Body fat does not affect venous bubble formation after air dives of moderate severity: theory and experiment

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Schellart NA, 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 114: 602–610, 2013. First published January 10, 2013; doi:10.1152/japplphysiol.00949.2012.—For over a century, studies on body fat (BF) in decompression sickness and venous gas embolism of divers have been inconsistent. A major problem is that BF, and maximal oxygen consumption (V\textsubscript{O\textsubscript{2max}}) show high multicollinearity. Using the Bühlmann model with eight parallel compartments, preceded by a blood compartment in series, nitrogen tensions and loads were calculated with a 40 min/3.1 bar (absolute) profile. Compared with Haldanian models, the new model showed a substantial delay in N\textsubscript{2} uptake and (especially) release. One hour after surfacing, an increase of 14–28% in BF resulted in a whole body increase of the N\textsubscript{2} load of 51%, but in only 15% in the blood compartment. This would result in an increase in the bubble grade of only 0.01 Kisman-Masurel (KM) units at the scale near KM = 1−. This outcome was tested indirectly by a dry dive simulation (air breathing) with 53 male divers with a small range in age and V\textsubscript{O\textsubscript{2max}}.

For over a century, studies on body fat (BF) in decompression sickness and venous gas embolism of divers have been inconsistent. A major problem is that BF, and maximal oxygen consumption (V\textsubscript{O\textsubscript{2max}}) show high multicollinearity. Using the Bühlmann model with eight parallel compartments, preceded by a blood compartment in series, nitrogen tensions and loads were calculated with a 40 min/3.1 bar (absolute) profile. Compared with Haldanian models, the new model showed a substantial delay in N\textsubscript{2} uptake and (especially) release. One hour after surfacing, an increase of 14–28% in BF resulted in a whole body increase of the N\textsubscript{2} load of 51%, but in only 15% in the blood compartment. This would result in an increase in the bubble grade of only 0.01 Kisman-Masurel (KM) units at the scale near KM = 1−. This outcome was tested indirectly by a dry dive simulation (air breathing) with 53 male divers with a small range in age and V\textsubscript{O\textsubscript{2max}}.

To suppress multicollinearity. BF was determined with the four-skinfold method. Precordial Doppler bubble grades determined at 40, 80, 120, and 160 min after surfacing were used to calculate the Kisman Integrated Severity Score and were also transformed to the logarithm of logB. The highest of the four scores yielded the number of bubbles/cm\textsuperscript{2} (logB). The highest of the four scores yielded the number of bubbles/cm\textsuperscript{2} (logB). The highest of the four scores yielded the number of bubbles/cm\textsuperscript{2} (logB). The highest of the four scores yielded the number of bubbles/cm\textsuperscript{2} (logB).

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BF and VGE (3). However, in another recent VGE study (the same dive as used in Ref. 3), the relations between the three demographic variables have been considered (7). It was indicated that the bubble grade (BG) of VGE is very significantly correlated to age and VO2max. Although BF also showed a significant correlation with BG, it was not concluded that BF controls BG (7). However, in those studies, no correction was made for (potential) confounding effects. The same applies to a study with very low hyperbarism [≤0.8 bar (g)] and very long exposures (3–48 h, P1/3 = 220 msw/min0.5, dry simulation), investigating the effect of BMI on VGE (6).

In a recent study (20 msw/40 min, total ascent time 9 min, P1/3 = 132 msw/min0.5, open sea), the problem of multicolinearity was reduced by calculating partial correlations (36). It was shown that BF is (probably) not causally related to BG, whereas age and VO2max are; however, there was a considerable range in both age and VO2max. Another limitation was the pooling of data of two (slightly) different profiles, as well as data of a first and identical second dive; therefore, that study does not allow one to draw firm conclusions (36). To avoid the limitations in the setup of that study, now the range in age and VO2max was considerably diminished. Also, apart from the effect of the amount of BF, the influence of the thickness of the subiliac fold was studied. The thickness of this fold is considered to be a measure of abdominal fat (37), which makes a large contribution to BF in men and may comprise the majority of BF. Also, abdominal fat is of interest since its metabolism is different from that of other types of fat (e.g., Ref. 28).

Over the last century, the physiology of decompression phenomena has been described by two classes of models: deterministic ones and probabilistic ones (39). Here, we restrict ourselves to the deterministic ones. Among these models, the oldest ones, the most often applied models are those with the tissues presented as independent compartments (no mutual interactions). Each compartment has its own half time of inert gas uptake and release (the Haldanian model), and, in addition, each has its own maximum (M)-value. With the latter extension, introduced by Workman (43) as a protocol to develop dive tables, the Haldanian model was evolved to the (deterministic) neo-Haldanian model. Other types of deterministic models are those with a number of compartments arranged in series, such as the Defense and Civil Institute of Environmental Medicine (DCIEM) model (31). In Ref. 39, a review can be found on the characteristics of deterministic models and the probabilistic models. In the latter models, which can also be used for table construction, the yes-or-no occurrence of DCS with a given dive profile is probabilistically calculated. In both classes of models, various types have been described (16, 39), and most models are also applicable to gas-mixture diving.

