Doppler Bubble Grades After Diving and Relevance of Body Fat

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Background: From the literature on venous gas embolism (VGE) and decompression sickness (DCS), it remains unclear whether body fat is a predisposing factor for VGE and DCS. Therefore, this study analyses body fat (range 16–44%) in relation to precordial VGE measured by Doppler bubble grades. Also examined is the effect of age (range 34-68 yr), body mass index (BMI; range 17-34 kg $\cdot$ m^{-2}), and a model estimate of $\dot{V}O_{2max}$ (maximal oxygen uptake; range 24-54 ml $\cdot$ kg^{-1} $\cdot$ min^{-1}). **Methods:** Bubble grades were determined in 43 recreational divers after an open sea air dive of 40 min to 20 m. Doppler bubble grade scores were transformed to the logarithm of the number of bubbles/cm^2, logB, and the logarithm of the Kissman Integrated Severity Score (KISS) to allow numerical analysis. Statistical analyses were performed with Pearson's regular and partial correlations, and uni- and multivariate linear regressions. **Results:** For divers in their midlife (and older), the analyses indicate that neither body fat nor BMI stimulate bubble formation, since correlations were nonsignificant. In contrast, age and especially $\dot{V}O_{2max}$ appeared to determine VGE. For these types of dives it was found that logB = $-1.1 + 0.02$age $- 0.04\dot{V}O_{2max}$. **Conclusion:** Based on these data we conclude that body fat and BMI seem less relevant for diving. We recommend that medical examinations pay more attention to $\dot{V}O_{2max}$ and age, and that international dive institutions come to a consensus regarding $\dot{V}O_{2max}$ criteria.

Keywords: adiposity, $\dot{V}O_{2max}$, age, bubble count, venous gas embolism.

A FTER A CENTURY, it remains uncertain which demographic factors promote or suppress the formation of intravenous bubbles. However, it is currently generally accepted that increasing age stimulates bubble formation (5–7,19) and decompression sickness (DCS) (19,23) and that a high $\dot{V}O_{2max}$ (maximal oxygen uptake per weight and time unit) suppresses bubble formation (5,6). Another predisposing factor might be body fat. Although for many decades it has been suggested that a high DCS risk is related to a higher body fat percentage (19), there is no consensus on whether the amount of body fat is related to venous gas embolism (VGE) (5,6,19). As nitrogen is five times more soluble in fatty liquids than in aqueous solutions, it is suggested that a high percentage of body fat enhances VGE. A complicating issue is that, in general, body fat increases with age and decreases with $\dot{V}O_{2max}$. Unfortunately, when analyzing the relation between body fat and DCS, old studies did not take into adequate account the potentially confounding relationships between age and $\dot{V}O_{2max}$ with DCS. However, recent studies did consider these relationships and found that the bubble grade (BG) of VGE was significantly related to age (2,5,6) and to $\dot{V}O_{2max}$

(5,6). Despite that body fat was significantly correlated with BG, it was not concluded that body fat controls BG (5,6); however, these studies did not correct for confounding effects.

The present study considers relatively older recreational divers (e.g., compare 2 and 5–7, also for additional references). Men and women in their midlife and beyond generally suffer from an increasing amount of body fat. Moreover, the average age of recreational divers has slowly increased due to aging of the population, better medical care, and increased prosperity. The lack of conformity in earlier research and the aging recreational diving community form the rationale for a new analysis to address the question of whether body fat affects VGE susceptibility.

Medical examinations often impose limitations on diving when $\dot{V}O_{2max}$ is low, or when body fat or body mass index (BMI) is high. In this study, BMI is included as an additional potential predictive parameter. Based on published reports, it is hypothesized that high body fat (or a high BMI, due to its high correlation with body fat) and age are related to a high BG, and a high $\dot{V}O_{2max}$ to a low BG. In this study the extent of VGE is measured by the precordial Doppler technique. Due to the established collinearity, the relationship between BG and age, and BG and $\dot{V}O_{2max}$ is also considered.

METHODS

Subjects

A total of 61 recreational divers volunteered to participate in the study. Fitness to dive and experience were established based on a valid medical certificate, an additional questionnaire about age, gender, dive experience

(number of years diving, total number of open-water dives, and maximal depth), and a (limited) medical examination. Subjects were selected on the basis of these data. To obtain standardized measurements, the subjects fasted from the night before the dive and did not drink anything prior to the medical examination.

