J Appl Physiol 106: 668–677, 2009.
First published November 13, 2008; doi:10.1152/japplphysiol.91104.2008.

HIGHLIGHTED TOPIC | *The Physiology and Pathophysiology of the Hyperbaric and Diving Environments*

Pulmonary gas exchange in diving

R. E. Moon,[1] A. D. Cherry,[1] B. W. Stolp,[1] and E. M. Camporesi[2]

[1]*Department of Anesthesiology, Department of Medicine, and Center for Hyperbaric Medicine and Environmental Physiology, Duke University Medical Center, Durham, North Carolina; and* [2]*Department of Molecular Pharmacology and Physiology, University of South Florida, Tampa, Florida*

Moon RE, Cherry AD, Stolp BW, Camporesi EM. Pulmonary gas exchange in diving. *J Appl Physiol* 106: 668–677, 2009. First published November 13, 2008; doi:10.1152/japplphysiol.91104.2008.—Diving-related pulmonary effects are due mostly to increased gas density, immersion-related increase in pulmonary blood volume, and (usually) a higher inspired P_{O_2}. Higher gas density produces an increase in airways resistance and work of breathing, and a reduced maximum breathing capacity. An additional mechanical load is due to immersion, which can impose a static transrespiratory pressure load as well as a decrease in pulmonary compliance. The combination of resistive and elastic loads is largely responsible for the reduction in ventilation during underwater exercise. Additionally, there is a density-related increase in dead space/tidal volume ratio (V_D/V_T), possibly due to impairment of intrapulmonary gas phase diffusion and distribution of ventilation. The net result of relative hypoventilation and increased V_D/V_T is hypercapnia. The effect of high inspired P_{O_2} and inert gas narcosis on respiratory drive appear to be minimal. Exchange of oxygen by the lung is not impaired, at least up to a gas density of 25 g/l. There are few effects of pressure per se, other than a reduction in the P50 of hemoglobin, probably due to either a conformational change or an effect of inert gas binding.

respiratory dead space; ventilation-perfusion ratio; respiratory mechanics

DESPITE HAVING EVOLVED in and adapted to an atmosphere with gas density close to 1 g/l, the performance of the human lung in the diving environment is remarkable. Adequate ventilation and gas exchange have been achieved at an ambient pressure up to 71 atmospheres absolute (ATA) [701 m of sea water (msw); 2,310 ft of sea water (fsw)] with an ambient P_{O_2} of 0.39 ATA (49), and with a P_{O_2} of 0.2 ATA up to a gas density of 25 g/l (50). Adequate exchange of oxygen and carbon dioxide while diving requires the ability to maintain ventilation in the face of significantly increased resistive and elastic loads. Resistance is increased primarily by the increase in breathing gas density. Elastic load is enhanced primarily by changes in transrespiratory pressure (P_{TR}). Inertial mechanical load is also increased, although this has a minimal effect on the diver. Added challenges include blunted respiratory drive due to elevated partial pressures of inert gas and oxygen, and possibly impaired diffusion within the alveolus (7). While in most dives the breathing gas is hyperoxic, thus precluding hypoxemia, hypercapnia is common. Hyperoxia, particularly in the venous blood, can induce a small reduction in CO_2 solubility, and hence an increase in venous P_{CO_2} via the Haldane effect (27, 122). Arterial P_{CO_2} (Pa_{CO_2}) is not affected by the Haldane effect because of regulation of breathing via the chemoreceptors, although hypercapnia does occur for other reasons as discussed below.

Studies of pulmonary gas exchange under hyperbaric conditions designed to simulate diving have been performed since the 1950s. Measurements have included ventilation, oxygen consumption, carbon dioxide elimination, and both end-tidal and arterial gas tensions (51, 53). Ensuing experiments demonstrated hypercapnia at rest (91), but to a greater extent during exercise (11, 25, 40–42, 52, 74, 89–91, 107, 118). The increase in Pa_{CO_2} is due to two phenomena: *1*) relative hypoventilation (6, 37, 40, 50, 55, 74, 91, 103, 104, 107, 126), and *2*) elevated dead space, as discussed below.

A recently described phenomenon is a change in breathing pattern in endurance underwater swimming [oxygen uptake ($\dot{V}_{O_2}$) of 1.5–2 l/min, depth of 4 ft]. Fifteen minutes after the start of constant exercise an abrupt 20–25% increase in ventilation has been observed (130). When the study was repeated at a depth of 55 ft (2.7 ATA) breathing air (P_{O_2} 0.56 ATA), there was a similar increase, although it occurred more gradually (85). The investigators interpreted these data as consistent with respiratory compensation for metabolic acidosis, and possibly respiratory muscle fatigue. The effects of this on blood gases, pH, pulmonary hemodynamics, and gas exchange are unknown.

Address for reprint requests and other correspondence: R. E. Moon, Dept. of Anesthesiology, Dept. of Medicine, and Center for Hyperbaric Medicine & Environmental Physiology, Duke Univ. Medical Center, Durham, NC 27710 (e-mail: richard.moon@duke.edu).

RESPIRATORY MECHANICS

Traditional measures of respiratory load include resistive, elastic, and inertial components. Diving induces an increase in all three components. The primary effect of diving on resistance is mediated by the proportional increase in breathing gas density with the depth of immersion. This occurs because breathing underwater can only occur if breathing gas is delivered to the diver at a pressure within a few cmH_2O of the ambient pressure at the diver's depth. For turbulent gas flow, which is present throughout most of the conducting airways, flow resistance is proportional to density. During diving the external breathing apparatus adds an additional resistive load. Additionally, there is an increase of the total inertance of the respiratory system due to increased mass of the breathing gas.

Internal resistance. Although gas viscosity is unchanged at increased pressure (at least within the pressure range to which humans have been exposed), gas density is increased in direct proportion to ambient pressure. Breathing gas density has a major effect on airways resistance. This can be readily measured by a reduction in forced expiratory volume in 1 s (FEV_1), peak expiratory flow, and maximum voluntary ventilation (MVV) (50, 65, 99, 114). The increase in airways resistance purely due to turbulent flow can be augmented further by expiratory flow limitation due to airway collapse (126). Peak expiratory flow or MVV at any gas density (ρ) can be approximated by the following formula (125, 128):

$$A = A_0(\rho/\rho_0)^{-k} \quad (1)$$

where A is either MVV or peak expiratory flow at a gas density ρ; A_0 is MVV (or peak expiratory flow) at 1 ATA; ρ_0 is gas density at 1 ATA; ρ is the gas density; and k is a constant with the value 0.4–0.5. A similar equation has been verified for the relationship between airway conductance and gas density (4).

External resistance. In addition to internal respiratory resistance, some amount of external resistance is present in all underwater breathing apparatus. Resistance varies with different apparatus, and resistance levels frequently differ between the inspired and expired breathing circuits. High breathing resistance increases subjective dyspnea scores (91, 117) and raises P_{CO_2} levels in subjects performing various levels of exercise at the surface (102, 132) and at a range of depths (117–119).

