Estimating the effect of lung collapse and pulmonary shunt on gas exchange during breath-hold diving: The Scholander and Kooyman legacy

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ABSTRACT

We developed a mathematical model to investigate the effect of lung compression and collapse (pulmonary shunt) on the uptake and removal of O₂, CO₂ and N₂ in blood and tissue of breath-hold diving mammals. We investigated the consequences of pressure (diving depth) and respiratory volume on pulmonary shunt and gas exchange as pressure compressed the alveoli. The model showed good agreement with previous studies of measured arterial O₂ tensions (PaO₂) from freely diving Weddell seals and measured arterial and venous N₂ tensions from captive elephant seals compressed in a hyperbaric chamber. Pulmonary compression resulted in a rapid spike in PaO₂ and arterial CO₂ tension, followed by cyclical variation with a periodicity determined by Q tot. The model showed that changes in diving lung volume are an efficient behavioural means to adjust the extent of gas exchange with depth. Differing models of lung compression and collapse depth caused major differences in blood and tissue N₂ estimates. Our integrated modelling approach contradicted predictions from simple models, and emphasised the complex nature of physiological interactions between circulation, lung compression and gas exchange. Overall, our work suggests the need for caution in interpretation of previous model results based on assumed collapse depths and all-or-nothing lung collapse models.

1. Introduction

Scholander suggested that the flexible rib cage, the rigid dead space (bronchi and trachea), the bag shaped diaphragm and the venous network on the pericardium of breath-hold diving marine mammals were anatomical adaptations that would allow the air from the alveoli to empty into the dead space during a dive (Scholander, 1940). The depth, or pressure, where the alveoli completely collapsed would be determined by the relative volumes of the dead space and alveoli. Assuming that the dead space does not compress until the alveoli are collapsed, this depth can be predicted using Boyle’s law as follows:

\[ P_{ambc} = (DVL \cdot V_D^{-1}) \cdot P_{amb}^{-1} \]

where \( P_{ambc} \) is the collapse pressure, \( DVL \) the initial diving lung volume, \( V_D \) the volume of the dead space and \( P_{amb} \) the ambient pressure at the surface.

However, Eq. (1) is based on the assumption that the dead space does not collapse while experimentally it has been shown to compress at depths <50 m (Ridgway, 1968; Kooyman and Hammond, 1970). A recent study modelled the simultaneous compression of dead space and alveoli predicting that Eq. (1) underestimates the depth at which the lungs collapse and a model that accounted for concurrent collapse of both the upper and lower respiratory system showed that the depth of complete alveolar collapse is dependent on \( DVL \), and in most cases does not occur until a depth well below 100 m (Bostrom et al., 2008).

Scholander proposed that with an increasing pressure, as the alveoli compressed, the gas diffusion rate would initially increase, reach a maximum and then decrease to zero upon alveolar collapse (Scholander, 1940). The increased diffusion rate early in the dive results from an increasing alveolar-venous partial pressure gradient as the ambient pressure increases. However, alveolar compression will reduce the surface area available for gas exchange and thicken the alveolar membrane, both causing a decrease in the diffusion rate. A proxy for measurement of diffusion rate, the pulmonary shunt, has been measured in harbour seals and California sea lions subjected to pressures up to 10 ATA in a hyperbaric chamber (90 m, Kooyman and Sinnett, 1982). Pulmonary shunt represents the amount of blood bypassing the lung.
and not participating in gas exchange. The shunt varies between 0% and 100%, where 0% represents a fully inflated lung with perfect gas exchange and 100% represents termination of gas exchange. Results indicated that pulmonary shunt increased with pressure but varied with DVL. At 90 m a 70% shunt was observed and it was predicted that complete collapse would not occur until a depth >150 m (Kooymann and Sinnett, 1982) which is significantly deeper than the 30 and 70 m that were predicted for lung collapse from measuring N₂ uptake and removal in the Weddell seal (Falke et al., 1985) and bottlenose dolphin, respectively (Ridgway and Howard, 1979; Bostrom et al. (2008) suggested that varying collapse depths found in different studies could be explained by assumptions used in predicting the effect of pressure on gas exchange. When N₂ uptake and removal (Ridgway and Howard, 1979; Falke et al., 1985) were used to indirectly estimate collapse depth, it was assumed that the rate of diffusion increased linearly with pressure until collapse, at which time gas exchange immediately ceased. This assumption was also used by other models attempting to estimate blood and tissue PN₂ levels in breath-holding diving mammals and birds (Falke et al., 2006, 2007; Zimmer and Tyack, 2007). The estimated blood and tissue PN₂ were used to determine if birds and mammals are ever at risk of decompression sickness (DCS), but with a better understanding of how lung compression and pulmonary shunt are manifested, this could be much improved.

In order to better understand how inert and metabolic gases are exchanged during breath-hold diving we therefore examine the potential error in estimated blood and tissue gas tensions caused by the previous assumption of a linearly increasing diffusion rate compared with a model incorporating a more realistic pressure dependent increase in pulmonary shunt. Since pulmonary shunt is affected by pressure and lung volume, predictions will vary for species according to mass specific lung volumes and metabolic rates. We formulate a new physiological model in which diffusion rate (shunt) is affected by the compression of the respiratory system during diving. In addition to consideration of N₂ exchange (Fahlman et al., 2006, 2007) this model also incorporates exchange of O₂ and CO₂. This allows us to assess how changes in lung gas during diving, as well as those affected by pulmonary compression, may affect gas exchange.

2. Material and methods

2.1. Model

The model described in this paper combines the breath-hold diving model developed by Fahlman et al. (2006) with the lung compression model developed by Bostrom et al. (2008). Exchange, production and consumption of O₂ and CO₂ were incorporated in addition to accounting for exchange of N₂.

The body was partitioned into 5 compartments or stores; blood (B), brain (B), fat (F), muscle (M) and central circulation (CC). The central circulatory compartment included heart, kidney, liver and alimentary tract while the muscle compartment included muscle, skin, bone, connective tissue and all other tissues. This partitioning differs from our earlier work and leaves the fat compartment containing only adipose tissue (Fahlman et al., 2006).

The model was parameterised and tested for elephant and Weddell seals and so was based on published values available for these species when possible, and failing this, on published values for other phocid species (as detailed below).

2.2. Lung gas stores

Gas exchange occurred between lung and blood and between blood and each compartment (Fig. 1 in Fahlman et al., 2006). The O₂, CO₂ and N₂ stores in the lung consisted only of a gas phase and were assumed to be homogenous. We assumed that there was no diffusion resistance at the lung surface interface when an animal was breathing at the surface (Farhi, 1967). Thus, arterial blood tension of N₂ (PA N₂), O₂ (PA O₂) and CO₂ (PA CO₂) were assumed to be equal to the alveolar partial pressures. All pressures were corrected for water vapour pressure, assuming that the respiratory system was fully saturated at 37 °C. For an animal breathing at the surface, we assumed that alveolar partial pressures of N₂ (PA N₂), O₂ (PA O₂) and CO₂ (PA CO₂) were, respectively, 0.74 ATA, 0.143 ATA (108.9 mmHg, Stephenson, 2005a) and 0.055 ATA (41.9 mmHg Stephenson, 2005a), with 0.062 ATA being water vapour. We assumed that all CO₂ that exchanged for O₂ remained in gas phase.