Procedure

This study, performed as a part of a diving medicine course 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. Nevertheless, the course members who volunteered as study subjects provided signed informed consent.

The divers performed two 40-min air dives (Dive1 and Dive2) to 20 msw with descents of 20 msw · min^{-1} and ascents of 10 msw · min^{-1}, and with a surface interval of 2 h and 30 min. Ascent times to the stops (made at a buoyancy line) are included in the stop times. Two dive profiles with a minor difference were used: one group made a dive with a single stop at 4 msw for 7 min (1Sdive); the other group performed the 40-min 20-msw dive with two stops (2Sdive); i.e., a 4-min stop at 10 msw and a 3-min stop at 4 msw. The subjects in the 1Sdive and the 2Sdive groups were matched with respect to age, body fat, and $\dot{V}o_{2max}$. 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 BGs of both profiles, see 20). 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.

Body fat was determined with the bio-impedance method (hand-held electrodes, Omron apparatus) and the 4-skinfolds method (8) in the early morning immediately after waking up. The individual mean of both methods was used as the final estimate, as the reliability of both methods is practically the same (13). To determine BMI (kg · m^{-2}) the subjects wore underwear only and were barefoot. For practical reasons, $\dot{V}o_{2max}$ was estimated by two models based on age (A), gender (G), and a questionnaire about endurance sport activity. The first method considers running pace during specific distances (18, Chap. 11, slightly modified to incorporate age):

$$\dot{V}o_{2max} = 44.9 + 7.04\,G - 0.82\,BMI + 0.69\,PFA$$
$$(1 - 0.006(A - 23)) + 0.74\,PA\text{-}R \qquad \text{Eq. 1}$$

where G is 2 for men and 0 for women, A is years, and the two pace-distance scores, PFA (perceived functional ability) and PA-R (physical activity rating) are used as defined in MacArdle et al. (18), Chap. 11.

The second method is based on a linear regression (with body fat and age as variables) constructed from literature data (18, Chap. 11) and step test data obtained according to Siconolfi et al. (22). This was refined by including the number of h/wk of extreme (E; HR > 0.92 HR$_{max}$, with HR = heart rate), heavy (H; 0.92 HR$_{max}$ > HR > 0.80 HR$_{max}$), and light (L; 0.6 HR < HR < 0.80 HR$_{max}$) endurance sport. The coefficients of the regression equation were further improved by cross-validating the estimates of a different sample of 70 recreational divers with the outcomes of two published models (10,14). The final result is:

$$\dot{V}o_{2max} = 57 + 2\,G - 0.24\,A - 0.59\,Bf$$
$$+ 4\,E + 2.5\,H + 1.4\,L \qquad \text{Eq. 2}$$

where Bf is body fat in %. The correlation of the outcomes of Eq. 2 with the outcomes of two literature models (10,14) is 0.92 and 0.80, respectively. Our model has an estimated standard error of the estimate of 16%; i.e., 2% more than the average of reported models (17).

In our study, the extent of VGE was measured twice: at 40 and at 100 min after surfacing. The intervals of 40 and 100 min were conditional on the transfer time by boat from the dive site to the examination room, the duration of a Doppler examination of a single subject, the number of subjects, and the availability of two examiners. The VGE measurements were performed precordially at the left third intercostal space with a 2.5-MHz continuous-wave Doppler DBM9008 with an array probe bubble detector (Techno Scientific, Toronto, Canada). All measurements were performed by the same two experienced Doppler examiners (certificated by DRDC Toronto). One individual session, lasting nearly 5 min, consisted of four measurements. The first measurement was made while the subject was standing at rest and the other three immediately after one deep knee bend (flex). The Doppler sounds were digitally recorded on a MP3-recorder and scored blinded, with BG expressed in Kisman-Masurel (KM) units (19). The highest value of the three deep knee bends was used for analysis in the present study. This yielded one score for the 40-min postdive measurement and another score for the 100-min postdive measurement.

Since BGs could be measured only at two moments after surfacing, a precise estimate of the maximum BG value is impossible. For best approximate maximum as possible, the highest of the 40- and 100-min scores was used, a method applied previously (19–21). To allow parametric statistics, the ordinal KM scores were transformed to a numerical scale: the number of bubbles/cm^2 [according to Table 10.3.8 of Nishi et al. (19)]. However, using the bubble count is inappropriate, since bubble counts deviate considerably between subjects, which results in a severe domination of high counts in the statistics (the outlier problem). Therefore, we used the logarithm of the bubble count (logB). Another advantage of using logB is that the distributions become more normal, allowing direct interpretation of the correlation coefficients.