Compliance. During water immersion there is a redistribution of 500–800 ml of blood from the legs into the large veins and pulmonary vessels. There is also a negative transthoracic pressure when the diver is in the head-up position (e.g., during head-out immersion), due to the pressure difference between the mouth and the centroid of the lung (see Fig. 1). As a consequence of this pressure difference, there is a reduction in lung volume and its subsets, for example residual volume, vital capacity, and expiratory reserve volume (ERV) (2). This occurs to a greater extent in cold water than in warm, presumably due to active peripheral vasoconstriction and hence greater volume of blood redistributed from the periphery into the pulmonary vessels (46).

Although chest wall compliance does not change significantly, most investigators have reported a concomitant reduction in lung compliance, particularly at low lung volumes, possibly due to the vascular engorgement (16). Others have attributed the compliance change and attendant increase in elastic work solely to the difference in hydrostatic pressure between the lung and the mouth, which is neutralized by supplying breathing gas at a pressure close to lung centroid pressure (105, 106).

ERV during exercise in a dry hyperbaric chamber at depth tends to be increased as subjects breathe at higher lung volumes (37, 98, 117). Similarly, the reduction in ERV during immersion tends to be attenuated at increasing depth as subjects breathe at higher lung volumes, probably in an attempt to increase airway diameter, thus reducing the increase in airways

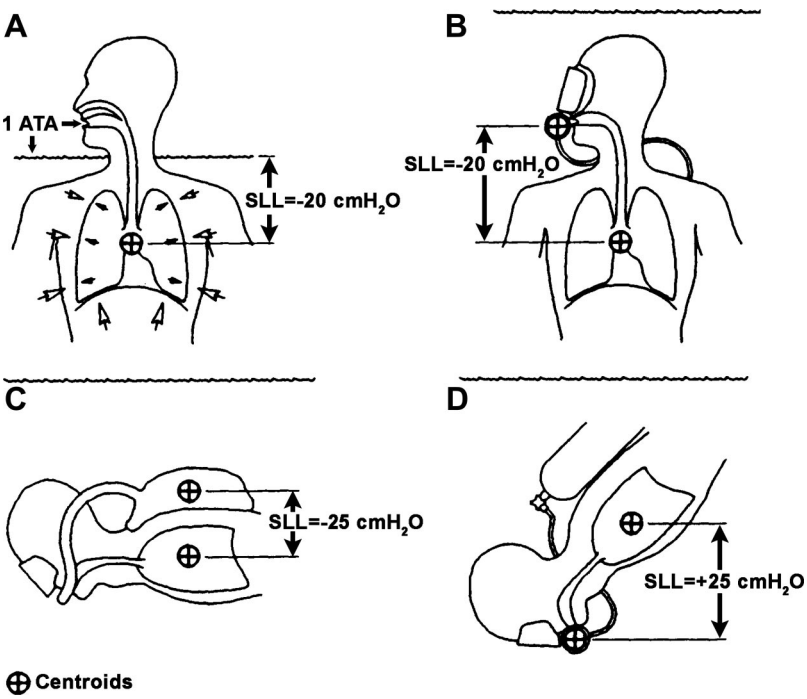

Fig. 1. Transrespiratory pressure (P_{TR}) [static lung load (SLL)]. *A*: a person immersed to the neck (negative P_{TR}). 1 ATA, 1 atm absolute. *B* and *D*: an open-circuit diver for whom the breathing regulator delivers gas at the hydrostatic pressure of the mouth. *C*: a closed-circuit rebreather diver, for whom the reservoir (counterlung) is at a lower hydrostatic pressure than the lung centroid (negative P_{TR}). In the head-up position P_{TR} is negative; in the head-down position P_{TR} is positive, analogous to the clinical application, continuous positive airway pressure (CPAP). [Reproduced from Lundgren (60) with permission. Copyright Informa Healthcare Books.]

resistance (37, 98, 106, 117). The increase in ERV has the effect of increasing internal respiratory load by raising the elastic lung load (14), which allows more passive expiration but results in a requirement for higher negative inspiratory pressures (76). The increased elastic load induced by immersion augments the gas density-related decrease in MVV (129).

Transrespiratory pressure (static lung load). In an immersed diver, a static positive or negative pressure may be exerted across the respiratory system [P_{TR}, or static lung load (SLL)] due to the difference between the pressure of the gas delivered to the mouth and the external hydrostatic pressure at the centroid of the lung (see Fig. 1). Positive or negative P_{TR} alters the equilibrium volume, and measurements in humans have revealed increased or decreased ERV, respectively (107). During negative P_{TR}, ERV is not determined simply by the relaxation volume of the thorax but is defended to some degree with active inspiratory muscle activity, thus causing additional inspiratory muscle work (106). P_{TR} is a major determinant of exercise performance in divers. Positive P_{TR} during immersed heavy exercise is associated with a reduction in dyspnea. Conversely, negative P_{TR} is poorly tolerated by divers, as it seems to increase dyspnea (107). One possible mechanism for the ameliorative effect of positive P_{TR} on dyspnea is the benefit of an increased lung volume (decreased airways resistance), which is offset by an increase in elastic work of breathing. P_{TR} could exert its beneficial effect by reducing the inspiratory elastic work necessary to maintain lung volume at a level that would minimize airways resistance.

Inertance. Inertance of the respiratory system and the breathing system is the property related to the mass of the chest wall and the gas flowing within the airways and breathing apparatus. There is also a small component due to the mass of the water surrounding the chest. Respiratory system inertance at 1 ATA, typically 0.01 $cmH_2O \cdot l^{-1} \cdot s^2$, increases in direct proportion to gas density (67, 81). Inertial impedance tends to offset elastic impedance. In a cyclic breathing pattern inertial impedance is less than elastic impedance at frequencies less than resonant frequency of the system, which at 1 ATA is typically 6 Hz; inertial impedance exceeds elastic impedance at frequencies greater than the resonant frequency. If breathing gas density increases 10-fold, the resonant frequency decreases to ~2 Hz. Thus, given the normally slower breathing frequency exhibited by exercising divers (36, 74, 91), inertial impedance has only a limited role in determining respiratory effort. In an exercising diver breathing a gas with density 10 g/l, assuming a peak acceleration of 30 l/s^2, the transrespiratory pressure due to inertance would be ~3 cmH_2O. On the other hand, if the inertance of a breathing circuit is deliberately increased such that the resonant frequency is reduced to within the normal breathing range, elastic work and inertial work can offset each other and reduce peak-to-peak (inspiratory-to-expiratory) pressure. Using a tunable closed-circuit breathing apparatus, Fothergill et al. (28) demonstrated that divers took advantage of this by adjusting their respiratory rate to equal the resonant frequency of the system.

On the other hand, during experimental measurements of ventilation using traditional open-circuit techniques in dense gas environments, gas inertance can produce artifacts. At high flow rate the gas can continue to flow from the inspired source through the valve system to the expired collection bag following end expiration and end inspiration (39). Such "blowby" will result in an artifactual increase in measured ventilation. This can be a problem particularly at high ventilation rates.