Since our only and exclusive aim is to calculate the N2 tensions in compartments, the deterministic approach was chosen since it relies on a sufficient number of compartments. These compartments are thought to represent, in some nondefinable way, the body with its tissues. By assigning the compartments, albeit somewhat arbitrarily, to tissues, the compartments can also be assigned a volume. With these assignments, estimates can be made of N2 tensions and N2 loads after decompression. With compressed air as breathing gas, the only inert gas of relevance is nitrogen. Since the inert nature of O2 is probably not present due to its small partial pressure (at most 0.65 bar, Ref. 33), we did not consider O2 as an inert gas to calculate compartment inert-gas tensions. Hence, the calculations were restricted to N2.

In the present study, the half times of the neo-Haldanian Bühlmann model, being the basis of decompression tables and many dive computer algorithms (19), are used to calculate N2 tensions.

In the Haldanian decompression theory (e.g., Refs. 5, 19, 39), the blood, as a separate theoretical compartment preceding the parallel compartments (the theoretical tissues of the body), is ignored (at least quantitatively). The rationale for this is its assumed very short (quasi) half time compared with compartments with a half time of ~5–640 min (5, 39). As an exception, the shortest half time of only 2.5 min attributed to a parallel blood compartment has been used by manufacturers of dive computers. In addition, it was implicitly assumed that the N2 throughput of the pulmonary-circulatory system is not a limiting factor for uploading and unloading the compartments.

One of the compartments presents fatty tissue, which volume has a large intersubject variation. The question as to whether or not fat divers produce more intravascular bubbles can possibly be solved when the blood is involved as a compartment preceding the parallel compartments of the Haldane model. Using such series-parallel models, the aim is to make a quantitative prediction about the (possibly) higher positive N2 tensions in the blood of a fat subject compared with a lean subject. These higher tensions are assumed to produce higher VGE grades. With experimental VGE data (obtained with different percentages of BF), the theoretical prediction can be tested indirectly. Details and performance of some series-parallel models are described in the first part of MATERIALS AND METHODS section.

MATERIAL AND METHODS

Theory and Models

Classical compartment paradigm: model 1. In decompression theory, loading and unloading of the compartments with a square dive can be described by a convex and concave exponential curve, respectively. The underlying physical model is a linear time-invariant system of the first order with an integrating behavior and is described by a first-order linear differential equation. In fluid dynamics, its analog is a system with a resistance to which the flow is subjected and a compliance of the wall of the tube through which the current flows. The electrical analog is a network with a resistance (R) and a capacity (C). For purposes of clarity, we describe the various models from the point of view of electrical analogs and for brevity’s sake described in Laplace notation. The input signals (ambient N2 pressure of the dive profile) and output signals (N2 tensions of the compartments) have the dimensions of electric potential.

A square dive with an infinite fast descent and ascent can be described as a positive step, [i.e., the increment of inspired partial pressure of N2 (PN2)], followed after bottom time with a negative step of the same size (decrease of inspired PN2 to surface level). The response of the system (i.e., the change of the PN2 in the compartment) is the superposition of the two sequential step responses. The unit step response is \( S(t) = \frac{1}{1 + \tau s} \), where \( \tau = RC \) is the time constant; \( \tau \) is the Laplace transformation; \( \tau = RC \) is the time constant \( T_{half}/n2 \), where \( T_{half} \) is the half time of the compartment; \( s = jo \), the imaginary angular frequency; and \( h(t) \) is the unit-impulse response. A step is introduced by a negative step of smaller size followed by a small step of, e.g., -3 msw. In fact, the descent and ascent speeds are finite (here: 15 msw/min). The response to a slope (in the dive profile) is the integral of the step response \( S(t) = \frac{1}{1 + \tau s} \), where \( \tau = \frac{1}{1 + \tau s} \). With this elementary approach, the response of any
compartment with known half time can be calculated for any multi-level dive by using the superposition principle for the input and output signal. In practice, it is often more convenient to perform the calculation piecewise (descent, isopression phase, etc.). Then, with any change of depth, the calculated tension before the change is used as the initial value of the new calculation.

This theory is used to calculate the tension of 8 of the 16 compartments of Bühlmanns ZH-L16 decompression table (5), with half times of 5–635 min. In addition to half times, compartment volumes are also needed to calculate N2 loads (see below). With 16 compartments, attributing a realistic set of 16 volumes is not possible. Therefore, 16 compartments are not a refinement leading to more reliable results. In this and subsequent models, the small effect of the bubbles on the hemodynamics affecting perfusion is ignored. (Total bubble volume is very small compared with blood volume.) A refinement would be to take into account the effects of the oxygen window; this window is dependent on O2 consumption per compartment, which, however, is not known. Apart from being infeasible, any refinement will barely affect differences between the lean and fat subject.

Table 1 presents the half times and the (more or less) arbitrarily chosen volumes and tissue types attributed to the compartments numbered 1 to 8 (based on Refs. 2, 5, and 27) of a hypothetical lean man. For a hypothetical fat man, compartment 6 is 23.4 liters (28% fat), and his whole body is 83 liters. All other values are the same for the lean and fat subjects.