To overcome the substantial intersubject scatter of data, pooling of data is the tool for reduction. For the 1Sdive and 2Sdive this was performed by calculating the difference in logB of the means of the 1Sdive and 2Sdive. It was earlier found that the 1Sdive and 2Sdive produced a logB difference of half a log unit (20). We adjusted for this difference between both mean logB values by adding (1Sdive) or subtracting (2Sdive) 0.26 log unit. In another study based on the same experiments, the first and identical second dive produced the same amount of bubbles rather well (difference of logB 0.14 log unit; $P = 0.32$) (21). Therefore, the data of these sequential dives were also pooled (directly).

Statistical Analysis

KM grade, an ordinal variable, can be used only in nonparametric analyses. However, a parametric approach with logB and the logarithm of the Kissman Integrated Severity Score (KISS) value [a common BG measure of the 40- and 100-min KM score, see Jankowski et al. (12)] as numeric dependent variables was preferred since it allowed more statistical methods of analysis. These methods are often mathematically more direct and more robust than nonparametric tests.

The major methods were calculating the Pearson binary correlation coefficient R, the Pearson partial correlation $\rho_{x\,y,r}$, with r the set of correcting (or controlling) variables (15), and calculating regressions. The partial correlation ρ measures the degree of association between two stochastic variables, with the effect of one or more other stochastic variables removed. Univariate and multivariable linear regressions were performed with logB as dependent variable and age, $\dot{V}o_{2max}$, and body fat as independent variables. Residual mean squares (MS_R) was a leading parameter for evaluating the analyses in addition to the significance of the calculated coefficients of the individual variables. The variance inflation factor (VIF) was used to have a measure of the collinearity within the multivariable regression model (16). VIF gives the square of the increase of the standard error of the coefficient of each independent variable due to collinearity. With values >10 the model should be rejected and between 5 and 10 the model is disputable. The above analyses were allowed since the distributions of age, $\dot{V}o_{2max}$, body fat, and BMI were (multivariate) normal and the logB distribution was sufficiently normal (Golmogorov-Smirnov normality test). Most subjects performed Dive1 and Dive2. After pooling the data of Dive1 and Dive2 a correction of P of ρ was obligatory since the logB of both dives were correlated. The *t*-value of the Student's *t*-test was multiplied by $1/(1 + |R|)^{0.5}$, with R being the correlation between both dives. This correction, which can be derived from Hotelling's T^2, was performed for the data of the divers who performed both Dive1 and Dive2. *P*-values < 0.05, tested double-sided (despite our hypotheses), were considered statistically significant. Correlations and regressions were calculated with SPSS 16.0.

RESULTS

Of the 61 included divers, 43 performed the intended dive profiles. In total, 31 divers (25 men, 6 women) performed the first dive (Dive1), 1Sdive, or 2Sdive, with 1 man and 1 woman not performing the second dive (Dive2). Dive2 was performed by 41 divers (34 men, 24 from the first dive and 10 additional men; 5 women from the first dive and 2 additional women). Thus, a total of 72 dives were analyzed. The repetitive dive was always of the same type (either S1dive or S2dive). The profiles of Dive1 and Dive2, averaged for subjects and time, show a negligible difference from the intended 20-msw dive; the deviation was 0.07 ± 0.08 msw (mean $\pm$ SE). At the bottom, the divers were swimming very slowly. No case of DCS was observed or reported by the divers.

Body fat values were average, whereas, having taken age into account, $\dot{V}o_{2max}$ was supra-normal (18, Chap. 7). The outcomes of the $\dot{V}o_{2max}$ exercise model of the authors, Eq. 2, and that of Eq. 1 showed a correlation coefficient R of 0.78. After averaging both sets of outcomes, the variability (SD/mean) decreased by 6%. The body fat values obtained with bio-impedance and with skinfolds were also highly correlated: R = 0.87. A procedure similar to that used for $\dot{V}o_{2max}$ decreased the variability of body fat (SD/mean) by 4%. **Table I** summarizes the demographic variables of age, body fat, BMI, and $\dot{V}o_{2max}$ and **Fig. 1** shows the relationship between body fat and BMI (separately for men and women).