GAS MIXING AND DIFFUSION

The process by which inspired gas mixes with gas resident in the alveoli at end expiration is determined by several processes (23). Convective mixing occurs in large conducting airways in which there is turbulent flow. Taylor dispersion occurs during laminar flow in small tubes where there is a parabolic distribution of flow, with the flow rate at the center of the tube being greater than at the periphery. This velocity gradient generates a radial concentration gradient; radial diffusion along such a gradient facilitates mixing between inspired and resident gases. Diffusion occurs in distal gas exchange units. Mixing is further augmented by cardiogenic oscillations (97).

An increase in density of the breathing gas could affect all of the factors listed above. An increase in density should expand the distribution of turbulent flow to more distal airways, thus enhancing convective mixing and improving the efficiency of gas exchange. High gas density has been predicted to enhance cardiogenic mixing (97). On the other hand a high gas density would diminish the effect of Taylor dispersion (and worsen gas exchange) by concomitantly reducing the number of airways with laminar flow. Increased density reduces gas phase diffusivity (113).

Diffusion depends not only on diffusivity, but also on concentration gradients, time for diffusion, and the shape of the space in which the gas is contained (112). A relevant principle is acinar diffusional screening. This refers to oxygen diffusion along the acinar airway, where it is absorbed preferentially by the more proximal alveolar surfaces along the path. Oxygen molecules may not reach the more distal alveoli, which are therefore functionally "screened" (92). In effect this process reduces the available gas exchange area for diffusion of oxygen and carbon dioxide. The screening effect would be more evident at high gas density (120) and would furthermore affect carbon dioxide to a greater degree than oxygen (92).

An observation that appeared to demonstrate gas phase diffusion impairment was the behavior of goats inside a hyperbaric chamber in a helium-oxygen atmosphere at 39.7 ATA. After increasing the pressure to 49.8 ATA by adding helium (density increase from 7.44 to 10.74 g/l), the animals displayed behavioral disturbances and progressive paralysis (9). This quickly resolved when the ambient P_{O_2} was raised from 154 to 191 mmHg. This observation, which was attributed to diffusion-related hypoxia, provided a major rationale for maintaining a high P_{O_2} in operational and experimental deep-dive exposures. Since then, studies in humans have refuted this hypothesis by demonstrating adequate blood oxygenation at even higher densities (50, 91).

Ventilation with the highest conceivable fluid density was achieved in experiments performed by Kylstra and colleagues, who examined oxygen and carbon dioxide diffusion by ventilating the lungs with saline. Studies in anesthetized dogs ventilated with hyperoxygenated saline (inspired P_{O_2} 3,300–3,640 mmHg) revealed that despite evidence for diffusion limitation of both oxygen and carbon dioxide exchange, adequate arterial P_{O_2} and P_{CO_2} could be achieved (47). These animal experiments were followed up by a study in patients

undergoing therapeutic lung lavage for alveolar proteinosis and a human volunteer, using a double-lumen endotracheal tube. Saline was cycled in and out of one lung while the contralateral lung was ventilated with oxygen (48). In these humans there was no evidence for incomplete diffusive equilibrium between alveoli and capillary blood. However, unlike the dog experiments the respiratory cycle time exceeded 30 s. The prolonged cycle time presumably permitted equilibrium to occur even in the face of extremely low diffusivity.

In summary, the effects of an increase in gas density are predicted to impair gas phase diffusion but augment convective mixing. Despite at least a theoretical understanding of these processes during static or quasi-static flow within conduits of simple geometry or in simple experimental models, with currently available technology it has been challenging to elucidate their respective contributions to pulmonary gas exchange (22, 77).

DISTRIBUTIONS OF VENTILATION, BLOOD FLOW, AND VENTILATION-PERFUSION RATIO

The distribution of ventilation is dependent on cyclic changes in externally applied pressure and regional mechanical properties. Despite the wide range in path length from large airways to gas exchange units within the lung, time constants of different lung units are close enough to one another such that under normal circumstances ventilation of different lung regions is acceptably uniform. Differences in time constants among lung regions would increase heterogeneity of ventilation. This could result from higher breathing gas density and increased turbulence in conducting airways, to a differing degree depending on diameter. In airways in which turbulent flow predominates, increased gas density would cause an increase in flow resistance to a degree dependent on the flow characteristics and airway geometry. Time constants would become more disperse and ventilation of different lung units more asynchronous. Breathing a gas of higher density must therefore result in an increased heterogeneity of ventilation. This is supported by the model of Pedley et al. (79) and the observation by Forkert et al. (26) that, compared with air, dynamic compliance is reduced by an increase in breathing gas density using SF_6-O_2.

Gas distribution may also depend on other factors. It is usually assumed that pleural pressure swings are uniform over the entire lung; however, there is evidence to the contrary (23). During resting breathing, regional pressure changes are less in the upper than in the lower chest (17). Regional pressure variations may occur due to gravitational effects, the position of the heart relative to the lung, interactions between the lung and the abdominal contents or between the shapes of the lung and the chest wall, or selective contraction of muscles of ventilation (23, 131). An additional mechanism that may produce asynchrony of ventilation is therefore topical variability of distribution of pleural pressure swings within the thorax, which under increased respiratory load in a dense gas environment could become more exaggerated.

Although evidence against regional differences in ventilation is provided by a study using ^{133}Xe to image topographic ventilation during SF_6-O_2 breathing, that technique is limited to visualization of differences between large regions; it cannot detect ventilation changes in small compartments within a region.

Unless inequalities of ventilation are matched by regional changes in perfusion then gas exchange would become less efficient. Intriguingly, although little is known about the effects of dense gas breathing on blood flow distribution per se, several investigators have reported that breathing dense gas is associated with a decrease in the alveolar-arterial P_{O_2} difference ($P_{A_{O_2}} - Pa_{O_2}$) (10, 25, 33, 89, 127) (see Fig. 2). This suggests more efficient matching of ventilation and perfusion. However, under similar conditions dead space/tidal volume ratio (V_D/V_T) is increased (66, 74, 89, 91, 127), an effect that appears independent of P_{O_2} over a range from 0.2 to 3 ATA.

Reduced diffusivity adversely affects gas exchange of both molecules, while enhanced cardiogenic mixing would effect an improvement. Wood et al. (127) have speculated that increased breathing gas density reduces $P_{A_{O_2}} - Pa_{O_2}$ because it promotes intraregional convective mixing and hence reduced ventilation/perfusion ($\dot{V}_A/\dot{Q}$) dispersion, which affects V_D/V_T to a lesser degree than $P_{A_{O_2}} - Pa_{O_2}$. Wood et al. have proposed that the increase in V_D/V_T is predominantly due to impaired molecular diffusion of carbon dioxide. Although oxygen diffusion should be similarly affected, they speculated that this is insufficient to offset the convective mixing effect. While there is no straightforward explanation for these two contradictory observations, preliminary observations using the multiple inert gas technique lend support for impaired distribution of ventilation as the cause of the increased dead space (see Fig. 3).