The fraction of N₂ (FN₂), O₂ (FO₂) and CO₂ (FCO₂) in the lung was computed at each time step after gas had been taken up or transferred to the arterial blood as:

\[ F_x = n_x \cdot (n_N₂ + n_O₂ + n_CO₂)^{-1} \]  

where \( F_x \) is the fraction of gas x and \( n_x \) the number of moles of gas x (N₂, O₂ and CO₂, respectively). Alveolar partial pressures were computed as the product between the ambient pressure (Pamb) and \( F_x \). Lung volume (Vl) was adjusted with removal or addition of gas to the lung according to the ideal gas law.

2.3. Blood gas stores

The blood was divided up into small packages that held N₂, O₂ and CO₂. The content of N₂ (CV N₂), CO₂ (CV CO₂) and O₂ (CV O₂) in each package (1 O₂ at 37 °C 1⁻¹ blood) was determined by:

\[ CV_{N₂} = P_{N₂} \cdot \alpha_{N₂} \]  

(2A)

for N₂ and by:

\[ CV_{CO₂} = [(1 - S) \cdot A_0 \cdot P_{Hb}^{\alpha} + S \cdot A_1 \cdot P_{Hb}^{\alpha_1}] \]  

(2B)

for CO₂ and by:

\[ CV_{O₂} = S \cdot C_{Hb} \cdot \beta_{Hb} + P_{O₂} \cdot \alpha_{O₂} \]  

(2C)

for O₂. In these equations, \( \alpha_{N₂} \) and \( \alpha_{O₂} \) are the Ostwald solubility coefficients for N₂ and O₂, respectively (1 g at 37 °C 1⁻¹ fluid ATA-1, Weathersby and Homer, 1980). \( A_0 \) and \( B_0 \) are parameters relating \( P_{O₂} \) to CV CO₂ for deoxygenated blood, and \( A_1 \) and \( B_1 \) for oxygenated blood. \( C_{Hb} \) is the concentration of haemoglobin and \( \beta_{Hb} \) the haemoglobin O₂ binding capacity. \( S \) is the O₂ saturation (%) given by:

\[ S = P^{\alpha_{Hb}} \cdot (P^{\alpha_{O₂}} + P^{\alpha_{Hb}})^{-1} \]  

(3A)

where \( \alpha_{Hb} \) is the Hill coefficient and \( P^{\alpha_{Hb}} \) the PO₂ at 50% saturation. The parameters in Eqs. (2B), (2C) and (3A) were determined from the properties reported for the bladdernose seal (currently called hooded seal, Clausen and Ersland, 1969) and are given in Table 1. \( P_{O₂} \) was directly proportional to \( P_{50} \) for seal blood and therefore we estimated the Bohr effect as:

\[ P_{50} = 0.02326 + 0.1465 \cdot P_{CO₂} \]  

(3B)

2.4. Tissue gas stores

Tissue CV N₂ was determined by Eq. (2A). The N₂ solubility in the fat and brain compartment were given a tissue-blood partition coefficient of 5 while for all other tissues it was assumed that N₂ solubility was identical to that of blood (Weathersby and Homer, 1980).
1980). Dissolved tissue CVCO₂ and CVO₂ were estimated by equations similar to Eq. (2A), using gas tensions for CO₂ and O₂, and Ostwald coefficients. The Ostwald solubility coefficients for CO₂ for the central circulation and muscle were 0.63 l CO₂·l⁻¹·atm⁻¹, for the fat compartment 1.36 l CO₂·l⁻¹·atm⁻¹, and for brain 0.56 l CO₂·l⁻¹·atm⁻¹ (Weathersby and Homer, 1980). The O₂ solubility for the central circulation and muscle was 0.26 l O₂·l⁻¹·atm⁻¹ and for the fat and brain compartment a value of 0.133 l O₂·l⁻¹·atm⁻¹ was used (Weathersby and Homer, 1980).

We assumed that only the muscle contained myoglobin bound O₂. The O₂ content of the muscle was estimated using Eq. (2C) with parameters for nMb and P50Mb specific for myoglobin for a deep diving animal (Table 1, Tamburrini et al., 1999). It was assumed that the P50Mb is not affected by changes in P̄CO₂ (Gayeski et al., 1987).

### 2.5. Gas exchange

#### 2.5.1. Tissue and lung

The blood packages were transferred around the circulatory system at a rate determined by cardiac output (Q̇tot, l min⁻¹). Each tissue received a portion of the blood in each package representing its fraction of total blood flow. To account for the specific metabolic rate of each tissue, a given volume of O₂ was removed from the blood while CO₂ was added to the tissue. Next, the tissue was allowed to exchange gas with the blood and it was assumed that the exchange between blood and tissue was complete once the blood left the capillary. In other words, the partial pressure of each gas was equal in blood and tissue as the blood left the capillary. At the surface, a similar equality was assumed at the lung-blood interface. That is, pulmonary end-capillary blood tension for each gas was assumed equal to the alveolar partial pressure. During diving, on the other hand, a pulmonary shunt developed as a consequence of the compression of the respiratory system (see below).

#### 2.6. Lung compression and pulmonary shunt

The model recently published by Bostrom et al. (2008) was used to estimate alveolar volume (DVₐ) at depth. Total lung capacity (TLC) included the volume of the dead space (trachea and bronchi, VD), and the maximum alveolar volume (Va), i.e. TLC = VD + Va. It was assumed that gas exchange only occurred in the alveoli and when DVₐ = 0, gas exchange stopped. For the elephant seal, TLC was assumed to be 50 ml kg⁻¹ and for the Weddell seal 40 ml kg⁻¹ (Kooyman et al., 1972; Kooyman and Simnett, 1982). Dead space volume was 10% of TLC (Stephenson, 2005a). Diving lung volumes were taken from previous studies (Kooyman et al., 1972; Kooyman and Simnett, 1982) and were 20.4 ml kg⁻¹ for the elephant seal (Kooyman et al., 1972), 22.0 ml kg⁻¹ for the Weddell seal (Kooyman et al., 1972; Kooyman and Simnett, 1982). As DVₐ was lower than TLC, i.e. pre-dive exhalation or partial inhalation, the reduced gas volume was subtracted from the alveolar gas space. That is, DVₐ before a dive (DVₐ₀) was DVₐ₀ = DVₐ − VD. Thus, for a 100 kg elephant seal VD = 0.51 l, DVₐ = 2.04 l, DVₐ₀ = 1.54 l.