In **Table II**, the inner 4×4 matrix gives the 6 Rs and the 6 ρs between the independent variables age, body fat, BMI, and $\dot{V}o_{2max}$ of the 43 divers. Above the diagonal (indicated by the '1s') the regular Rs are given in regular font and, below the diagonal, the partial ρs are given in italics. Numbers between parentheses are two-tailed P-values. Given the collinearity between the independent

TABLE I. DATA ON DEMOGRAPHIC VARIABLES AND VALUES OF logB (LOG(#BUBBLES/CM$^2 \cdot$ MIN^{-1})) OF DIVE1, DIVE2, AND BOTH DIVES POOLED.

	Age (yr)	Body Fat (%)	BMI (kg $\cdot$ m^{-2})	$\dot{V}o_{2max}$ (ml $\cdot$ kg$^{-1} \cdot$ min^{-1})	logB Dive1	logB Dive2	logB Dives 1&2
Mean	51.5	27.3	26.0	35.9	−1.34	−1.40	−1.37
Median	49.0	25.9	25.7	33.9	−0.97	−1.17	−1.04
Range	38.1–76.0	16.4–43.6	17.3–34.3	20.4–54.0	−3.3–0.11	−3.3–0.42	−3.3–0.42
SD	9.4	6.9	3.8	7.5	0.98	1.16	1.08
N	43	43	43	43	31	41	72
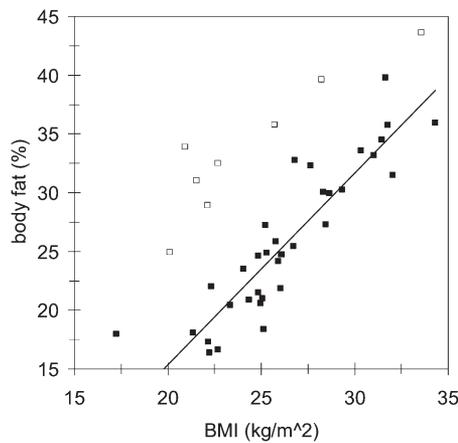
Fig. 1. Body fat versus body mass index (BMI) for male and female volunteers. Black symbols indicate men and white symbols indicate women. The regression for the men is Bf = 1.63BMI – 17.4.

variables, the analysis was refined by calculating ρs between two of the variables age, $\dot{V}O_{2max}$, body fat, and BMI, with the remaining two as control variables. The significant correlation between age and body fat that is generally found (5) was not confirmed in our study by the ρ between body fat and age. The sign reversal of this correlation is remarkable compared to $R_{Bf\,A}$. However, the ρs between $\dot{V}O_{2max}$ and body fat, and between $\dot{V}O_{2max}$ and age were highly significant. The partial correlations of BMI with body fat, $\dot{V}O_{2max}$, and age show a high level of significance (Fig. 1), hardly any significance, and no significance, respectively (Table II). Having discussed the interrelationships within the demographic variables, we now discuss their relation with logB.

Table I also presents the basic statistics of logB of Dive1, Dive2, and the pooled data of these two dives. The individual KM values can be found in previous papers (20,21). **Fig. 2** presents scatter plots of the (dependent) variable logB versus the three demographic (independent) variables age, $\dot{V}O_{2max}$, and body fat. In Table II, the right column and the lower line (both in bold) give Rs and ρs between logB and the independent variables, respectively. The correlation of both logBs of Dive1 and Dive2 is 0.73, resulting in a correction factor of 0.76. Applied to the 29 pairs of repetitive dives, this reduced the *t*-values of the Rs and ρs by 19%.

In Table II, comparing the Rs of the right column with the ρs of the bottom line clearly shows the effect of

removing the influence of confounders. The regular significant correlation with age changed from significant to nonsignificant. Surprisingly, the nonsignificant regular correlations of fat and BMI changed the sign, but remained nonsignificant, whereas the significance level of the correlation with $\dot{V}O_{2max}$ remained the same.

Univariate regression between logB and one of the demographic variables is best described by a linear relationship, as shown in Fig. 2. **Table III** presents results of the coefficients of the univariate model. BMI is no longer included in the analysis due to its total lack of correlation with BG. The constant of the models logB(constant,age) and logB(constant,Bf) are significant, but the coefficient of the latter model is not (nor is the model itself). Also, the constant of logB(constant,Vm) is not significant (Vm is $\dot{V}O_{2max}$).