Since model 1 lacks the blood compartment, it is unable to answer the question whether or not obese divers would have a higher BG than lean divers.

A series-parallel model with independent behavior of compartments: model 2. In this model, a blood compartment (including the airways) precedes the parallel compartments. From a xenon diffusion study of the airways–alveoli blood system with xenon in the inspired airways (39), the (quasi-)half time of this system was estimated. Using numerical values of the nine individual R2 blood and R2 compartments; fat/lean, ratio of fat to lean.

Table 1. Half-times and volumes of compartments and N2 loads and N2 load ratios of the fat and lean subject 1 h after surfacing

<table>
<thead>
<tr>
<th>No.</th>
<th>Compartment</th>
<th>Thalf, min</th>
<th>Volume, liter</th>
<th>Lean, ml</th>
<th>Fat/Lean</th>
<th>Lean, ml</th>
<th>Fat/Lean</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blood</td>
<td>0.5</td>
<td>5</td>
<td>2.3</td>
<td>1.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Neural tissue, heart</td>
<td>5</td>
<td>2</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.13</td>
</tr>
<tr>
<td>3</td>
<td>Lung</td>
<td>12.5</td>
<td>1</td>
<td>0.2</td>
<td>1.0</td>
<td>1.1</td>
<td>1.03</td>
</tr>
<tr>
<td>4</td>
<td>Liver</td>
<td>27</td>
<td>3</td>
<td>5.0</td>
<td>1.0</td>
<td>8.6</td>
<td>0.97</td>
</tr>
<tr>
<td>5</td>
<td>Muscle active</td>
<td>54.3</td>
<td>24</td>
<td>89.0</td>
<td>1.0</td>
<td>89.5</td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>Muscle inactive, intestines, skin</td>
<td>109</td>
<td>13</td>
<td>41.6</td>
<td>1.0</td>
<td>39.3</td>
<td>0.96</td>
</tr>
<tr>
<td>7</td>
<td>Fat</td>
<td>187</td>
<td>9.7</td>
<td>24.0</td>
<td>2.4</td>
<td>105</td>
<td>2.31</td>
</tr>
<tr>
<td>8</td>
<td>Bone, tendons</td>
<td>305</td>
<td>4</td>
<td>7.9</td>
<td>1.0</td>
<td>6.0</td>
<td>0.96</td>
</tr>
<tr>
<td>9</td>
<td>Bone</td>
<td>635</td>
<td>8</td>
<td>12.5</td>
<td>1.0</td>
<td>6.3</td>
<td>0.96</td>
</tr>
<tr>
<td>10</td>
<td>Sum blood and // compartments</td>
<td>69.7</td>
<td>180</td>
<td>1.18</td>
<td>258</td>
<td>1.51</td>
<td></td>
</tr>
</tbody>
</table>
can be solved with analytic mathematics, but only with a computer-aided analytic equation solver. With pilot calculations using Mathematica (Wolfram Research, Champaign, IL), we found 3,228 coefficients in the description of the denominator of $R_{H2}$. After fracture decomposition to solve the equation and backward transformation to the time domain, the unit-step response $S(t)$ of the blood compartment was found; this comprised nine exponentials:

$$S_{N2blood}(t) = 1 - \sum_{j=1}^{9} a_j e^{-r_j t} \text{ with } 9 \text{ terms}$$

The constants $a_j$ and $r_j$ are real polynomials of the underlying nine $R$ values and nine $C$ values.

In physiological physics, several models are available to calculate time constants of the compartments. Some rely on perfusion and others on a mixed perfusion-diffusion approach (e.g., Refs. 39, 42). Unfortunately, in those studies, the equations of the time constants could not be transformed to time constants comprising the product of a $R$ and $C$ with known numerical values.

To calculate $N_2$ loads of the compartments, their volumes are needed. Because time constants are material constants, $H(s)$ does not take compartment volumes into account. Volumes can be accounted for by introducing $k$ (an integer) parallel compartments of each original compartment with $k$ proportional to the compartment volume (see Fig. 1) (for the fat compartment $5 \times k_{fat}$). This complication plus the fact that the values of $R$ and $C$ are unknown was the rationale to abandon the analytic approach of model 3. Therefore, we decided on a simple heuristic, numeric approach, which was sufficient for our purposes, but still based on the principle of model 3.

Model 3 approximated by a recurrent numerical procedure: model 4. To estimate the delayed on- and off-gassing of the blood compartment due to the release (ascent and isopression phase) into and re-uptake (ascent and time after surfacing) from the eight parallel compartments, a numerical approximation of model 3 was constructed. It was based on the difference between the $N_2$, loads at time $t$ and time $t+1$ in the parallel compartment. Each minute, the decrease or increase of blood tension, $PN_2$ blood, was calculated from the release or re-uptake by the blood compartment given by the above difference. The change of $PN_2$ blood was found by applying Henry’s law (from volume to tension) for the summed change of loads of the parallel compartments.