To determine the relationship between pulmonary shunt and compression collapse a prediction equation was created from previously published pulmonary shunt data and the estimated ratio DVₐ/Va = 1⁻¹. The multivariate linear regression published for harbour seals diving in a hyperbaric chamber, relating pulmonary shunt to ambient pressure (Pamb) and DVₐ (shunt = 34.8 + 5.1 Pamb − 0.431), was used to obtain estimates of the shunt at a number of different pressures (3–11 ATA) and DVₐ's (100–20% of TLC). The corresponding DVₐ's were used to estimate DVₐ/Va = 1⁻¹ at pressures in the same range. Finally, the relationship between shunt and DVₐ/Va = 1⁻¹ was determined using a power function (Bostrom et al., 2008) for data from both harbour seals and California sea lions.

\[
\text{Shunt} = 1 - \left( a \cdot \left( \frac{DV_{a}}{Va} \right)^{b} \right)
\]

#### 2.7. Compartment size, cardiac output and blood flow distribution

In the absence of direct anatomical or physiological data for the elephant seal, data reported for the Weddell seal were used (Davis and Kanatous, 1999). We assume no differences between the elephant seal and the Weddell seal except for Mb. The relative size of each compartment was 46.9% for the muscle compartment (with 35% as muscle mass), 4.53% for central circulation, 0.13% for brain, 21.33% for blood and 27.11% for fat (Table 2). The muscle compartment included muscle and all other tissues that were not included in central circulation, fat and brain, e.g. skin, bone, connective tissue. As myoglobin is only present in the muscle, the percent of Mb used to calculate the O₂ store was 35%, i.e. muscle only (Table 2).

In this model, Q̇tot at the surface was assumed to be in the midrange (8.0 ml kg⁻¹ s⁻¹, range 3–12 ml kg⁻¹ s⁻¹) of those measured for harbour seals (Mb range 28–39 kg) swimming at different work loads (Ponganis et al., 1990). To account for differences in Mb, mass specific Q̇tot(sQ̇tot) was adjusted using the equation presented by Davis and Kanatous (1999) for allometrically adjusting VD₂. Thus, sQ̇tot was estimated by:

\[
s\text{Q}_{\text{tot}} = 8 \times (M_b^{0.25} \times 34^{0.25})
\]

where 8 and 34 are, respectively, the Q̇tot and Mb of the harbour seals (Ponganis et al., 1990). We assumed that the reduction in Q̇tot associated with submergence was between 1/2 and 1/3 of the surface value, quantitatively similar to the reduction in heart rate measured in freely diving elephant seals (Andrews et al., 1997). Blood flow distribution to each tissue at the surface was assumed similar to that measured in Weddell seals resting at the surface (Zapol et
al., 1979), where 31% of $\dot{Q}_{\text{tot}}$ was directed to the central circulation, 67% to the muscle (psosas, diaphragm, intercostal, testis, pituitary, thyroid, pancreas, adrenals, rib/bone, skin, spleen, retina, tongue, vagina, uterus, ovary), 1.3% to the brain and 0.7% to the fat (Zapol et al., 1989). During diving, on the other hand, the blood flow distribution was iteratively tested to maximize utilization of $O_2$ to increase the aerobic dive duration.

2.8. Model variations

Two hypothetical dives were created for a 100 kg elephant seal. The dives were chosen to resemble the average dive on and off the continental shelf for an elephant seal (Andrews et al., 1997) and consisted of a single dive to 70 m for 10 min or a 17 min dive to 305 m. Each dive had a constant and symmetrical descent and consisted of a single dive to 70 m for 10 min or a 17 min dive to 305 m. Maximum and end dive $P_{\text{PAO}_2}$ were considered.

2.9. The effect of changes in $DV_V$ on $N_2$ uptake during a single dive

To investigate how pre-dive exhalation, or partial inhalation, affected gas exchange during diving Model A was repeated as detailed above for dives to 70 and 305 m with $DV_V$ varied between 0% and 100%, while pre-dive $V_D$ was kept constant at 0.5 l.

2.10. Comparing the model output with measured data

The model was used to estimate blood and tissue $P_{O_2}$, $P_{CO_2}$, and $P_{N_2}$ and we compared estimated values to data from previous studies that either directly measured blood and tissue $P_{O_2}$, $P_{N_2}$, and $P_{CO_2}$ (Kooyman et al., 1972; Kooyman et al., 1973; Qvist et al., 1986), or from respirometry data (Kooyman et al., 1973; Ponganis et al., 1993).

2.10.1. Weddell seal $P_{AO_2}$ measurements

We compared our model estimates for $P_{AO_2}$ for a 450 kg adult Weddell seal, with observed data on $P_{AO_2}$ collected for several dives (Table 4 in Ponganis et al., 1993). As the metabolic rate changed with dive duration we adjusted the mass specific rate of $O_2$ consumption ($s\dot{V}_{O_2}$) accordingly. At the surface and for dives $<10$ min $s\dot{V}_{O_2}$ was 5.0 ml $O_2$ kg$^{-1}$ min$^{-1}$, for a dive $>10$ min and $<20$ min $s\dot{V}_{O_2}$ was 2.5 ml $O_2$ kg$^{-1}$ min$^{-1}$ and for dives $>20$ min $s\dot{V}_{O_2}$ was set at 1.7 ml $O_2$ kg$^{-1}$ min$^{-1}$. There was one dive that was exceptionally long (dive # 9, 57 min) but this was not used in this analysis as the observed respirometry data was not reliable. The myoglobin concentration was measured to be 4.2 g $\times$ 100 g muscle$^{-1}$ for this seal (Ponganis et al., 1993). We assumed $P_{AO_2}$ = 42.7 min$^{-1}$ at the surface with a 50% reduction during diving. The blood flow distribution while diving was 60% to central circulation, 35% to the muscle, 3% to the brain and 2% to the fat compartment. Due to a lack of information we assumed all dives had a constant descent and ascent rate of 1.5 m s$^{-1}$ (Andrews et al., 1997). Dives $\leq 2$ min were assumed to be to 20 m, dives $<10$ min to 40 m and all other dives to 160 m (Burns, 1999).

2.10.2. Elephant seal $P_{N_2}$ measurements

Estimates of $P_{N_2}$ and venous $P_{N_2}$ were compared with observed values during forced dives in elephant seals (Kooyman et al., 1972). We limited the model calibration of $N_2$ levels to this one study and species as we were able to obtain heart rates ($f_h$, Kooyman pers. comm.), $DV_V$ and time specific values for blood $P_{N_2}$ for this species (Kooyman et al., 1972). Mixed venous $P_{N_2}$ s ($P_{N_2}$) and $P_{N_2}$ s reported for forced diving (4–28 ATA) were compared with the output from Model A for an animal weighing 104 kg. As the animal was not active during these forced dives, we used a conservative estimate for $P_{N_2}$ at 0.01 g ml$^{-1}$ at the surface. The average heart rate was ~115 beats min$^{-1}$ at the surface and 15 beats min$^{-1}$ during a dive to 4 ATA, 11 beats min$^{-1}$ for a dive to 7.8 ATA and 22 beats min$^{-1}$ for a dive to 14.6 ATA (Kooyman pers. comm). From these data, we assumed that $P_{N_2}$ during diving was 12.5% of the surface value. Blood flow distributions used during diving were CC: 45%, M: 40%, B: 14%, F: 1%. To test the effect of ashen exhalation on gas exchange, the model was run for the deep dive with a shunt of 80% during the ascent as well as while the animal was still submerged at the surface (1 ATA).

3. Results

3.1. Pulmonary shunt and gas exchange

The relationship between estimated shunt and $DV_A \cdot V_A^{-1}$ available for the harbour seal (Kooyman and Simen, 1982) was fitted with a power function ($P<0.001$, $r^2=0.96$, Fig. 1) resulting in the following equation

$$\text{Shunt}_{\text{HS}} = 1 - 1.495 \cdot (DV_A \cdot V_A^{-1})^{0.320} \tag{6A}$$
Fig. 1. Estimated fractional alveolar volume (DVA/VA - 1) against observed pulmonary shunt (1-shunt) in harbour seals (black filled circles) and California sea lions (red filled circles). The data was fitted with a power function (Eq. (4)) and the resulting best fit is shown as a solid line.