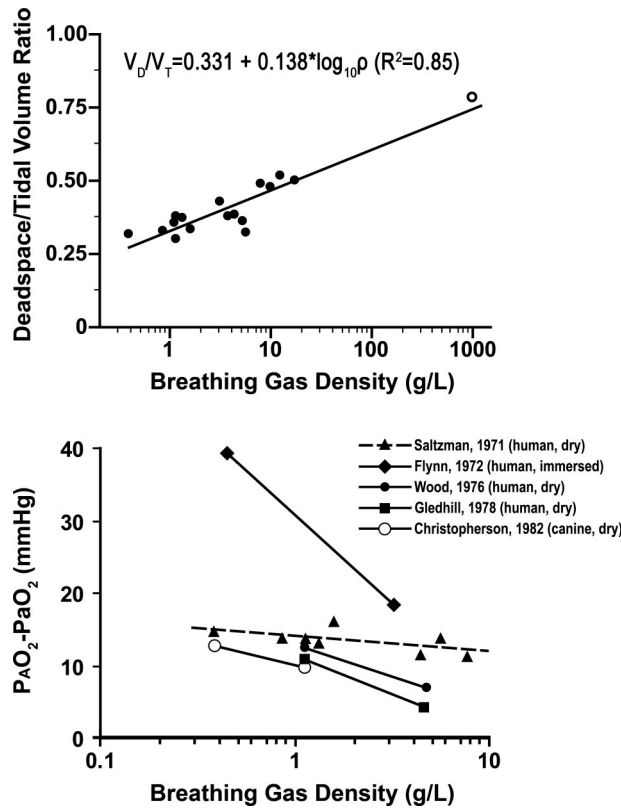

Fig. 2. *Top*: effect of gas density (ρ) on dead space. V_D/V_T, dead space/tidal volume ratio. Data from Saltzman et al. (89), Wood et al. (127), Salzano et al. (91), McMahon et al. (66), and Mummery et al. (74). ●, Human data; ○ is from a liquid-breathing experiment in dogs (47). *Bottom*: alveolar-arterial P_{O_2} difference ($P_{A_{O_2}} - Pa_{O_2}$) as a function of breathing gas density. Data from Saltzman et al. (▲; 89), Flynn et al. (◆; 25), Wood et al. (●; 127), Gledhill et al. (■; 33), and Christopherson and Hlastala (○; 10).

Effects of immersion on ventilation and perfusion. The engorgement of the pulmonary vessels and reduction in lung volume tend to be associated with several effects that could affect gas exchange. Several investigators have observed an increase in closing volume (CV) (5, 19, 83), consistent with some gas trapping. Also in support of gas trapping is the observation that during immersion residual volume by body plethysmography exceeds that measured by inert gas dilution (87). When CV exceeds ERV in upright immersion, there is an inversion of the normal cephalo-caudad distribution of blood flow, such that blood flow per gas exchange unit is higher at the apex than at the base of the lung (83). However, varied effects have been observed on pulmonary gas exchange. During immersion, one study indicated an increase in $P_{A_{O_2}} - P_{a_{O_2}}$ (13), while one other observed a transient decrease, and after a few minutes of immersion, a return to baseline (20). In the presence of mild pulmonary pathology, immersion may have an additional effect: loss of an observable phase IV of the single-breath inert gas washout curve, which is traditionally interpreted as signaling the onset of airway closure (54), which, in a group of mild asthmatic subjects, was interpreted by the investigators as evidence of airway closure throughout the entire vital capacity maneuver.

It has been hypothesized that if CV impinges on tidal volume (i.e., CV exceeds ERV), $P_{a_{O_2}}$ should decrease. This was confirmed by Cohen et al. (13) and Prefaut et al. (84), but not by Derion et al. (20). In the latter study, shunt measured by multiple inert gas elimination was slightly increased in older subjects (ages 40–54 yr) but not in younger subjects (ages 20–29 yr). $P_{a_{O_2}}$ did not decrease in the older subjects, possibly because of a large increase in V_T, which could have reduced the fraction of V_T within CV. However, when the observations from two studies were combined, there was a clear increase in $P_{A_{O_2}} - P_{a_{O_2}}$ as CV approached ERV + V_T (see Fig. 4).

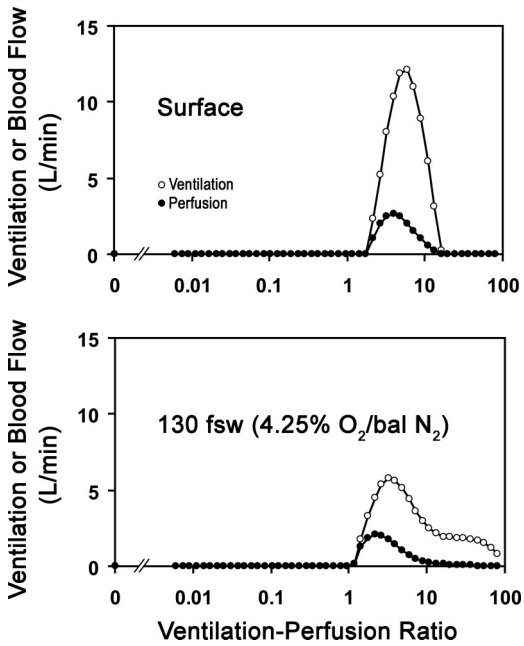

Fig. 3. Ventilation/perfusion distribution using the multiple inert gas (MIG) elimination technique in a human volunteer during upright dry exercise at 1 ATA (*top*) and a pressure equivalent to 130 feet of sea water (fsw) (4.94 ATA, *bottom*), breathing 4.25% O_2/balance (bal) N_2 measured in a dry hyperbaric chamber. Minute ventilations were, respectively, 94 and 62 l/min. Bohr dead space was higher at depth (0.29 vs. 0.21 liter); dead space measured using the MIG technique (116) was 0.15 and 0.03 liter, respectively. The data are consistent with the higher Bohr dead space at pressure being due to increased dispersion of ventilation (log SD of the ventilation distribution 0.55 and 1.12 at 1 and 4.94 ATA, respectively).

Pulmonary-blood transfer of oxygen. Altered affinity of hemoglobin for oxygen has been observed at high pressures. Increased hemoglobin-oxygen affinity has been observed in studies in vitro (32, 43, 44, 86) and in a human in vivo study during a saturation dive to 69 ATA (101) (Fig. 5). During the latter study, erythrocyte 2,3-DPG levels were slightly decreased from control (mean ± SD, control: 15.9 ± 3.5; hyperbaric exposure: 13.7 ± 2.6 μmol/g Hb); however, the change was insufficient to explain the decrease in the P_{O_2} at 50% hemoglobin saturation (P50) (100). These small changes in P50 appear to be due to conformational changes in hemoglobin induced by high pressure and, to a small extent with gases actually breathed by divers, binding by inert gas. It is unlikely that these small changes in hemoglobin P50 have any significant effect on pulmonary gas exchange or exercise capacity (115).