The model with the three demographic variables yields a nonsignificant coefficient of age. However, age is hardly subjected to collinearity (VIF = 1.3). In these multiple regression models, the negative contribution of Bf is in line with the negative $\rho_{Bf\,logB,r}$. The coefficient of Bf is also not significant. Moreover, body fat has a large VIF. Therefore, and since body fat reduces MS_R by only 3%, body fat was removed from the model. Removal of age, instead of body fat, yielded a model with similar reliability, with the exception that the VIF of age is three times less. For these reasons, the model that performs best is:

$$logB(A,Vm) = -1.11 + 0.023\,A - 0.041\,Vm \quad \text{Eq. 3}$$

In **Fig. 3**, logB is depicted as a function of $\dot{V}O_{2max}$ for a younger (35 yr) and an older diver (60 yr). Eq. 3 becomes $logB_{35} = -0.30 - 0.041\,Vm$ and $logB_{60} = +0.27 - 0.041\,Vm$ for 35 and 60 yr, respectively. From McArdle et al. (18, Chap. 7), norm values of $\dot{V}O_{2max}$ as a function of age can be modeled directly. For men this yields:

$$\dot{V}O_{2max,man} = 48.4 - 0.43\,A + 0.0020\,A^2 \quad \text{Eq. 4}$$

(with an SD value, for each age, of 5 ml · min^{-1} · kg^{-1}). This yields norm values of $\dot{V}O_{2max}$ of 35.8 and 29.8 ml · min^{-1} · kg^{-1} for 35 and 60 yr, respectively. Fig. 3 visualizes Eq. 3 for ages 35 and 60 yr. The thick line (35 yr) and thin line (60 yr) start at the value 'norm – 5' (ml · min^{-1} · kg^{-1}) and end at 'norm + 15' (note that 1 SD = 5 ml · min^{-1} · kg^{-1}). This range of $\dot{V}O_{2max}$ appeared to be realistic for recreational divers. Using the confidence limits

TABLE II. DATA ON REGULAR (REGULAR AND REGULAR-BOLD) CORRELATION COEFFICIENTS BETWEEN AGE, BODY FAT, BMI, $\dot{V}O_{2max}$, AND logB; AND PARTIAL (ITALIC AND BOLD-ITALIC) CORRELATION COEFFICIENTS BETWEEN AGE, BODY FAT, BMI, $\dot{V}O_{2max}$, AND logB AFTER CORRECTION FOR THE OTHER (TWO OR THREE) REMAINING VARIABLES.

	Age	Body Fat	BMI	$\dot{V}O_{2max}$	logB
Age	1	0.22 (0.15)	−0.017 (0.91)	−0.42** (0.006)	**0.333* (0.017)**
Body Fat	*−0.146 (0.362)*	1	0.68** (0.000)	−0.84** (0.000)	**0.213 (0.13)**
BMI	*−0.21 (0.184)*	*0.41** (0.009)*	1	−0.68** (0.000)	**0.091 (0.45)**
$\dot{V}O_{2max}$	*−0.442** (0.004)*	*−0.729** (0.000)*	*−0.097 (0.55)*	1	**−0.384** (0.0051)**
logB	***0.15 (0.31)***	***−0.138 (0.35)***	***−0.037 (0.80)***	***−0.296* (0.039)***	1