This equation results in a 100% shunt when the alveoli collapse. As no information exists on gas exchange at very low lung volumes, collapse was assumed to occur when DVA/VA - 1 ≤ 0.001. The maximum shunt before collapse was therefore 83.6%. For DVA/VA > 28.5% VA the shunt was negative and therefore set to 0. The estimated data for the California sea lion fell on or slightly below the best fit line for harbour seals (Fig. 1). The best fit power function was (P<0.05, \( r^2 = 0.46 \), Fig. 1)

\[
\text{Shunt}_{\text{CSL}} = 1 - 1.072 \cdot (\text{DVA} \cdot \text{VA}^{-1})^{0.210}
\]  

(6B)

3.2. The effect of changes in DVL on N\(_2\) uptake during a single dive

Fig. 2 shows the effect of a constant V\(_D\) (0.5l) and a variable DVL (50 ml kg\(^{-1}\), 40 ml kg\(^{-1}\), 30 ml kg\(^{-1}\), 20 ml kg\(^{-1}\) and 10 ml kg\(^{-1}\)) on P\(_{\text{AN}}\) and P\(_{\text{VN}}\) for a 100 kg elephant seal during a dive to 70 m (Fig. 2A and B) and 305 m (Fig. 2C and D). It was assumed that the animal experienced a 50% reduction in blood flow (due to vasoconstriction) during the dive and the blood flow distributions were the same as in Model A. For a dive to 70 m, maximum P\(_{\text{AN}}\) decreased by 56% and P\(_{\text{VN}}\) decreased 63% as the ratio between V\(_D\) and DVAo (DVAo/VA - 1) decreased from 9 to 1
For a $\Delta V_{A0} \cdot V_D^{-1}$ ratio of 1, the alveoli collapsed 145 s into the dive (Fig. 2A). $P_{N2}$ before alveolar collapse was 1.63 ATA and dropped immediately to 1.11 ATA, the corresponding $P_{V2}$ 37 s earlier, i.e. 108 s into the dive. During a dive to 305 m, alveolar collapse occurred for all $\Delta V_{A0} \cdot V_D^{-1}$ ratios (Fig. 2C and D). Only for a $\Delta V_{A0} \cdot V_D^{-1}$ ratio of 9 were the alveoli open during the entire descent, but they collapsed soon after the bottom had been reached as removal of $N_2$ from the lung decreased the lung volume. Maximum $P_{N2}$ decreased by 69% as $\Delta V_{A0} \cdot V_D^{-1}$ decreased from 9 to 1 (Fig. 2C). Collapse depth increased exponentially as $\Delta V_{A0} \cdot V_D^{-1}$ increased ($r^2 = 0.99, P < 0.01$) according to

$$\text{End dive } P_{N2} = 3.26 \cdot (1 - e^{(-0.312 \cdot \Delta V_{A0} \cdot V_D^{-1})}) \quad (8A)$$

showing that the end dive $P_{N2}$ decreased relatively more for a given decrease in the $\Delta V_{A0} \cdot V_D^{-1}$ ratio. For the dive to 305 m, on the other hand, $P_{N2}$ increased exponentially as $\Delta V_{A0} \cdot V_D^{-1}$ increased

$$\text{End dive } P_{N2} = 0.362 + 0.3315 \cdot [\Delta V_{A0} \cdot V_D^{-1}] \quad (8B)$$

It can therefore be seen that there is no simple relationship between these variables and pressure.

3.3. Estimated metabolic gas tensions

$P_{O2}$ increased rapidly during the descent phase, causing a spike in $P_{O2}$ with a maximum at 6 m (0.066 ATA) followed by a rapid decline to 0.058 ATA, a value 5% higher than the pre-dive $P_{O2}$ (Fig. 3A). $P_{CO2}$ increased immediately upon submergence as the blood flow distribution changed, and a sharp peak appeared during descent with a maximum of 0.067 ATA occurring at 5.5 ATA (45 m), 0.45 min into the dive (Fig. 3B). Following the descent peak, both $P_{CO2}$ and $P_{VCO2}$ cycled with a period equal to the blood transit time during diving (66 s, 22 s arterial and 44 s venous) although each cycle was out of phase by 22 s. Both $P_{CO2}$ and $P_{VCO2}$ showed an overall increase throughout the dive with $P_{CO2}$ reaching 0.077 ATA (58.5 mmHg) immediately before decompression and $P_{VCO2}$ reaching 0.084 ATA upon return to the surface (Fig. 3).

$Lung$ compression during descent increased $P_{O2}$ to a maximum of 0.226 ATA (172 mmHg) at 3 ATA, an increase of 59% from $P_{O2}$ at the start of the dive was 20.4 ml kg$^{-1}$ with a dead space volume of 0.5 l.
ATA to 0.098 ATA as the blood flow distribution changed upon immersion (Fig. 3B). This was followed by an increase that lagged behind the arterial peak and that reached 0.124 ATA. As the animal approached the surface, PaO₂ decreased more rapidly and at 20 m the rate of decline had doubled compared to that at 70 m. This more rapid decline was caused by the expanding respiratory system and, together with changes in the blood flow distribution upon surfacing, resulted in a large drop in PvO₂ soon after surfacing.

The pulmonary shunt increased during the descent, reaching 54% at the maximum depth, 8 ATA. The shunt continued to increase asymptotically throughout the dive as gas was absorbed by the body. Lung collapse, i.e. 100% pulmonary shunt, finally occurred 7.6 min into the dive.

3.4. Comparing the model output with measured data

3.4.1. Weddell seal PAO₂ measurements

Fig. 4 shows observed and estimated end dive PAO₂ from a 450 kg adult Weddell seal. Open circles show data from short dives (<5 min) while the solid circles are from long dives (>5 min). The model underestimated ([predicted – observed]/observed × 100) observed values by –1% (range: 73% to –47%). When separated into short and long dives, the error was –9% (range 17% to –39%) and 5% (range 73% to –47%), respectively. Estimated end dive PAO₂ for the 57 min dive was 10 mmHg. PaO₂ for the longest dive is not shown as the observed data was not reliable.

When the model was run without a reduction in \( \dot{Q}_{\text{tot}} \) during diving, the PAO₂ for long dives were overestimated by 11% and the short dives underestimated by –6%. With \( \dot{Q}_{\text{tot}} \) at 25% of the surface value during diving, the predicted values for the long and short dives were –10% and 28%, respectively. With a diving \( \dot{Q}_{\text{tot}} \) that was...
50% of the surface value, an increase in $\text{DV}_{1}$ (50 ml kg$^{-1}$) resulted in an overestimation of $\text{PaO}_2$ by 11% with a range from 81% to 51%. With a $\text{DV}_{1}$ of 10 ml kg$^{-1}$, the error decreased to 2% with a range from 74% to 45%.

### 3.4.2. Elephant seal $\text{PN}_2$ measurements

We initially used a blood flow distribution during diving of that was similar to those measured in forced-dive Weddell seals (CC: 34%; M: 51%; Br: 14.5%; F: 0.5%, Kooyman et al., 1972). However, this depleted $\text{O}_2$ before the end of the dive for the central circulation and the fat. We therefore adjusted the blood flow distribution so that more $\text{O}_2$ was going to the central circulation (45%) and fat (1%) while less was directed to the muscle (40%) and the brain (14%).