VENTILATORY DRIVE

Hypercapnic ventilatory response (HVR) varies among individuals and has been proposed as a predictor of P_{CO_2} during underwater exercise. In one case study (71), a diver with an extremely low HVR was studied during exercise at 4 atmospheres absolute (ATA) and demonstrated hypoventilation and hypercapnia to an extent far greater than that seen in most normal volunteers. Other studies have indeed shown a correlation between low HVR and hypercapnia in exercise studies at the surface and at depth (52, 70). Overall, however, HVR is a poor predictor of P_{CO_2} at depth (8, 62). In a study of military divers, only 60% of subjects with hypercapnia at depth also had a low HVR (52).

This poor predictive value may be due to intrasubject HVR variability on different days (88) and in different conditions. It can also be affected by respiratory muscle training, which tends to decrease the HVR of both low and high responders toward the mean (80): muscle training attenuates the HVR of individuals with high values and increases it in low responders. HVR tends to be decreased in scuba divers (24, 71, 93) although not all studies have confirmed this (29). Kerem et al. (42) observed higher end-tidal P_{CO_2} ($P_{ET_{CO_2}}$) in divers compared with nondivers during exercise at 1 ATA, but there was no difference between the diver and control groups when breathing 40% O_2 and 60% N_2 at 4 ATA (42). Unfortunately, it is difficult to compare surface vs. depth P_{CO_2} during exercise using end-tidal measurements, since $P_{ET_{CO_2}}$ overestimates $P_{a_{CO_2}}$ at the surface (56, 74) but more accurately reflects $P_{a_{CO_2}}$ under hyperbaric conditions (74).

Effect of hyperoxia. Respiratory drive could be affected by a high partial pressure of oxygen, which for a fixed O_2 fraction increases linearly with depth. Hyperoxia therefore occurs in divers even when diving with a breathing gas that is normoxic at the surface. Still higher P_{O_2} is produced by enriched oxygen breathing gas mixtures that are intentionally used in an effort to reduce inert gas load. Hyperoxia attenuates the ventilatory response to hypercapnia (15, 30, 69, 78) and has been noted to decrease ventilation during exercise (1, 21, 38, 51, 68, 82,

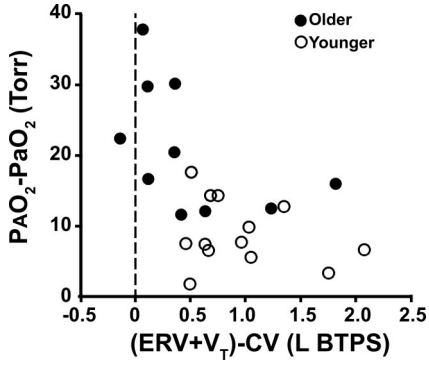

Fig. 4. Effect of closing volume (CV) on oxygen exchange as assessed by alveolar-arterial gradient. ERV, expiratory reserve volume. Data are from Derion et al. (20) and Prefaut et al. (84). [Redrawn from Derion and Guy (19), copyright 1994, with permission from Elsevier.]

124). Mild hypercapnia (Pa_{CO_2} = 44 mmHg) has been observed during heavy exercise while breathing 100% O_2 at 2 ATA (11). Few hyperbaric studies exist in which exercise was tested as a function of P_{O_2} at constant breathing gas density. One such study demonstrated attenuation of the ventilatory response to heavy bicycle exercise in the dry at 2 ATA (103). Arterial blood samples were obtained 7–9 min following completion of 5 min of exercise up to 1,800 Kp·m·min^{-1}, and demonstrated slightly higher pH and lower base deficits in hyperoxia. Therefore it was not possible to confirm a direct effect of hyperoxia on respiratory drive. Another study failed to find an effect of P_{O_2} on arterial P_{CO_2} between 0.7 and 1.3 ATA during immersed prone exercise at 4.7 ATA (8). Factors besides respiratory drive attenuation that may contribute to the reduction in exercise ventilation include peripheral chemoreceptor inhibition and attenuation of the acidemia that occurs during heavy exercise (51).

Paradoxically, in some studies, after a few minutes of hyperoxia at 1 ATA, hyperventilation has been observed (18). A possible explanation has been proposed, based on observations of increased firing rates of solitary complex neurons in brain slices exposed to hyperbaric hyperoxia (73). However, despite increased ventilation and reduced $P_{ET_{CO_2}}$, Pa_{CO_2} in human hyperoxia studies is generally normal (27, 35). The observations in brain slices (73), in which tissue P_{O_2} is higher than could occur in human divers, may reflect toxic effects of oxygen.

Effect of narcosis. It has been suggested that when breathing nitrogen-oxygen mixtures, nitrogen narcosis could also contribute to hypercapnia during diving. While HVR is attenuated at increased ambient pressure, studies using nonnarcotic gases support increased gas density vs. nitrogen narcosis as the mechanism (8, 31, 61).

Effect of mechanical load and ventilation. A major contributor to hypoventilation and increased Pa_{CO_2} seen in diving is increased work of breathing as discussed above. Investigators have traditionally argued that in the setting of increased respiratory load, ventilatory effort (and hence the alveolar ventilation) represents a compromise between the drive to maintain normocapnia and the greater work of breathing that would be required to achieve it (63). Several studies have supported a major effect of increased gas density on exercise ventilation. A human study by Linnarsson et al. (55) in a dry hyperbaric chamber measured exercise ventilation while breathing four different gases (air and SF_6-O_2 at 1–1.3 ATA; He-O_2, and N_2-O_2 at 5.5 ATA). These combinations created two different gas densities (1.1 and 6.0 g/l) at each ambient pressure. P_{O_2} was 0.2 ATA under all conditions. There was a significant density-related decrease in exercise ventilation (Fig. 6). In explaining the hypoventilation during exercise in divers, this experiment excluded ambient pressure and supported the major role of increased gas density, although a narcosis effect could not be excluded. A recent study demonstrated that external resistive load increased Pa_{CO_2} during prone immersed exercise at 4.7 ATA (8).

During the transition from rest to exercise at the surface, carbon dioxide levels can increase by a small but significant amount in normal subjects (12). It is thought that this effect is due to a low ventilatory response to low levels of exercise. With submersion, this effect is slightly more pronounced (107) and is generally explained by the increased work of breathing during immersion, as discussed above. Submersion causes reduced lung compliance due to a redistribution of blood into

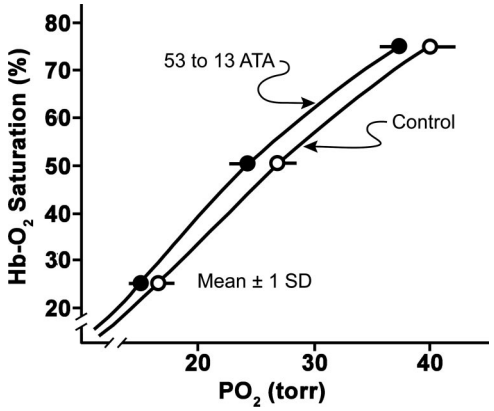

Fig. 5. Hemoglobin-oxygen (Hb-O_2) dissociation curve measured at pressure during a saturation dive (mean ± SD of all measurements in 3 divers over the pressure range indicated). Control curve was obtained at 1 ATA; $P < 0.05$. [Redrawn from Stolp et al. (101), copyright 1984, with permission from Undersea and Hyperbaric Medical Society.]