The procedure was as follows. At time $t = 1$ min after the start of the descent, from $PN_2$, calculated with model 2 the dissolved gas mass [in liter with a pressure of 1 bar ($1_{bar}$)] in each of the parallel compartments was calculated according to Henry’s law (volume/volume notation):

$$V_{N2,1bar} = \alpha \cdot PN_2 \cdot V_{i,1bar}$$

where $V_{N2,1bar}$ is the dissolved volume of nitrogen, reduced to 1 bar and 37°C, and $\alpha$ is the Bunsen solubility coefficient (liter gas/liter liquid). Blood has a solubility coefficient of 0.0127 $l_{N2,1bar}$ at 37.3°C (15, 41). On the basis of Ref. 41, we assumed that watery tissue has more or less the same $\alpha$ as blood. Nitrogen is 5.15 times more soluble in olive oil than in blood. Although adipose tissue is for ~95% fatty substance, the convention is followed that absorption of the whole fatty tissue is five times that of blood.

Resuming the calculations, $PN_2$, at $t = 2$ was calculated from its previous value with blood pressure in model 4 ($PN_2^{4}$ blood) at $t = 1$ as its temporary asymptote (driving force). Then, with the new loads at $t = 2$ in the parallel compartments, the increase in load from $t = 1$ to $t = 2$ was summed for all eight compartments, and Henry’s law was applied from volume to tension, yielding change in pressure ($\Delta P$). Next, $PN_2^{4}$ blood at $t = 2$ was calculated from $PN_2$ blood at $t = 1$, and $\Delta P$ was subtracted since the blood compartment supplied the load increase of the parallel compartments. Then the cycle started again with the calculation of $PN_2$, at $t = 3$. The cycles were repeated for all 1-min samples of the profile, as well as those after surfacing.

**Experimental Methods**

Subjects and experimental study design. The study was approved by the Ethic Committee of the Medical Faculty of the University of Amsterdam, and by the Surgeon General and Superintendent of Diving of the Netherlands Royal Navy. All subjects signed an informed consent and were informed about the tests by means of a scenario. The experiments conformed to the standards of the Declaration of Helsinki (2011) and to Dutch law on medical scientific research on humans (World Health Organization, 1998, 2012).

A total of 53 male divers (21 divers of the Netherlands Royal Navy, 3 commercial divers, and 29 recreational divers) volunteered to participate in the study. Fitness to dive and experience were established by a medical examination according to the Navy protocol (similar to the NATO protocol) and a questionnaire. The examination took place several weeks (range 1–12 wk) before the experimental session. The recreational divers were preselected based on answers to a questionnaire about dive experience (number of years diving and total number of open-water dives), age, height, and body weight (BMI), and the numbers of hours per week spent on endurance sport to estimate $V_{O2}$ max (based on a model with age, BMI, and hours of endurance sport; Ref. 28). Women and smokers were excluded from the study. After selection, these recreational divers were included for the medical examination. All subjects who passed the medical examination were not allowed to dive 48 h before the dive simulation (to avoid the repetition effect), should not perform endurance sport (which might diminish VGE (11)), and should not use any stimulating drugs for (at least) 1 day before the examination. To obtain standardized measurements, the subjects fasted the night before (from 10 Pm). After awakening, at least 2 h before the experimental session, they consumed one glass of water or tea, and 1 h before the session one glass of water or tea and a few prepared slices of bread, in accordance with their corrected ideal body weight (28).

The divers performed a simulated dry 40-min just-decompression dive on air to 21 msw with compression and decompression paces of 15 msw/min and with a 5-min stop at 3 msw, in accordance with the DCIEM tables ($J/Pr^{0.5, dr} = 132 msw/min^{0.5}$). The dive was performed in the dry compartment of the dive simulator (Medusa, Hauk, Germany) of the Royal Navy. During bottom time, the subjects performed 10 blocks of 3.5 min of light to moderate exercise while seated. These
exercises comprised scheduled repeated movements of head, hands, arms, trunk, legs, and feet, made according to the instructions of a dive supervisor, who was also in the hyperbaric chamber. The exercises were performed to mimic swimming and moderately light physical labor.

During the isopression phase, at rest, the subjects (wearing t-shirt and shorts) would be close to thermal equilibrium, since the chamber temperature was 24.7–26.4°C (depending on the season) and was stable in the isopression phase (within ~0.1°C).

**Measurements**

**VGE measurements.** The extent of VGE was measured four times, i.e., at 40, 80, 120, and 160 min (as averages) after surfacing time. 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 Doppler technician [T. van Rees Vellinga, certified by Defence R&D Canada (DRDC), Toronto].

One Doppler session (lasting almost 5 min) consisted of four measurements. The first was made with the subject standing at rest, and the remaining three immediately after a deep knee bend (flex). The Doppler sounds were digitally recorded on a personal computer. The recordings were scored blindly by a Doppler expert of DRDC (Toronto, Canada), with BG expressed in Kisman-Masurel (KM) units (30). The highest score after the knee bends was used for further analysis.