Measured $\text{PaN}_2$, during dives to depths between 30 and 136 m (4 ATA to 14.6 ATA) ranged from 1.34 ATA to 2.74 ATA and did not differ significantly with depth (Kooyman et al., 1972). Until 400 s into the dive, there was reasonable agreement between estimated and observed $\text{PaN}_2$ (Fig. 5). After 400 s into the dive, $\text{PaN}_2$ from the model mostly overestimated observed values by 0.5 ATA and 0.9 ATA (Fig. 5). Estimated pulmonary shunt when reaching 4 ATA was 42%, at 7.8 ATA it was 60% and at 14.6 ATA 77%. The pulmonary shunt increased during the time at depth, as $\text{O}_2$ and $\text{N}_2$ were taken up, reaching a maximum of 49% at 4 ATA, 70% at 7.8 ATA and 87% at 14.6 ATA.

In the study by Kooyman et al. (1972) the seals were kept submerged after having returned to the surface so blood samples could be taken while still holding their breath. The average observed ($\pm$1 SD, all $n$ = 5) $\text{PaN}_2$ (1.27 $\pm$ 0.14 ATA) at this time was significantly higher than those before the dive (0.84 $\pm$ 0.11 ATA) and 200 s after the seal had begun breathing (0.83 $\pm$ 0.13 ATA, $P < 0.01$ way ANOVA with Bonferroni correction post-hoc analysis). Average predicted $\text{PaN}_2$ at 1 ATA while still submerged, on the other hand, was 0.78 ATA and 200 s after the end of the submersion it was 0.75 ATA (Fig. 5).

While still submerged at 1 ATA, predicted pulmonary shunt was 9% after the dive to 4 ATA and 14% after the dive to 14.6 ATA. The predicted shunt decreased slightly as $\text{N}_2$ exchanged with the pulmonary capillary and entered the lung, but was still >7% at the end of the submersion (800 s) immediately before the animal could breathe. When the predicted pulmonary shunt was maintained at 80% throughout the ascent after the dive to 14.6 ATA, i.e. caused by exhalation during the dive, estimated $\text{PaN}_2$, upon reaching 1 ATA was 1.02 ATA and increased to 1.48 ATA at the end of the submersion.

Measured $\text{PaN}_2$ from the intravertebral vein, in which cerebral flow is a major component, was similar to or slightly higher (average 0.81 ATA, 0.71 to 0.98 ATA) than estimated $\text{PaN}_2$ and $\text{PvN}_2$ (0.70 ATA) before the dive (Fig. 5B and C). Immediately before decompression, intravertebral $\text{PaN}_2$ had increased to between 1.27 ATA and 1.98 ATA (average 1.72 $\pm$ 0.29 ATA). After 200 s at 1 ATA while still submerged, average intravertebral $\text{PaN}_2$ had decreased to 1.34 $\pm$ 0.26 ATA (range: 1.00–1.66 ATA) and 200 s after the end of the dive it had further decreased to 0.84 $\pm$ 0.14 ATA. The $\text{PvN}_2$ estimates agreed fairly well with observed intravertebral $\text{PvN}_2$ during and after the dive, but all estimates underestimated the maximum values observed before decompression (Fig. 5B). Estimated brain $\text{PaN}_2$, on the other hand, generally overestimated observed values (Fig. 5C).

### 3.5. Comparing end dive $\text{Pn}_2$ estimates with previous models

An analysis that tested the effect of adjusting variables that determined the degree of pulmonary shunt with depth is presented in Table 3. Model A is the base model to which all other models are compared. Model F, which is the same as Model A but does not account for exchange of $\text{O}_2$ and $\text{CO}_2$, can be seen to have relatively little effect on $\text{Pn}_2$ values compared to the other models. For the dive to 70 m, not accounting for exchange of $\text{O}_2$ and $\text{CO}_2$ (Model F) decreased end dive $\text{Pn}_2$ by 0.6–2.8% compared with Model A. For the dive to 305 m, on the other hand, end dive $\text{Pn}_2$ increased by 3.3–7.2% when not accounting for the metabolic gases.

Compression between models with differing lung collapse assumptions showed much greater variability (Table 3). For a dive to 70 m, the lung collapsed after 7.6 min into the dive for Model A leading to end dive $\text{Pn}_2$ approximately twice the surface value (Table 3). For the dive to 305 m, gas exchange ceased at 176 m for Model A and end dive $\text{Pn}_2$ was lower than the shorter and shallower dive to 70 m using the same model (Model A 70 m vs. 305 m). When the pulmonary shunt was assumed to occur instantaneously at 30 m, $\text{PvN}_2$ decreased by 50% for a 70 m and 45% for a 305 m dive compared with Model A (Model A vs. B). The reduction in end dive $\text{Pn}_2$ of the other tissues was between 14% and 72% for the dive to 70 m and between 14% and 68% for the dive to 305 m (Table 3, Model A vs. B). With a collapse depth of 70 m (Model C), or without lung collapse (Model E), end dive $\text{Pn}_2$ was similar to Model A for the 70 m dive. For the 305 m dive, collapse at 70 m increased end dive $\text{Pn}_2$ in the fast tissues (CC and B) while it decreased in F and M (Table 3 Model A vs. C) while for the model with without collapse (Model E), end dive $\text{Pn}_2$ decreased compared with Model A. End dive $\text{Pn}_2$ was greater for a 70 m lung collapse depth (Model C) than it was for a 30 m lung collapse depth (Model B) for both dive depths. However, counter-intuitively, with a lung collapse depth of 160 m (Model D) or without lung collapse (Model E), end dive $\text{Pn}_2$ decreased for CC and mixed venous (Model C vs. D, or Model C vs. E) for the dive to 305 m.

### 4. Discussion

In this paper, we present a model to estimate how gas exchange is altered during breath-hold diving. This is the first comprehensive attempt to quantify how gas exchange is affected by the physical parameters and variables of a marine mammal’s respiratory system. The current model differs from previous models in two significant ways. First, it includes an estimation of the volumes of the respiratory system allowing a more realistic prediction of pulmonary shunt. Secondly, it includes uptake and removal of $\text{O}_2$ and $\text{CO}_2$. Our model provides interesting and, at times, counter-intuitive predictions that emphasize the importance of this type of modelling approach to understand the complex physiological events that underlie how diving mammals manage metabolic and inert gases.

Despite the fact that Scholander proposed that the alveoli collapse in marine mammals during diving well over half a century ago, few studies have verified this hypothesis, partly because of logistical difficulties in measuring lung volumes or gas exchange during diving. Even though much work has and is being conducted recently (2007) our understanding of how gas exchange is affected during breath-hold diving is rudimentary at best. Since continued gas exchange during diving may significantly affect blood and tissue $\text{O}_2$, $\text{CO}_2$ and $\text{N}_2$ levels and as studies on large mammals are logistically and ethically challenging, mathematical models are useful to help generate hypotheses as to the mechanics of gas exchange during diving.