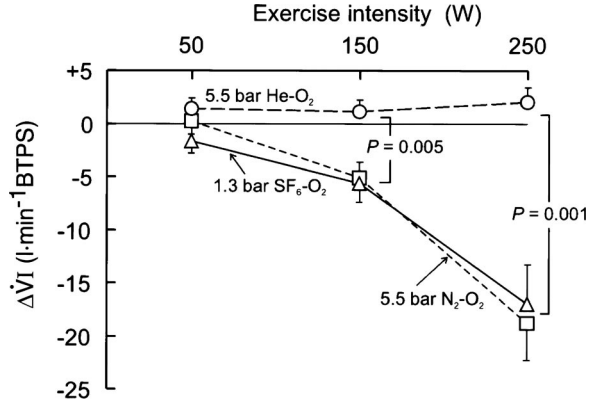

Fig. 6. Differences in exercise ventilation ($\Delta\dot{V}I$) between 1-bar air (control) and 3 gas + pressure conditions with normal (5.5-bar He-O_2) or 5.5 times increased gas density (1.3-bar SF_6-O_2, 5.5-bar N_2-O_2). Values are means ± SE. Effect of gas density on ventilatory response to exercise. Air at 1 ATA and heliox at 5.5 have density 1.1 g/l; SF_6-O_2 at 1.3 ATA and N_2-O_2 at 5.5 ATA have density 6 g/l. All gas mixtures were normoxic (P_{O_2} = 0.2 ATA). [Reproduced from Linnarsson et al. (55).]

the thorax and engorgement of the pulmonary capillaries (16, 72), which can be augmented by a negative P_{TR}.

Work of breathing is also elevated with the addition of negative (72) or positive (14) P_{TR}. The increased work of breathing with negative P_{TR} can be attributed to an increase in internal respiratory resistance due to compression of the extrathoracic airways (2). Positive P_{TR} causes subjects to have a higher expiratory reserve volume and increased elastic recoil of the lungs (14). However, several studies have shown that the increased work of breathing caused by changes in P_{TR} between $+10$ and -20 cmH_2O during exercise can cause dyspnea but does not translate into higher $P_{ET_{CO_2}}$ (40, 75, 107), although in these studies it is possible that Pa_{CO_2} was underestimated by $P_{ET_{CO_2}}$. It is also possible that positive P_{TR} could increase dead space by increasing the caliber of the large airways, and thus increase Pa_{CO_2}, although there is not yet any evidence to support this hypothesis.

All but a few studies examining contributors to hypercapnia at depth (8, 51, 74, 89–91) have used $P_{ET_{CO_2}}$ as an estimate of Pa_{CO_2}, which under resting conditions is a good approximation. During exercise the approximation is not as good: $P_{ET_{CO_2}}$ is higher than Pa_{CO_2} during exercise at 1 ATA (56) and lower in conditions under which there is increased dead space, as may be the case with diving. Only one study has directly correlated the two in diving, in the dry at 2.8 ATA (74), demonstrating a reasonable correlation.

Pressure. Theoretically, there could also be some effect of extremely high pressure on the control of breathing. A study in subjects at rest (89) found that while increased pressure caused Pa_{CO_2} to rise, gas density had only a small effect. However, that study investigated only resting conditions. Studies of hyperbaric exercise have tended to exclude pressure having any significant influence on ventilation (55).

PATHOLOGICAL EFFECTS OF DIVING

Impaired gas exchange after saturation dives. During saturation dives, divers remain in a hyperbaric environment for many days or weeks. Physical activity is limited, thus engendering loss of cardiorespiratory fitness, and the ambient P_{O_2} is higher than normal (typically 0.4–0.5 ATA), thus exposing the divers to oxygen tensions that could be mildly toxic to the lung. Additionally, venous gas embolism may occur during decompression, which can last several days. Observations by Thorsen et al. suggest that saturation dives may have persistent cardiorespiratory effects on divers. After deep saturation dives to 37 ATA, maximal $\dot{V}_{O_2}$ ($\dot{V}_{O_{2max}}$) and carbon monoxide transfer factor are reduced and respiratory dead space is increased (108). While the reduction in $\dot{V}_{O_{2max}}$ may in part reflect deconditioning due to many days of reduced aerobic exercise in the confined environment of a diving chamber, other explanations were proposed for the gas exchange impairment. The first was a cumulative effect of venous gas embolism on the lung. In support of this hypothesis was the observation that the fractional reduction in $\dot{V}_{O_{2max}}$ after the dive correlated with the cumulative venous bubble score as detected by ultrasound (108). The second proposed explanation was mild pulmonary oxygen toxicity, due to an inspired P_{O_2} of 0.4–0.5 ATA during the 18–28 days in which the divers were continuously under pressure. This second hypothesis is supported by a study in which volunteers were exposed in a hyperbaric chamber to a lower pressure (2.5 ATA) but with duration and inspired P_{O_2} similar to the deep dives, but with no detectable venous gas emboli. After this exposure there was a similar reduction in $\dot{V}_{O_{2max}}$ and carbon monoxide transfer factor. A control dive of similar duration but at a lower pressure (1.5 ATA) and P_{O_2} (0.2 ATA) produced no effect on carbon monoxide transfer factor (110). Logistic regression analysis of possible risk factors after a series of saturation dives implicated both hyperoxia and venous gas embolism as factors contributing to impairment in pulmonary gas exchange (109). These data suggest that hyperoxia, albeit at levels traditionally considered nontoxic, is a major contributor to pulmonary gas impairment after long saturation dives.

Immersion pulmonary edema. Immersion pulmonary edema (IPE) is a condition in which cough, hemoptysis, dyspnea, and hypoxemia develop after surface swimming or diving, often in young, healthy individuals (34, 45, 57, 64, 96, 123), including exceptionally fit military divers (59, 64, 95, 121). It occurs predominantly in males. The condition usually resolves spontaneously or with β_2-adrenergic agonist or diuretic therapy, but it can be fatal (96). Risk factors may include cold water (45, 123), exertion (34, 94, 95, 121), fluid loading (121), negative P_{TR} (111) or low vital capacity (95). The cause is unknown, although hydrostatic pulmonary edema is a strong possibility. Pulmonary artery wedge pressure in IPE at the time of evaluation has been reported as normal (34), although thus far there have been no measurements in IPE during the acute event. Post-event echocardiography is usually normal (34, 45, 57, 96). Bronchoalveolar lavage studies have revealed no evidence of inflammation. Capillary stress failure due to high pulmonary capillary flow/pressure has been implicated (45, 58). Proposed mechanisms involve the additive effects of immersion-induced increase in pulmonary blood volume and pulmonary artery hypertension due to exertion, and cold water (46).