P-values are indicated in parentheses. * $P < 0.05$, ** $P < 0.01$
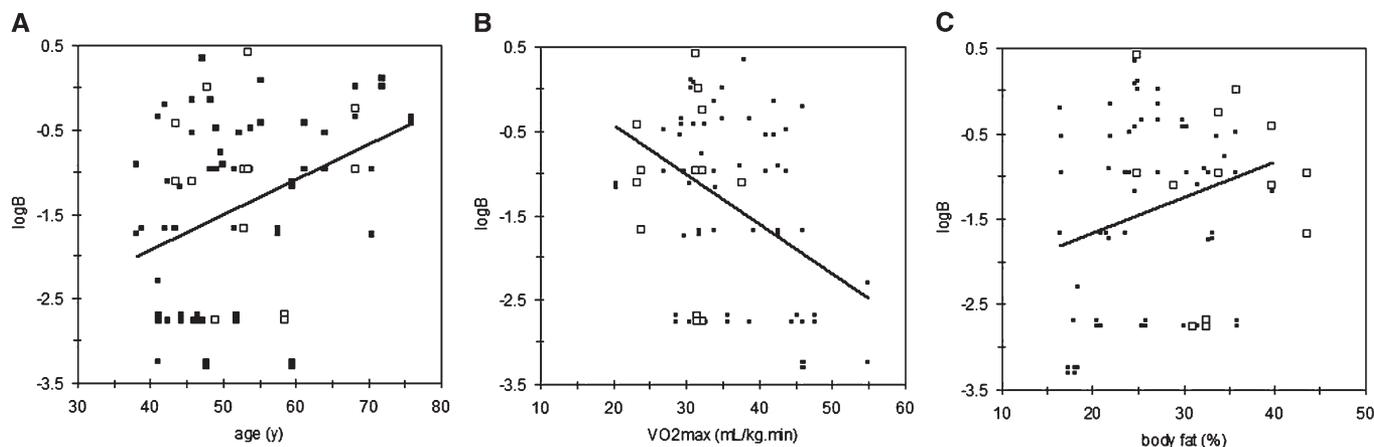
Fig. 2. logB versus A) age, B) $\dot{V}_{O_{2max}}$, and C) body fat, with regression lines indicated. Black symbols indicate men and white symbols indicate women. The regression lines of A, B, and C, based on the male data, are logB = 0.042A – 3.6, logB = – 0.059Vm + 0.75, and logB = 0.014Bf – 2.5, respectively.

of Eq. 3 in Table III and ignoring the confidence limits of the constant, for 35 yr $logB_{35}$ = –0.30 ± 0.46 – 0.041 ± 0.017 Vm and for 60 yr $logB_{60}$ = 0.27 ± 0.78 – 0.041 ± 0.017 Vm were obtained.

In addition to the above analyses, a logKISS analysis was also done (12). The Bf-logKISS correlation coefficients (R and ρ) were nonsignificant. Model 4 of Table III, now for logKISS, yields a nonsignificant coefficient of body fat (P = 0.24). With its high VIF this allowed the removal of body fat from the logKISS model. After removal, MS_R did not change, making the logKISS(constant,age,Vm) model (age 0.028 ± 0.015 and $\dot{V}_{O_{2max}}$ – 0.052 ± 0.020) the most suitable one (1).

DISCUSSION

This study investigated the influence of age, $\dot{V}_{O_{2max}}$, and, in particular, body fat (with BMI as related variable) on the extent of VGE as measured by the precordial Doppler technique. Special attention was also paid to the collinearity of these factors. It was found that the statistical behavior of body fat is inconsistent and that there are no indications that body fat enhances VGE. In fact there is no indication at all that BMI is related to bubble grade. Age and $\dot{V}_{O_{2max}}$ appeared to be more promising as a BG determinant. All age effects were consistent. Taking these results of age together, there is a
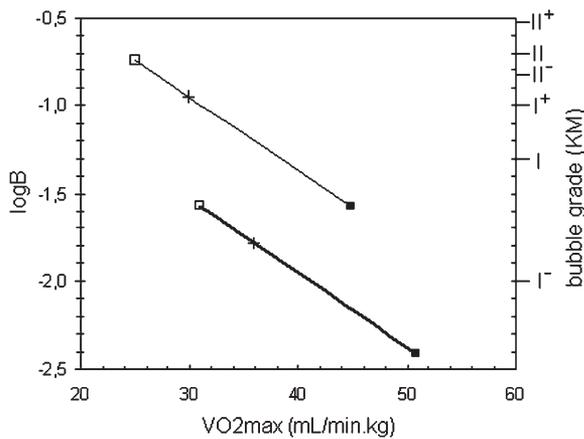
tendency for a bubble-promoting effect, but less strong and convincing than reported in other studies (5–7). In our sample, the oldest divers have a long dive history with many hundreds of dives and no DCS history; this may imply that their susceptibility for VGE is relatively small.