#### 4.1. Comparison of the model to measured data

Mathematical models are only as good as the data from which they are constructed. Ground-truthing such models against measured data is therefore vital to establish their validity. We compared model output with both $\text{PaO}_2$ and $\text{Pn}_2$ data from two previous studies.
Predicted end dive $P_{A\text{O}_2}$ was similar to the observed data for a 450 kg Weddell seal (Fig. 4), despite assumptions of constant $Q_{\text{tot}}$, blood flow distribution and diving metabolic rate throughout a dive. There were some notable exceptions, however. Predicted end dive $P_{A\text{O}_2}$ was generally around 51 mmHg for short dives. Average predicted $P_{A\text{O}_2}$ underestimated observed values by 9%. The lowest predicted $P_{A\text{O}_2}$ was 30 mmHg and this was the end dive value after the first dive. The first value depends on the previous dive history and this may explain why this value was significantly below the observed $P_{A\text{O}_2}$, of 50 mmHg. For the short dives, the differences could be attributed to an incorrect choice of $Q_{\text{tot}}$ during diving. Observed $P_{A\text{O}_2}$ for 1 min dives ranged between 45 and 70 mmHg while the model predicted $P_{A\text{O}_2}$ mostly around 51 mmHg. It is possible that the seal did not experience a reduction in $Q_{\text{tot}}$ during these short underwater excursions and when $Q_{\text{tot}}$ was kept constant during the dive the difference was reduced. For the long duration dives, predicted values were generally to within 2–3 mmHg (~10–20%) of observed values and the largest error was 9 mmHg. For both long and short dives, the error changed with changes in $Q_{\text{tot}}$ and $D_{\text{VL}}$. Improving our understanding how diving animals adjust blood flow and its distribution during diving as well as the effect of pressure on gas exchange will therefore be important to improve our understanding of gas management during diving.

Model $P_{N_2}$ estimates also agreed well with observed data. Kooyman et al. (1972) reported that measured $P_{N_2}$ and intravertebral venous $P_{N_2}$ in forced diving elephant seals, diving on 40% of TLC, did not differ with depths ranging between 4 ATA and 14.6 ATA. The model estimated $P_{N_2}$ values agreed fairly well up to ~300 s into the dive after which observed $P_{N_2}$ was substantially lower (Fig. 5). When the alveoli collapse, $P_{N_2}$ should equal $P_{V\text{N}_2}$ and therefore reflect overall $N_2$ saturation. Observed intravertebral $P_{N_2}$ was similar or higher than $P_{N_2}$ before the end of the dive (Kooyman et al., 1972). Such an observation can be explained if the pulmonary shunt was ~100% at the end of the dive or if most of the $N_2$ in the lung had been taken up by the blood. If the gas exchange rate was higher than predicted by the model or if the seals exhaled during the dive alveolar collapse would occur early in the dive. This may explain the discrepancy in observed and predicted $P_{N_2}$. Predicted $P_{N_2}$ agreed fairly well with observed intravertebral $P_{N_2}$ (Fig. 5B). However, a significant portion of the intravertebral vein receives blood from the brain and is therefore not a good estimate of mixed venous blood. This may explain why estimated brain $P_{N_2}$ was slightly higher than observed intravertebral $P_{N_2}$ (Fig. 5C). In other words, $P_{N_2}$ in the intravertebral vein is a mixture of mixed venous ($P_{N_2}$) and brain ($P_{N_2}$) blood. Thus, overall the model gives reasonable predictions of blood and tissue $P_{N_2}$ given accurate estimates for pulmonary shunt, $Q_{\text{tot}}$ and blood flow distribution.

### 4.2. Addition of $O_2$ and $CO_2$ to the model

To investigate the effect of metabolic gases could have on model output, exchange of $O_2$ and $CO_2$ was added to the previously published model that only accounted for exchange of $N_2$ (Fahlman et al., 2006). As gas exchange alters the volume of the lung and also the fractional amount of each gas, it was important to evaluate if addition of the metabolic gases would significantly alter estimated $P_{N_2}$ levels. For the shallow dive that was 10 min in duration, addition of the metabolic gases increased end dive $P_{N_2}$ for all tissues while it decreased $P_{N_2}$ during the deeper and longer dive (Table 3, Model A vs. F). In Model F, $P_{A\text{O}_2}$ continually decrease as $N_2$ is taken up as the pressure increases while it is assumed that $O_2$ and $CO_2$ content remain constant. Therefore, less $N_2$ is taken up during a short dive in Model F compared with Model A (Table 3). With addition of metabolic gases (Model A), $O_2$ and $N_2$ is taken up while $CO_2$ is returned to the lung. The resulting changes in alveolar partial pressures are therefore complex and depend on the metabolic rate, the duration of the dive and the dive depth. In the deep and long dive, therefore, accounting for the metabolic gases (Model A) resulted in end dive tissue tensions that were lower than those for Model F. This shows that despite the rather negligible change in estimated end dive $P_{N_2}$ with the addition of $O_2$ and $CO_2$ (Model A vs. F, Table 3), accounting for all pulmonary gases is important to reduce errors. Consequently, previous models that have separately estimated $O_2$ and $CO_2$ (Stephenson, 2005a) or $N_2$ (Fahlman et al., 2006, 2007; Zimmer and Tyack, 2007) will have some extent of error and future studies should assess this.

Estimated data for the metabolic gases during the 10 min dive to 70 m shows how the hydrostatic compression of the respiratory system increases the pulmonary partial pressures during descent (Fig. 3), resulting in a spike in $P_{A\text{O}_2}$ and $P_{A\text{CO}_2}$. Estimated maximum $P_{A\text{O}_2}$ (172 mmHg) was somewhat lower than the value reported in freely diving Weddell seals (232 mmHg, Zapol et al., 1989) and the estimated maximum occurred at 3 ATA (Fig. 3A, 20 m), which is similar to measured $P_{A\text{N}_2}$ (Falke et al., 1985). Adjustment of $D_{\text{VL}}$, and therefore the extent of pulmonary shunt, the exchange capacity of the blood and the pulmonary blood flow influence the magnitude of the maximum and the depth where it occurs. For example, when $D_{\text{VL}}$ was increased to 30 ml kg $^{-1}$, the peak occurred at 3.8 ATA and was 0.276 ATA (299 mmHg). Once the seal reached the bottom, $P_{A\text{O}_2}$ decayed exponentially throughout the dive and reached 0.045 ATA (34.2 mmHg) immediately before surfacing (Fig. 3A). This value is within the range reported for $P_{A\text{O}_2}$ and $P_{A\text{CO}_2}$ in the freely diving Weddell seal diving for <17 min (see Fig. 2 in Zapol et al., 1989; and Fig. 3 in Ponganis et al., 1993). However, the predicted $P_{A\text{O}_2}$ is less than the measured end-tidal $P_{A\text{O}_2}$ of 70 mmHg after an 11.5 min dive in the Weddell seal but close to the $P_{A\text{O}_2}$ of 40 mmHg for dives ranging between 25 and 47 min (Kooyman et al., 1973). Weddell seal dive durations <20 min tend to be deep (200–400 m) while longer dives are often shallow and seldom exceed 130 m (Kooyman et al., 1973). Kooyman et al. (1973) suggested that if alveolar collapse is incomplete during the longer shallower dives but complete during the short deep dives, continued pulmonary gas exchange would reduce $O_2$ in the lung and explain this counter-intuitive result of a PAO2 that was lower following a long dive (25–47 min) compared with a short one (<20 min). The differences in dive depth used for estimating the data in Fig. 4 compared with those observed in freely diving animals explain why estimated $P_{A\text{O}_2}$ is different from the observed $P_{A\text{O}_2}$ after a short dive.