Age, BF, BMI, and VO₂max. During the medical examination, VO₂max was calculated by a maximal test with ergometry and gas analysis. The load of the ergometer (Excalibur Sport, Lode, Groningen, the Netherlands) was stepwise increased. (During the first minute the body weight in kg as wattage, and every subsequent minute an increase of 25% of the weight.) For inclusion, VO₂max was restricted to the range 35–52 ml·kg⁻¹·min⁻¹, resulting in a maximum/minimum factor of 1.5. Without restriction of VO₂max and age, this factor of recreational divers is 3–4 (8, 36).

Age was expressed in years (accuracy in days). All subjects were aged 40–50 yr; on average, this is higher than the average age of professional and recreational divers. The rationale to select this age range was that older divers have a higher level of bubble stress (e.g., Ref. 7).

To determine BMI (kg/m²), the subjects wore only underwear and had bare feet. Weight (kg) and height (m) were measured with an accuracy to 1 and 3 decimal places, respectively.

After the first Doppler measurement, BF (in %; recorded with an accuracy to 1 decimal place) was determined with the four-skinfolds method (12). This simple and long-established method has also been used in studies of the DCS-BF relation (10, 26) and appeared to be sufficiently precise for our study (21, 23, 32). There were no limitations for BF.

**Analysis of Measurements**

To allow parametric statistics, the ordinal KM scores were transformed to a numerical scale: the number of bubbles per centimeter squared (according to Table 10.3.8 of Ref. 30), as used in earlier studies (13, 18, 34, 36). However, the direct use of bubble counts can be inappropriate, since they show considerable deviation between subjects, which results in domination of high counts in the statistical analysis (the outlier problem). Therefore, we used the logarithm of the bubble count (logB) (34, 36). (The rationale for applying logB is discussed in Ref. 35.) For KM = 0 logB = -3 is adopted (e.g., Ref. 34).

For analysis, the four logB values of the KM scores (the largest of the four) and the logarithm of the Kisman Integrated Severity Score (KISS, a measure of multiple KM scores over time) were used (20, 30).

**Statistical Analysis**

As numeric dependent variables, logB and logKISS were used in parametric statistics. The main methods were calculation of the Pearson binary correlation coefficient R and the Pearson partial correlation rxy, ab, . . . . where a, b, . . . are the correcting (or controlling) variables (24). P values <0.05, tested double-sided (Student's t-test), were considered statistically significant. Correlations were calculated with SPSS version 16.0.

**RESULTS**

**Model 1 and Model 2**

The loads of model 1 and model 2 are almost identical. In model 2, the action of the blood compartment on the tensions of the parallel compartments can be described by a latency. This is because T_{half\ blood} \ll T_{half\ i}. The latency can be approximated by d = \pi T_{half\ blood}/2ln2 [from \frac{d\varepsilon(0)}{d\omega} \rightarrow 0, where \varepsilon(\omega) is the phase characteristic of H_{blood}(j\omega)]. For T_{half\ blood} = 0.5 min, d is 68 s, the time shift between the curves of model 1 and model 2, illustrated with compartment 1 in Fig. 2. The latency is also the reason why the tensions of fast compartments in Fig. 2 do not decrease immediately after the start of decompression.

One hour after surfacing, the N₂ load of the fat compartment (lean subject; model 2) is 83% of the amount at the start of decompression, whereas for model 4 this is 90%. However, the load with model 4 is 27% less than that of model 2, due to the delayed transport.

**Model 3**

In model 3, uploading and unloading of the blood compartment is delayed compared with model 2, as indicated by Eq. 3. This is due to the second term (j = 2) and (to a smaller extent) to the third term. Explorative calculations showed that the coefficients of the remaining terms are too small to produce any effect. The uploading and unloading of the parallel compartments are also delayed, since PN₂, is the convolution of SN₂, blood(t) (by approximation the first 3 terms of Eq. 3) with h_i(t), the impulse response of compartment i.

![Fig. 2. Nitrogen tensions of the blood and 8 parallel compartments of model 2. Top curve: profile, followed by tension of blood compartment. The dashed curve is the model 1 curve for compartment 1. Below the dashed curve are the curves of the 8 parallel compartments (top one is compartment 1, etc.). msw, Meters of seawater.](http://jap.physiology.org/Downloaded from at Universiteit van Amsterdam on March 12, 2013)
caused by the blood compartment. The delay appeared to be mainly compartment that lasts for many hours (Fig. 3). This emphasis the decease is much smaller or even nil.

The basic values of the demographic characteristics are given in Table 2. The distribution of age, \( V_{O2\text{max}} \), BF, and the subiliac fold was (multivariate) normal. BF values were 5 units lower than the Caucasian age-matched mean, and \( V_{O2\text{max}} \) was supranormal (10 units) after taking age into account (22, 27). Age showed no significant partial correlation with \( V_{O2\text{max}} \) or with BF, whereas \( V_{O2\text{max}} \) and BF were correlated (\( r = -0.41 \), \( P = 0.02 \)). No case of DCS was observed or reported by the divers.