The outcomes of the $\dot{V}_{O_{2max}}$ –logB association were highly consistent; i.e., we found significant negative Rs, ρs, and regression coefficients. Therefore, $\dot{V}_{O_{2max}}$ appears to be an important predisposing factor for VGE, as also concluded in an earlier study (5). After reducing the regression model to the independent variables age and $\dot{V}_{O_{2max}}$, the remaining collinearity was 10% and, thus, practically removed (VIF = 1.2). This model, Eq. 3, has a highly significant $\dot{V}_{O_{2max}}$ coefficient and an age coefficient close to significance (P = 0.080). The SE of the coefficients of this favorite model are too large to use for precise predictive purposes. Considering this model and model 6 of Table III together, logB increases some 0.3 units in every decade (i.e., doubling bubble counts) and logB increases some 0.4 units (factor 2.5) with a 10-point decrease of $\dot{V}_{O_{2max}}$. Although these data can only be seen as a numerical trend, increased age and diminished $\dot{V}_{O_{2max}}$ do increase VGE and, consequently, the risk of DCS. A 0.3 logB increase enhances BG by nearly one-third of a KM unit (above grade I). This is

TABLE III. DATA ON LINEAR REGRESSIONS BETWEEN DEMOGRAPHIC VARIABLES AND logB.

Model	Model Description	Coefficient of Model	SE of Coefficient	P-value of Coefficient	VIF	P-Value of Model
1	logB(constant,A)	0.036	0.012	0.004*		0.004*
2	logB(constant,Vm)	−0.053	0.015	0.001**		0.001**
3	logB(constant,Bf)	0.033	0.018	0.072		0.072
4	logB(constant,A,Vm,Bf)	0.018 [1]	0.013	0.19	1.3	0.001**
		−0.078 [2]	0.031	0.013*	4.2	
		−0.045 [3]	0.032	0.16	3.7	
5	logB(constant,A,Vm)	0.023[1]	0.013	0.080	1.2	0.001**
		−0.041[2]	0.017	0.049*		
6	logB(constant,A,Vm)	0.043[1]	0.019	0.035*	1.3	0.001**
	Carturan et al. (6)	−0.035[2]	0.018	0.050*		

[1] Age, [2] $\dot{V}_{O_{2max}}$, [3] body fat, * P < 0.05, ** P < 0.01.

Fig. 3. LogB-$\dot{V}O_{2max}$ relationship. The thick line is the regression of a diver 35 yr of age, $\log B_{35} = -0.30 - 0.041 Vm$ and the thin line is the regression of a diver 60 yr of age, $\log B_{60} = 0.27 - 0.041 Vm$. + norm value, white square norm -5 mL/min.kg and black square norm $+15$ ml · $min^{-1} \cdot kg^{-1}$.

equivalent to an increase of DCS risk by a factor of 1.25 as calculated from Schellart and Sterk (21), and with older divers probably more, since the functionality of the lung bubble filter is assumed to decrease with age.

Another study reported on the effect of body fat on VGE in men and women, with the effect being larger in men (2). However, it is questionable whether the men-women comparison in that study is valid, since men and women were not matched with respect to body fat (women had a factor of 1.43 more fat) and their $\dot{V}O_{2max}$ was unknown (2). Therefore, the association between body fat and VGE in the earlier study (2) could be caused by the collinearity of body fat with $\dot{V}O_{2max}$. Since the difference in VGE susceptibility between men and women remains obscure, and considering Fig. 2, it seems acceptable to process the female and male data together. This was confirmed by reanalyses including male subjects only, in which the new results led to conclusions similar to the original ones.

Our data show no statistical difference in BGs between the 40- and 100-min samples, suggesting that the maximum is somewhere in between. Some studies applied more measurements of VGE, whereas others made only one measurement (5-7). As an estimate of the individual maximum we used the highest of the two scores. The correlation between the highest and logKISS is R = 0.99. The literature gives no indication that the maximum is beyond 100 min, with the exception of much heavier and longer dives. In our new study (unpublished data; 21-msw 40-min profile), BGs at 40 and 80 min were the same, and those at 120 and 160 min were considerably lower. A study with a slightly heavier profile did not show bubbles after 50 min (2). All this suggests that, for the present study, the intervals of 40 and 100 min were an appropriate choice. After correcting for the mean logB difference between the 1Sdive and 2Sdive, the variability of logB was reduced, thus improving the reliability of the analysis. Pooling of the Dive1 and Dive2 logB values maximized the number of cases in the analyses and thus improved its reliability.

The determination of $\dot{V}O_{2max}$ is based on two different arithmetic models. Taking the mean of both per subject reduced the coefficient of variation by 6% (in accordance with error theory), making the analyses less "noisy." Similarly, for body fat the coefficient of variation was reduced by 4%, also indicating an improved estimate.