### 4.3. Changes in blood gases during a dive

The cyclical changes in $P_{A\text{CO}_2}$ and $P_{V\text{CO}_2}$ are not immediately intuitive. During lung compression, the $P_{A\text{CO}_2}$ increases resulting in a spike in $P_{A\text{CO}_2}$. As the arterial blood reaches tissues 22 s later (the arterial transit time), it equilibrates with it. As not all the additional $CO_2$ is delivered to the tissue, so $P_{V\text{CO}_2}$ increases and reaches a peak which then returns to the lung. This spike keeps recurring with a period that is equal to the transit time but offset in the venous and arterial blood. With each turn of the circulatory system, the relative size of the peak is reduced as a portion of the $CO_2$ is taken up by the tissues. The height of the initial peak depends on the metabolic rate, the blood flow distribution and $Q_{\text{tot}}$. When the distribution was adjusted so that 40% of $Q_{\text{tot}}$ was directed to central circulation, 5% to the muscle, 4% to the brain and 1% to the fat, these changes were significantly dampened and were hardly noticeable. Thus, these cyclical changes are dependent on the tissue.
volume and blood flow and will change depending on cardiovascular variation. As the blood flow distribution changes as the animal dives, one would expect to see little variation in \( P_{v\text{CO}_2} \) draining from certain tissues while great variation would be observed in others. These changes were also observed for \( O_2 \), but as \( O_2 \) is consumed at the tissues the height of this spike was less extreme and was only observed for a greater change in blood flow distribution. As period of the peak in venous and arterial \( P_{\text{CO}_2} \) (and \( P_{\text{O}_2} \)) is directly related to the transit time and as the arterial and venous values are offset, these cyclical changes could be used to estimate \( Q_{\text{dot}} \). However, these cyclical changes may be damped in marine mammals by large venous anatomical structures such as the hepatic sinus.

The delay in equilibration of blood gases may explain previous estimates of lung collapse. Falcke et al. (1985) sampled arterial blood of freely diving Weddell seals every 30 s during the descent phase of dives. Their results showed that, independent of the maximum dive depth (80–200 m), \( P_{\text{AN}_2} \) continued to increase during descent to a depth of 30 m. This was followed by a continual decline in \( P_{\text{AN}_2} \), as the animal continued the descent (Falcke et al., 1985). It was concluded that this was evidence of alveolar collapse and termination of gas exchange at a depth of 30 m, and the gradual decline in \( P_{\text{AN}_2} \) was caused by tissue absorption of the available \( N_2 \) in the blood. However, this conclusion is incompatible with cardiopulmonary physiology and rather than evidence of complete alveolar collapse, it suggests a pulmonary shunt that increases with depth (Bostrom et al., 2008). If the data were evidence of alveolar collapse one would expect \( P_{\text{AN}_2} \), to immediately approach \( P_{\text{AN}_2} \) by the time the alveoli collapse and gas exchange ceased (as seen in Fig. 2). The circulatory transit time (the time for a volume of blood to go from the lung to tissues and back to the lung) was measured at between 2 and 3 min in Weddell seals during forced chamber dives (Kooyman et al., 1972). Thus, 2 min into the dive when the seal reached 30 m, \( P_{\text{AN}_2} \) would be close to ambient levels, and if alveoli collapsed this would cause a substantial drop in \( P_{\text{AN}_2} \) (similar to the rapid drop in \( P_{\text{AN}_2} \) associated with lung collapse during the dive to 305 m, Fig. 2C). The observed \( P_{\text{AN}_2} \), in the Weddell seal did not show such a dramatic drop. In fact the Weddell seal data was qualitatively similar to our data in Fig. 2A which initially increased to a maximum and then gradually declined.

During the surface interval following a forced dive, Scholander (1940) reported temporal changes in the respiratory exchange ratio (\( RER, V_{\text{CO}_2}/V_{\text{O}_2} \)). The initial \( RER \) was <0.7 followed by a gradual increase to values >1.0 which thereafter asymptotically approached values within the theoretically expected range between 0.7 and 1.0. A similar observation was reported in freely diving seals (Kooyman et al., 1973; Boutillier et al., 2001). Kooyman et al. (1973) proposed that these temporal changes represented a rapid uptake of \( O_2 \) from depleted haemoglobin and myoglobin with a delay in \( CO_2 \) removal as \( CO_2 \) and lactic acid is released from the tissue. The model agrees with this suggestion and shows that \( CO_2 \) removal lags re-saturation of the \( O_2 \) stores by almost 2 min (Fig. 2). Previous studies in freely diving sea lions (Fahlman et al., 2008a,b,c) suggest that an \( O_2 \) debt develops during the first dive in a dive bout and this debt is not repaid until the end of the bout. As the gas exchange rate decreases throughout the surface interval it would be most efficient for a diver to exchange \( O_2 \) only on the steep portion of the \( O_2 \) dissociation curve (Fahlman et al., 2008b). Therefore, diving should resume before the tissues have completely re-saturated with \( O_2 \) (Kramer, 1988), and this would maximize the time spent underwater during a foraging bout (Thompson and Fedak, 2001). This results in a gradual accumulation of \( CO_2 \) with each subsequent dive, eventually forcing a prolonged surface interval or a period of very short and shallow dives. Consequently, the duration of each dive may be determined by \( O_2 \) management while the duration of a bout may be a result of how well \( CO_2 \) is handled.

4.4. Adjustment of lung volume and compression (pulmonary shunt)

Kooyman et al. (1972) showed that in forced diving elephant seals, after decompression, \( P_{\text{AN}_2} \) remained elevated while the seal was still submerged at 1 ATA (Fig. 5A). Our model suggested that the pulmonary shunt would be between 5% and 14% upon reaching 1 ATA, but this level of shunt resulted in predicted \( P_{\text{N}_2} \) that was significantly lower than the observed \( P_{\text{N}_2} \) (Fig. 5A). Kooyman et al. (1972) reported that seals appeared to exhale on occasion, which would increase the shunt while submerged at 1 ATA. To test this, we ran the model by forcing the shunt to be 80% during the decompression phase and while submerged at 1 ATA. Predicted \( P_{\text{AN}_2} \) from this attempt agreed well with the observed data, suggesting that the seal may indeed have exhaled during the dive.