VGE Scores, Log Bubble Counts, and BF

The logB values calculated from the VGE scores at 40, 80, 120, and 180 min are 1.26 ± 0.17, 1.20 ± 0.16, 0.87 ± 0.12, and 0.73 ± 0.10 (means ± SE), respectively. The latter two are significantly lower than the former two (all \( P \) values < 0.0009, paired Student’s \( t \)-test). Table 2 gives the primary statistics of the highest of the scores obtained at 40, 80, 120, and 180 min. Figure 5 presents scatter plots of the four KM scores vs. BF. At 120 and 160 min after surfacing, scores higher than KM = 1 were rare. No significant correlations (\( R \) and \( r \)) between BF and the log bubble counts of KM1 to KM4 were found (very large \( P \) values). The most relevant data are the largest of the four logB values (shown in Table 2 with the demographics). Its partial correlation (control variables age and \( V_{O2\text{max}} \)) with BF was not significant (\( P = 0.50 \)). Also with logKISS, no significant partial correlation coefficient was found (\( P = 0.51 \)). Similar results were found for the thickness of the subiliac fold.

For VGE, it is not the \( N_2 \) load of the body or of the fat compartment but the release into the blood that is the relevant parameter, since that increases the blood \( N_2 \) tension, being the driving force for bubble growth. One hour after surfacing, the fat-to-lean ratio of \( P_{N_2\text{blood}} \) was 1.15, and in the interval from surfing until 80 min after surfing the fat subject has (on average) a 9% higher \( P_{N_2\text{blood}} \).

Demography of the Subjects

The basic values of the demographic characteristics are given in Table 2. The distribution of age, \( V_{O2\text{max}} \), BF, and the subiliac fold was (multivariate) normal. BF values were 5 units lower than the Caucasian age-matched mean, and \( V_{O2\text{max}} \) was supranormal (10 units) after taking age into account (22, 27). Age showed no significant partial correlation with \( V_{O2\text{max}} \) or with BF, whereas \( V_{O2\text{max}} \) and BF were correlated (\( r = -0.41 \), \( P = 0.02 \)). No case of DCS was observed or reported by the divers.

Model 4

Figure 4 shows the eight compartment tensions and \( P_{N_2\text{blood}} \) of the lean and fat subject. Table 1 gives the \( N_2 \) loads of all compartments of the lean subject at the end of the isopressure phase. The fat-to-lean ratio of the loads is increased compared with model 1.

From \( t = 0 \) to the time of decompression (infinite descent pace), \( P_{N_2\text{blood}}(t) \) is by approximation:

\[
P_{N_2\text{blood}}(t) = 1.60 \left[ 1 - (0.47 \times 2^{-0.72 t} + 0.53 \times 2^{-0.27 t}) \right] \text{bar (rel surface)}
\]

with standard error of estimate of 0.0017. The first term has a time constant that is \( \sim 50\% \) higher than the half time of the blood compartment. Both terms contribute almost equally, thus accounting for the large delay in the on-gassing of the blood compartment that lasts for many hours (Fig. 3). This emphasizes the considerable influence of the restricted flow through the blood compartment. The delay appeared to be mainly caused by compartments 4–6, which have the highest load (Fig. 4). These compartments (assuming that they comprise muscle and fatty tissue) release 5–100 times more than the other compartments.

With a 5-min stop at 3 msw, the effect of off-gassing is considerable for the blood. This is supposed to result in a strong reduction of VGE bubble stress, but for other compartments the decease is much smaller or even nil.

After surfacing, the relative contribution of fat increases slowly, as can also be concluded from Fig. 4. From 86 min after surfacing, the fat compartment has the highest load of all compartments. For the fat subject, at 60 min after surfacing, the fat compartment comprises 62% of the total body load (for the lean subject 41%), whereas, at the start of decompression, this is 40% (for the lean subject 22%). One hour after surfacing, an increase of 14–28% in BF resulted in a whole body increase of the \( N_2 \) load of 51%, but in only 15% in the blood compartment.

Figure 4 shows that the \( N_2 \) loads of the lean and fat subject are very similar (thick solid curve and dashed thick curve, respectively); the difference is negligible (left lower dotted and thin solid curve, respectively).
DISCUSSION

General Observations

Calculation of the N₂ tension of the blood compartment from its half time and from the changing N₂ loads of the parallel compartments is the basis and the theoretical newness of this study. The model uses the half times of the ZH-L16 decompression table. Small and mostly even moderate changes of volumes and half times (up to 25%, also for the blood compartment) of the linear series-parallel model produced similar outcomes. Hence, half times and compartment volumes are far from critical. The same holds for $T_{\text{half blood}}$; doubling gives only some slower transport and slightly smaller fat-to-lean ratios. The delayed gas release appears to be an intrinsic property of decompression physiology, as described in various earlier studies (e.g., Refs. 16, 18). Delayed dissolved gas transport has been described for a three-compartment parallel model with mutual asymmetric interactions (16), a model that is inappropriate to calculate blood tensions compared with our models.

