) yielded the same results.

The measured difference (fewer bubbles with dive2) is incompatible with the theoretically expected increase. Now, the question arises as to why this discrepancy was found. Is the model incorrect, or were there special conditions of the dives which do not allow application of the model as described? We see no reasons to think that the (modified) Model2 is basically incorrect, especially since the approach via N2 saturations yields similar results. Also the pDCS-logB model will basically be correct. In our opinion, the reason should be found in non-standard conditions and demography of the divers.

Age: It is generally found that a higher age results in more bubbles (for instance, references 9,13,14,15 and unpublished observations of the authors). This is possibly due to a poorer circulation, resulting in increased tissue half-times. During decompression a slower release would be the result (provided that saturation was not reached), since the driving force for outwash is then smaller. In our study, the mean age is probably higher than that of divers whose data have been used for the construction of decompression tables and Model2 (mostly Navy divers). Higher half-times slow down the outwash. This leads to higher-than-expected bubble grades for dive2.

Rest: From the literature it is known that aerobic exercise preceding diving has been found to reduce precordial BGs [16,17] and the number of VG bubbles in the right ventricle measured with Doppler echocardiograms [16,18] compared to those measured when a period of rest preceded the dive. Without exercise preceding the dive, more nuclei are circulating. It is possible that the high age of our divers has strengthened this effect due to their poorer vascular condition (more crevices for bubble formation). In the (open) literature it cannot be found whether the subjects (generally military divers) with whom tables were validated, performed some aerobic activity or whether they were subjected to a day of rest before diving. Possibly the tables are only optimally valid for young divers who perform sport activity almost every day. Unfortunately, for practical reasons, it was not possible to let the same divers in our experiment perform the two dives with physical exertion on the day preceding the dives.

Dive break: Multiday diving appeared to decrease sensitivity for VGE [5]. Speculating, the reverse possibly also holds; not diving for some months previously makes divers more vulnerable for VGE and DCS. From the results of the two versions (modified and direct via tissue saturations) of Model2-logB it may be concluded that the measured difference in Doppler score between dive1 and dive2 was smaller than calculated. The comparatively high age of our subjects, combined with some days of no aerobic exercise and possibly a long dive break, may have made them more vulnerable than expected for VGE after dive1. However, pDCS-logB model is based on the data pool of Nishi *et al.* [7] that can be regarded on average as a standard with respect to demographic and diving conditions. This means that Model2 generates a too small an outcome for dive1 (our subjects were older and did not exercise.). But dive2 is assumed to be less affected since the supposed excess of bubble nuclei before dive1 (no exercise) is consumed during the surface interval. (Suppose that Model2 adjusted for our subjects gives a pDCS that is Δ higher than with Model2modified; $pDCS_{corr}$ will be only about R x Δ higher.) Consequently, the difference in pDCS between both dives becomes smaller than under standard conditions.

CONCLUSIONS

Given the conditions of the subjects, the above suggests that the outcome of Model2 for dive1 is too low. With a higher outcome the difference between both dives would have been smaller, and this is what the measurements show. Therefore, with reservation, it may be recommended that after a long period of not diving and not exercising for several days, divers – possibly the older ones in particular – should dive more conservatively than dive tables and computers indicate.

However, more research is needed to study the bubble grades of identical repetitive dives near the transition of no-stop diving after rest and exercise in both older and younger divers in order to optimize the use of tables and algorithms of dive computers.

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