One elephant seal that dove with an unusually large \( DV_{\text{AO}} \) showed an increasing \( P_{\text{AN}_2} \), with dive depth (see Fig. 3 in Kooyman et al., 1972). This is further evidence that the lungs do not collapse at a constant depth but that gas exchange is affected by \( DV_{\text{AO}} \), providing diving marine mammals with a behavioural mechanism to adjust collapse depth. Bostrom et al. (2008) suggested that the collapse depth decreases linearly with a decrease in \( DV_{\text{AO}} \), although their analysis did not account for changes in lung gas during a dive. The model presented here allowed us to quantify the extent to which gas exchange is affected by these volume changes. Our data showed that end dive \( P_{\text{AN}_2} \) decreases with a decreasing \( DV_{\text{AO}} \) to \( V_{\text{O}_2}/V_{\text{N}_2} \) ratio (Eqs. (8A) and (8B)), verifying that pre-dive exhalation, or partial inhalation, is an efficient mechanism for adjusting gas exchange during diving. The current model also shows that pre-dive exhalation affects end dive \( P_{\text{N}_2} \) in a non-linear fashion for shallow dives (Fig. 5). The diffusion rate is affected by several variables that change as the pressure is increased and as air is exchanged across the alveoli. Consequently, gas exchange and the level of pulmonary shunt cannot be investigated separately as they are not independent. In addition, \( DV_{\text{AO}} \) has a significant effect on the level of the shunt and the rate at which it changes with depth.

Empirical evidence for this suggestion was presented by Kooyman and Simnett (1982), where they elegantly showed that following the initial increase in pulmonary shunt during descent (compression), the shunt further increased while the animal was held at pressure (see Fig. 1 in their study). The rate of increase in shunt at the bottom was positively correlated with \( DV_{\text{AO}} \). Assuming that the only difference is \( DV_{\text{AO}} \), diving with a larger \( DV_{\text{AO}} \), reduces the shunt. The larger \( DV_{\text{AO}} \) also results in more \( O_2 \) and \( N_2 \) in the lung, leading to a higher \( P_{\text{AN}_2} \) and \( P_{\text{AO}_2} \) during descent (compression). At the bottom, the lower shunt enhances gas exchange. The higher rate of gas exchange increases absorption of \( O_2 \) and \( N_2 \), resulting in a rapid increase in the shunt. Previously reported data from harbour seal #4 support this (see Fig. 1 in Kooyman and Simnett, 1982). When this animal submerged with a larger \( DV_{\text{V}} \), the pulmonary shunt when reaching the bottom was less and the rate of change in pulmonary shunt was larger.

Our model suggests that adjustment of pulmonary volumes is theoretically plausible and fits data collected from captive studies. Several species of marine mammals (e.g. cetaceans, otariid seals) dive on either full or partial inhalation. An inhalation diver, the Antarctic fur seal, has recently been found to exhale during ascent from dives (Hooker et al., 2005). Expansion of the lungs during ascent decreases pulmonary shunt and therefore increases the rate of arterial \( O_2 \) uptake (see the increasing rate of decline at ~20 m, Fig. 3). This may lead to a \( P_{\text{AO}_2} \) that is lower than \( P_{\text{N}_2} \), resulting in a reversal of \( O_2 \) exchange. This has been suggested as one of the reasons for shallow water blackout that is sometimes observed in breath-hold diving humans after dives that severely deplete tissue and blood \( P_{\text{O}_2} \). Ascent exhalations reported in fur seals have
been suggested to maintain the pulmonary shunt by maintaining or reducing the DVA/VA−1 ratio and therefore the PAO2 in the expanding lung (Hooker et al., 2005). By reducing the amount of O2 that is returned to the lung, PAO2 may be maintained >10 mmHg, and prevent EEG changes (Elsner et al., 1970; Kerem and Elsner, 1973). These results emphasize the importance of understanding how gas exchange is modified during diving and how diving animals manage gases and pulmonary shunt to enhance performance.

4.5. Comparison with previous models

Previous modeling attempts have assumed that gas exchange cease instantaneously at some pre-determined depth (Ridgway and Howard, 1979; Falke et al., 1985; Stephenson, 2005b; Fahlman et al., 2006; Zimmer and Tyack, 2007), with collapse depth ranging between 30 m for the Weddell seal (Falke et al., 1985) to 70 m for the bottlenose dolphin (Ridgway and Howard, 1979). We have previously shown that instantaneous collapse is unlikely to occur (Bostrom et al., 2008) and we proposed that compression of the alveoli leads to a pulmonary shunt that is related to the pressure and DVA similar to the empirical data reported for California sea lion and harbour seal (Kooyman and Sinnett, 1982). In this paper we show that the assumption of instantaneous collapse and the choice of collapse depth significantly alter model output and estimated PN2 levels (Table 3).

For models assuming an all-or-nothing type of lung collapse, end dive PN2 increased by 89% when the collapse depth changed from 30 to 70 m for both dive depths (Model B vs. C Table 3), illustrating the large effect of lung collapse depth on end dive PN2 estimates. For a dive to 70 m without lung collapse, end dive PN2 increased slightly in venous blood and most tissues (Model C vs. D, Table 3). However, counter intuitively, for the dive to 305 m, end dive PN2 decreased for central circulation, brain and mixed venous blood with the deepest collapse depth of 160 m or with no lung collapse at all (Model D and E vs. C Table 3). This appears to contradict predictions from simple models that show inconsistent results (Ridgway and Howard, 1979; Kooyman and Sinnett, 1982; Falke et al., 1985).

While mathematical models only provide a theoretical framework to understand complex physiological problems, we used empirical data to verify our model estimates and our results highlight the value of our integrated modelling approach. In fact, despite continued N2 uptake when the collapse depth is increased from 70 to 160 m, the removal begins much sooner and thus compensates for the additional N2 uptake. Although maximum PN2 is much higher at these deeper collapse depths, depending on the blood flow distribution, the washout can be so fast that it is actually more beneficial (in terms of mitigating the risk of decompression sickness) to have functional gas exchange.

Variation in end dive PN2 is much greater for changes in lung collapse depth than for the addition of O2 and CO2 to the model (Table 3). Accounting for pulmonary shunt therefore appears to be fundamental in the estimation of PN2 levels. Consequently, conclusions from models that attempt to predict blood and tissue gas tensions during breath-hold diving by assuming an all-or-nothing type gas exchange will be heavily influenced by the chosen lung collapse depth and the species studied in terms of its average dive depth.

Estimated PN2 from the current model is consistent with the data and analysis for the bottlenose dolphin that assumed a collapse depth of 70 m (Model A vs. C, Ridgway and Howard, 1979). Our model estimates also confirm the qualitative analysis of Bostrom et al. (2008), in that a pulmonary shunt that increases with depth provides an alternative explanation for the data presented in the bottlenose dolphin (Ridgway and Howard, 1979) and the Weddell seal (Falke et al., 1985). Similarly to the empirical data presented by Kooyman and Sinnett (1982) our model estimates suggest that complete collapse does not occur until depth >150 m, even at low DV02. As the average dive depths for many diving mammals are shallower than this collapse depth and the deep divers (e.g., elephant seals, Weddell seals, beaked whales) spend a considerable portion of their time transiting this region, gas exchange will resume for a significant portion of a dive. Therefore, we need to re-assess the assumption that diving mammals are protected against decompression sickness. Repeated dives may result in tissue and blood PN2 levels that cause symptomatic bubble formation and may force the diver to end a foraging bout to safely remove excessive N2 (Fahlman et al., 2007).

This work is intended as a framework to show how gas exchange can vary during diving. Despite several assumptions in our parameter estimates, this mathematical modeling approach has been useful to bridge the gap between studies proposing quite different lung collapse depths. It has also allowed us to quantify the extent that lung collapse affects tissue and blood gas tensions. Our results emphasize our lack of understanding of how pulmonary compression affects gas exchange and we desperately need more experimental data to describe this.

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