The experimental novelty of our approach is the restricted age and $V_{O2\text{max}}$max, which practically eliminated the collinearity between BF and the demographic parameters of age and $V_{O2\text{max}}$. BF appeared not to influence VGE.

Theoretical Study

With an increase from 14 to 28% BF, the 9% increase of $P_{N2\text{ blood}}$ (from 0 to 60 min after surfacing) will increase the bubble volume by 9%, assuming proportionality between the blood N₂ tension and bubble volume. This will result in (at most) a 9% increase in detectable bubbles. Ignoring that the KM scale is ordinal, this difference yields ~0.01 KM units. In fact, measurement shows that the mean logB (highest of the four) is ~1.78 (no. of bubbles/cm² = 0.017), which is equivalent to a BG slightly less than I—. Taking into account that, in a group of divers, the KM grades range 3 or 4 units, the difference of 0.01 KM unit is negligible.

Increasing the length of the isopressure phase will increase the fat-to-lean ratio of $P_{N2\text{ blood}}$ after surfacing. In the extreme case, for a hypothetical saturation dive (with an N₂ enriched mixture), this ratio becomes 1.4 (0- to 60-min interval after surfacing). This would finally result in a BG of the fat diver of about an additional 1/8 KM units. To make this difference in logB significant, a study including about 500 saturation divers is needed. This theoretical example suggests that, for many types of exposures, BF is irrelevant on the basis of the model. From Fig. 3, it can be seen that all compartments have a delayed washout. Although remaining tensions are low, this may give rise to a longer period of gas uptake by existing bubbles. Especially for the fast compartments, e.g., the neural tissue, this is a disadvantage.

Washout is always, to some extent, delayed by, e.g., pulmonary physiology and bubble formation (e.g., Ref. 5). Proportional lengthening of all nine half times after surfacing is a time transformation that does not change the conclusions. Selective lengthening does change the ratios of and differences between lean and fat. Therefore, in the model, we introduced a lengthening of 20% of the half times of compartments 1–5 and that of the blood compartment. Besides the minor effect on the tensions, visible in a tension-time diagram, the change in loads is minuscule, such that, in Fig. 4, these changes are practically invisible. This again demonstrates the robustness of model 4.

Experimental Study

It was found that, 40–80 min after surfacing, VGE is maximal, as also found theoretically. Between 80 and 120 min, VGE decreased sharply. In addition to the lack of an effect of total BF, also abdominal fat does not affect VGE. That neither age nor $V_{O2\text{max}}$ showed a significant correlation with BGs is attributed to their small range, which is three to four times the range of logB or logKISS.

Fig. 5. The four Kisman-Masurel (KM) scores, KM1 (diamonds, left), KM2 (squares, left), KM3 (triangles, right), and KM4 (circles, right), measured at 40, 80, 120, and 160 min after surfacing, respectively, vs. body fat. For all scores with KM = 0, a random number between ~0.4 and 0.4 was added to distinguish them from neighboring data points. Spearman correlation coefficients of body fat and KM scores were not significant.

Table 2. Demography and values of logB and logKISS

<table>
<thead>
<tr>
<th>KM score</th>
<th>Age, yr</th>
<th>$V_{O2\text{max}}$, ml·kg⁻¹·min⁻¹</th>
<th>Body Fat, %</th>
<th>Subiliac Fold, mm</th>
<th>logB</th>
<th>logKISS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>45.9</td>
<td>42.5</td>
<td>21.0</td>
<td>12.9</td>
<td>−1.78</td>
<td>−0.71</td>
</tr>
<tr>
<td>Median</td>
<td>46.0</td>
<td>41.7</td>
<td>21.3</td>
<td>12.0</td>
<td>−1.31</td>
<td>−0.58</td>
</tr>
<tr>
<td>Range</td>
<td>40.0–50.9</td>
<td>34.4–52.8</td>
<td>13.4–28.9</td>
<td>5.0–37</td>
<td>−3 to +1</td>
<td>−2.00 to +1.82</td>
</tr>
<tr>
<td>SD</td>
<td>3.31</td>
<td>5.68</td>
<td>3.77</td>
<td>6.5</td>
<td>1.29</td>
<td>1.37</td>
</tr>
</tbody>
</table>

$V_{O2\text{max}}$, maximal oxygen consumption; logB, log of the no. bubbles/cm²; KISS, Kisman Integrated Severity Score.
smaller than in similar studies (e.g., Ref. 8). Although \( V_{O2\text{max}} \)
and fat were negatively correlated, the confounding effect of
\( V_{O2\text{max}} \) is practically eliminated, and the outcome of the partial
correlation between BF and logKISS can be considered as not
contaminated. A multivariable linear regression (with BF and
\( V_{O2\text{max}} \) as independent variables) and logKISS yielded nonsignif-
icant coefficients and a variance inflation factor of 1.8, indicating practically no collinearity.