CONCLUSION

Despite the diving-related increase in resistance to bulk flow and impairment of gas phase diffusion, it is surprising that the human lung is at all capable of supporting oxygenation and carbon dioxide elimination at gas densities severalfold higher than normal. Nevertheless, there remain several open questions. Ventilation/perfusion relationships during dense gas breathing have not yet been elucidated. Recent studies at 1 ATA suggest that the normal exercise-induced rise in cardiac output can be attenuated by external breathing resistance (3). However, studies to examine the effect on cardiac output of increased pulmonary resistive load are lacking. Although both physiological and safety-related measurements rely mostly on the analysis of end-tidal gas, only one study has been published comparing $P_{ET_{CO_2}}$ and arterial P_{CO_2} during exercise, breathing air at 2.8 ATA (density 3.2 g/l) (74). There have been no reported studies at higher densities or P_{O_2}. The effect of P_{O_2} on regulation of ventilation and arterial P_{CO_2} has been incompletely studied during exercise, with the controls in most studies consisting of exercise runs at a different density (1 ATA), thus precluding the elimination of gas density as a confounder. Finally, indirect evidence of metabolic acidosis and respiratory muscle fatigue during endurance exercise pose questions related to the effects on cardiovascular performance and gas exchange. Intriguing recent evidence that respiratory

muscle training may affect ventilatory control and endurance in divers needs further study.

GRANTS

This study was supported by US Navy NAVSEA contract no. N61331-03-C-0015.

REFERENCES

1. **Adams RP, Welch HG.** Oxygen uptake, acid-base status, and performance with varied inspired oxygen fractions. *J Appl Physiol* 49: 863–868, 1980.
2. **Agostoni E, Gurtner G, Torri G, Rahn H.** Respiratory mechanics during submersion and negative pressure breathing. *J Appl Physiol* 21: 251–258, 1966.
3. **Aliverti A, Dellaca RL, Lotti P, Bertini S, Duranti R, Scano G, Heyman J, Lo Mauro A, Pedotti A, Macklem PT.** Influence of expiratory flow-limitation during exercise on systemic oxygen delivery in humans. *Eur J Appl Physiol* 95: 229–242, 2005.
4. **Anthonisen NR, Bradley ME, Vorosmarti J, Linaweaver PG.** Mechanics of breathing with helium-oxygen and neon-oxygen breathing mixtures in deep saturation diving. In: *Underwater Physiology IV: Proceedings of the Fourth Symposium on Underwater Physiology*, edited by Lambertsen CJ. New York: Academic, 1971, p. 339–345.
5. **Bondi KR, Young JM, Bennett RM, Bradley ME.** Closing volumes in man immersed to the neck in water. *J Appl Physiol* 40: 736–740, 1976.
6. **Camporesi EM, Bosco G.** Ventilation, gas exchange and exercise under pressure. In: *The Physiology and Medicine of Diving*, edited by Brubakk AO, Neuman TS. New York: Elsevier Science, 2003, p. 77–114.
7. **Chang H, Tai RC, Farhi LE.** Some implications of ternary diffusion in the lung. *Respir Physiol* 23: 109–120, 1975.
8. **Cherry AD, Forkner IF, Frederick HJ, Natoli MJ, Schinazi EA, Longphre JP, Conard JL, White WD, Freiberger JJ, Stolp BW, Pollock NW, Doar PO, Boso AE, Alford EL, Walker AJ, Ma AC, Rhodes MA, Moon RE.** Predictors of increased Pa_{CO_2} during immersed prone exercise at 4.7 ATA. *J Appl Physiol* (September 11, 2008). doi:10.1152/japplphysiol.00885.2007.
9. **Chouteau J.** Respiratory gas exchange in animals during exposure to extreme ambient pressures. In: *Underwater Physiology: Proceedings of the Fourth Symposium on Underwater Physiology*, edited by Lambertsen CJ. New York: Academic, 1971, p. 385–397.
10. **Christopherson SK, Hlastala MP.** Pulmonary gas exchange during altered density gas breathing. *J Appl Physiol* 52: 221–225, 1982.
11. **Clark JM, Gelfand R, Lambertsen CJ, Stevens WC, Beck G Jr, Fisher DG.** Human tolerance and physiological responses to exercise while breathing oxygen at 20 ATA. *Aviat Space Environ Med* 66: 336–345, 1995.
12. **Clark JM, Sinclair RD, Lenox JB.** Chemical and nonchemical components of ventilation during hypercapnic exercise in man. *J Appl Physiol* 48: 1065–1076, 1980.
13. **Cohen R, Bell WH, Saltzman HA, Kylstra JA.** Alveolar-arterial oxygen pressure difference in man immersed up to the neck in water. *J Appl Physiol* 30: 720–723, 1971.
14. **Collett PW, Engel LA.** Influence of lung volume on oxygen cost of resistive breathing. *J Appl Physiol* 61: 16–24, 1986.
15. **Dahan A, DeGoede J, Berkenbosch A, Olievier IC.** The influence of oxygen on the ventilatory response to carbon dioxide in man. *J Physiol* 428: 485–499, 1990.
16. **Dahlback GO, Jonsson E, Liner MH.** Influence of hydrostatic compression of the chest and intrathoracic blood pooling on static lung mechanics during head-out immersion. *Undersea Biomed Res* 5: 71–85, 1978.
17. **Daly WJ, Bondurant S.** Direct measurement of respiratory pleural pressure changes in normal man. *J Appl Physiol* 18: 513–518, 1963.
18. **Dean JB, Mulkey DK, Henderson RA 3rd, Potter SJ, Putnam RW.** Hyperoxia, reactive oxygen species, and hyperventilation: oxygen sensitivity of brain stem neurons. *J Appl Physiol* 96: 784–791, 2004.
19. **Derion T, Guy HJ.** Effects of age on closing volume during head-out water immersion. *Respir Physiol* 95: 273–280, 1994.
20. **Derion T, Guy HJ, Tsukimoto K, Schaffartzik W, Prediletto R, Poole DC, Knight DR, Wagner PD.** Ventilation-perfusion relationships in the lung during head-out water immersion. *J Appl Physiol* 72: 64–72, 1992.
21. **Ekblom B, Huot R, Stein EM, Thorstensson AT.** Effect of changes in arterial oxygen content on circulation and physical performance. *J Appl Physiol* 39: 71–75, 1975.
22. **Engel LA.** Gas mixing within the acinus of the lung. *J Appl Physiol* 54: 609–618, 1983.
23. **Engel LA, Macklem PT.** Gas mixing and distribution in the lung. *Int Rev Physiol* 14: 37–82, 1977.
24. **Florio JT, Morrison JB, Butt WS.** Breathing pattern and ventilatory response to carbon dioxide in divers. *J Appl Physiol* 46: 1076–1080, 1979.
25. **Flynn ET, Saltzman HA, Summitt JK.** Effects of head-out immersion at 19.18 Ata on pulmonary gas exchange in man. *J Appl Physiol* 33: 113–119, 1972.
26. **Forkert L, Wood LD, Cherniack RM.** Effect of gas density on dynamic pulmonary compliance. *J Appl Physiol* 39: 906–910, 1975.
27. **Forkner IF, Piantadosi CA, Scafetta N, Moon RE.** Hyperoxia-induced tissue hypoxia: a danger? *Anesthesiology* 106: 1051–1055, 2007.
28. **Fothergill DM, Joye DD, Carlson NA.** Diver respiratory responses to a tunable closed-circuit breathing apparatus. *Undersea Hyperb Med* 24: 91–105, 1997.
29. **Froeb HF.** Ventilatory response of scuba divers to CO_2 inhalations. *J Appl Physiol* 16: 8–10, 1961.
30. **Gelfand R, Lambertsen CJ.** Dynamic respiratory response to abrupt change of inspired CO_2 at normal and high P_{O_2}. *J Appl Physiol* 35: 903–913, 1973.
31. **Gelfand R, Lambertsen CJ, Peterson RE.** Human respiratory control at high ambient pressures and inspired gas densities. *J Appl Physiol* 48: 528–539, 1980.
32. **Gerth WA.** Nitrogen binding to deoxyhemoglobin at high pressures and its relation to changes in hemoglobin-oxygen affinity. *J Biol Chem* 263: 13515–13521, 1988.
33. **Gledhill N, Froese AB, Buick FJ, Bryan AC.** $\dot{V}_A/\dot{Q}$ inhomogeneity and AaD_{O_2} in man during exercise: effect of SF6 breathing. *J Appl Physiol* 45: 512–515, 1978.
34. **Hampson NB, Dunford RG.** Pulmonary edema of scuba divers. *Undersea Hyperb Med* 24: 29–33, 1997.
35. **Her C.** Hyperoxia-induced decrease in organ blood flow. *Anesthesiology* 108: 168–169; author reply 169–170, 2008.
36. **Hesser CM, Lind F, Linnarsson D.** Significance of airway resistance for the pattern of breathing and lung volumes in exercising humans. *J Appl Physiol* 68: 1875–1882, 1990.
37. **Hesser CM, Linnarsson D, Fagraeus L.** Pulmonary mechanisms and work of breathing at maximal ventilation and raised air pressure. *J Appl Physiol* 50: 747–753, 1981.
38. **Hickam JB, Pryor WW, Page EB, Atwell RJ.** Respiratory regulation during exercise in unconditioned subjects. *J Clin Invest* 30: 503–516, 1951.
39. **Hickey DD, Marky DC, Smith RJ.** Gas inertia and ventilatory measurements under pressure: methodological considerations. *Undersea Biomed Res* 10: 273–279, 1983.
40. **Hickey DD, Norfleet WT, Pasche AJ, Lundgren CE.** Respiratory function in the upright, working diver at 6.8 ATA (190 fsw). *Undersea Biomed Res* 14: 241–262, 1987.
41. **Jarrett AS.** Alveolar carbon dioxide tension at increased ambient pressures. *J Appl Physiol* 21: 158–162, 1966.
42. **Kerem D, Daskalovic YI, Arieli R, Shupak A.** CO_2 retention during hyperbaric exercise while breathing 40/60 nitrox. *Undersea Hyperb Med* 22: 339–346, 1995.
43. **Kiesow LA.** Hyperbaric inert gases and the hemoglobin-oxygen equilibrium in red blood cells. *Undersea Biomed Res* 1: 29–43, 1974.
44. **Kiesow LA, Bless JW, Shelton JB.** Oxygen dissociation in human erythrocytes: its response to hyperbaric environments. *Science* 179: 1236–1238, 1973.
45. **Koehle MS, Lepawsky M, McKenzie DC.** Pulmonary oedema of immersion. *Sports Med* 35: 183–190, 2005.
46. **Kurss DI, Lundgren CEG, Pasche AJ.** Effect of water temperature on vital capacity in head-out immersion. In: *Underwater Physiology VII: Proceedings of the 7th Symposium on Underwater Physiology*, edited by Bachrach AJ, Matzen MM. Bethesda, MD: Undersea Medical Society, 1981, p. 297–301.
47. **Kylstra JA, Paganelli CV, Lanphier EH.** Pulmonary gas exchange in dogs ventilated with hyperbarically oxygenated liquid. *J Appl Physiol* 21: 177–184, 1966.