The study of Carturan et al. (5) considered an open water dive of 35 msw for 25 min (total decompression time 18 min) performed by recreational divers with a mean age of 37 ± 10 yr. Our reanalyses [R, ρ, and (multivariate) regressions] of their data (with one BG score 60 min after surfacing) was performed with the BG scores transformed to logB. The various analyses revealed outcomes similar to ours, considering the signs and significances of Rs, ρs, and the coefficients of the regressions.

The strong collinearity between the independent variables means, as a consequence, that a significant R between such a variable and bubble count does not necessarily imply that this variable affects the extent of VGE. The data from Carturan et al. (6) and from our study show a considerable reduction of the regular correlation when recalculated as a partial correlation. In their study (6), the partial correlation between body fat and age showed a tendency toward significance, but $\rho_{Bf\ logB,r}$ was far from significant, $\rho_{A\ logB,r}$ was only just significant, and that between $\dot{V}O_{2max}$ and logB almost significant. The regression analyses of logB(constant,A,Vm,Bf) and of logB(constant,A,Vm) yielded the same summed square errors of the residuals, and the same holds for the summed square errors of the regression. Therefore, body fat (with a significance of $P = 0.97$) must be deleted from the model (1). Consequently, in that study (6), body fat seems to be irrelevant for ages of 20 yr and older.

A high $\dot{V}O_{2max}$ is associated with a high capillary density in the muscles. This ensures better perfusion and, therefore, faster release of N_2 than in the case of a low $\dot{V}O_{2max}$. This may be the most important reason for the negative correlation between $\dot{V}O_{2max}$ and VGE. The half-time of fatty tissue is about 200 min (4) and the solubility of nitrogen is about five times that of watery tissue. Consequently, more fat should result in a delayed release that (as a hypothetical consequence) is thought to allow the microbubbles in the blood to expand more. However, the measurements do not support this common hypothesis. With a slow swimming diver under thermal neutrality (i.e., our conditions), the oxygen consumption in the skeletal muscles is two-thirds of total body consumption of about 11 ml · kg^{-1} · min^{-1} (4 and 18, Chap. 26) and the muscles have the highest contribution of total body perfusion. The muscle compartment is about 33% of total body volume (4) and the fat compartment about 25% (our subjects). Together with the short half-time of muscles (supposed to be some tens of minutes, much smaller than generally thought), muscles will encompass more nitrogen at the end of a light and moderate dive than the fat compartment. After surfacing, the muscles become close to inactive, considerably lengthening their half-time. All this reduces the importance of the fat compartment. Therefore, one wonders whether considerable body fat indeed gives a substantial delayed

off-gassing of the blood compared to less fat. This problem is the topic of a future study as sequel to this one.

In the current medical examination of professional divers, body fat >25% is a relative contraindication. BMI values >25 kg · m^{-2} are considered as progressively decreasing the fitness to dive and, therefore, increasing the risk of DCS. BMI values >30 kg · m^{-2} may indicate excessive body fat, which should be ≤30% of total bodyweight for fitness to dive (11). In the light of the present findings, one wonders whether these fat and BMI criteria of professional divers have an appropriate scientific basis.

In the Dutch practice of examination of Navy and other professional divers, fitness to dive is assumed for a $\dot{V}o_{2max}$ >40 ml · min^{-1} · kg^{-1} (9). For recreational divers there is no formal criterion for $\dot{V}o_{2max}$ (and body fat or BMI); even for professional divers there is no general consensus. A gas-ergometric $\dot{V}o_{2max}$ measurement or, otherwise, a model estimate of $\dot{V}o_{2max}$ seems necessary to allow an evaluation using a formal criterion. A swimming pace of a diver of 0.5 m · s^{-1} (1 kn · h^{-1}) is realized with a $\dot{V}o_{2max}$ of 25 ml · min^{-1} · kg^{-1} (3 and own measurements). A poor $\dot{V}o_{2max}$ not only results in more bubbles, but also restricts the physical reserve. One would argue that 25 ml · min^{-1} · kg^{-1} is the absolute minimum for any recreational diver.

The present study indicates that body fat and BMI are not predisposing factors for bubble formation, and that $\dot{V}o_{2max}$ is an important predisposing factor, possibly more than age. This holds at least for deco-dives of intermediate depth with short to moderate decompression times and for divers in their midlife (and older) who do not perform demanding work at depth. We recommend that the medical examination of recreational divers pay more attention to $\dot{V}o_{2max}$ and that international dive institutions come to a consensus regarding minimum $\dot{V}o_{2max}$ criteria for all divers.

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