**Professional vs. Recreational Divers**

The present study included both types of divers to obtain a
sufficiently large sample. Although the recreational divers had
1.3% more fat and were 1.2 yr younger, the differences were
not significant. Their \( V_{O2\text{max}} \) is 2.7 points lower, tending to
significance. However, all correlations of the subgroups
showed nonsignificant outcomes, similar as for the whole
group. The recreational divers made 570 ± 473 (mean ± SD)
dives over a period of 13 ± 6.9 yr. We conclude that, for
the aim of the present study, the professional and recreational
divers can be considered as a homogenous group.

**Choice of Times of BG Measurement**

Since unloading of the fat compartment takes several hours,
we were interested in BGs over a period of ~3 h. Peaking of
BG is possibly later the longer the dive (due to the increasing
importance of slow tissue). Peaking slightly before 40 min has
only been found for a short, deep dive (ca. 38 min, Ref. 3).
Therefore 40, 80, 120, and 160 min after surfacing were chosen
as measurement times. VGE is highest during the first 1.5 h
after surfacing, as found in other studies. This means that the
influence of BF on bubble growth after this time period is
further diminished.

**Effect of Exercise**

During the isopression phase, since the subjects were exer-
cising (almost without interruption), almost 100% of the vol-
untary muscles were active, and not about 80% as suggested in
Table 1. It is estimated that \( O_2 \) consumption during the iso-
pression phase was ~25 ml·min\(^{-1}\)·kg\(^{-1}\). This implies that
most of the circulation is directed to the voluntary muscles,
with a circulation time of ~30 s (5, 27). Therefore, the \( T_{\text{half}} \)
of compartment 4 (active muscles) mentioned in
Table 1 is supposed to be much shorter, possibly by a factor of
about 2 (not exercising is ~12 ml·min\(^{-1}\)·kg\(^{-1}\), Ref. 27). A
similar change applies (in part) for compartment 5. Compart-
ment 4 will start decompression closer to saturation. As a
result, the majority (in a lean subject) or almost the majority (in
a fat subject) of total body \( N_2 \) load resides in the muscles.
During and after the decompression phase, the majority of
the muscle compartment is close to rest, resulting in the half time
of compartment 5. Therefore, in Fig. 3, curve 4 should be
shifted a factor 2 upward, and, after the start of the ascent, it
should coincide with curve 5 and obtain the slope of the latter.
Consequently, the muscle \( N_2 \) load dominates the fat \( N_2 \) load.
The final result is that the relative difference of the 9% of
\( P_{N_2} \)\(^{\text{blood}} \) of the lean and fat subject shows a strong decrease,
resulting in a nil difference in VGE.

**Conclusions**

The new series-parallel model, linear and intrinsic symmetric,
suggests that the rate of nitrogen release (or that of another inert
gas) from the parallel compartments takes longer compared with
the classical Haldanian model. The theoretical analysis indicates
that the original large difference in \( N_2 \) load of the fat compartment
between the lean and fat diver is reduced to a very small differ-
ence in \( N_2 \) tension of the blood compartment and will finally be
reduced to a negligible difference in VGE BG. Moreover, the
profile hardly influences the relative tension difference. This
suggests that the classical explanation of the influence of BF on
VGE and DCS probably does not appear to be valid. The model
outcome is in line with the analysis of our experimental data
showing that BF does not affect VGE BG.

The analyses of the data sets of two other studies produced
the same results: the study by Schellart et al. (36) with an open water
just-decompression dive, and (in this latter study) a reanalysis of
the data from the study of Carturan et al. (8) obtained with a
close-to-heavy decompression dive. However, although these pro-
files have severities (estimated by the \( P^{O.5} \) model, see Introduc-
tion) that cover a great part of recreational and Navy dives on air,
they do not cover the whole theoretical profile space. For instance,
extreme decompression dives and saturation dives may behave
differently, despite the model predictions.

The above-mentioned studies (8, 36) and those of others (see
Introduction) show that age and \( V_{O2\text{max}} \) are relevant predispos-
factors. They also showed that, for air dives with low and
moderate severity, BF is a strongly correlated covariable. To
reassess the role of BF, more studies with different profiles
under various conditions are needed. Then it will become clear
whether BF can still be used as a basic physical characteristic
(together with the predisposing factors age and \( V_{O2\text{max}} \)), or
whether BF will become less important for the medical exam-
ination and for DCS risk assessment.

However, also when future studies confirm our results, BF
will remain (to some extent) an indicator for VGE stress and
DCS risk. Diving medicine institutions can then decide
whether they will set up a double or triple criterion, based on
a combination of age, \( V_{O2\text{max}} \), and BF, to pass the examination
for recreational and professional divers.

We have no arguments to exclude women from the conclusions.

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**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).
AUTHOR CONTRIBUTIONS

Author contributions: N.A.S., T.P.v.R.V., and R.A.v.H. conception and design of research; N.A.S. and T.P.v.R.V. performed experiments; N.A.S. analyzed data; N.A.S. interpreted results of experiments; N.A.S. prepared figures; N.A.S. drafted manuscript; N.A.S., T.P.v.R.V., and R.A.v.H. edited and revised manuscript; N.A.S., T.P.v.R.V., and R.A.v.H. approved final version of manuscript.

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