48. **Kylstra JA, Schoenfisch WH, Herron JM, Blenkarn GD.** Gas exchange in saline-filled lungs of man. *J Appl Physiol* 35: 136–142, 1973.
49. **Lafay V, Barthelemy P, Comet B, Frances Y, Jammes Y.** ECG changes during the experimental human dive HYDRA 10 (71 atm/7,200 kPa). *Undersea Hyperb Med* 22: 51–60, 1995.
50. **Lambertsen CJ, Gelfand R, Peterson R, Strauss R, Wright WB, Dickson JG Jr, Puglia C, Hamilton RW Jr.** Human tolerance to He, Ne, and N_2 at respiratory gas densities equivalent to He-O_2 breathing at depths to 1200, 2000, 3000, 4000, and 5000 feet of sea water (Predictive Studies III). *Aviat Space Environ Med* 48: 843–855, 1977.
51. **Lambertsen CJ, Owen SG, Wendel H, Stroud MW, Lurie AA, Lochner W, Clark GF.** Respiratory and cerebral circulatory control during exercise at 21 and 20 atmospheres inspired P_{O_2}. *J Appl Physiol* 14: 966–982, 1959.
52. **Lanphier E.** *Nitrogen-Oxygen Mixture Physiology. Phase 4: Carbon Dioxide Sensitivity as a Potential Means of Personnel Selection. Phase 6: Carbon Dioxide Regulation Under Diving Conditions*. Washington, DC: Navy Experimental Diving Unit, Washington Navy Yard, 1958.
53. **Lanphier E.** *Nitrogen-Oxygen Mixture Physiology: Phases 1 and 2*. Washington, DC: Navy Experimental Diving Unit, Washington Navy Yard, 1955.
54. **Leddy JJ, Roberts A, Moalem J, Curry T, Lundgren CE.** Effects of water immersion on pulmonary function in asthmatics. *Undersea Hyperb Med* 28: 75–82, 2001.
55. **Linnarsson D, Ostlund A, Lind F, Hesser CM.** Hyperbaric bradycardia and hypoventilation in exercising men: effects of ambient pressure and breathing gas. *J Appl Physiol* 87: 1428–1432, 1999.
56. **Liu Z, Vargas F, Stansbury D, Sasse SA, Light RW.** Comparison of the end-tidal arterial P_{CO_2} gradient during exercise in normal subjects and in patients with severe COPD. *Chest* 107: 1218–1224, 1995.
57. **Ludwig B, Mahon RT.** Cardiopulmonary risk factors in swimming induced pulmonary edema (Abstract). *Am J Respir Crit Care Med* 167: A564, 2003.
58. **Ludwig BB, Mahon RT, Parrish JS, Lamb C, Kerr S.** Pulmonary edema in combat swimmers: clinical and bronchoalveolar lavage description demonstrating stress failure of the pulmonary capillaries. *Undersea Hyperb Med* 31: 318, 2004.
59. **Lund KL, Mahon RT, Tanen DA, Bakhda S.** Swimming-induced pulmonary edema. *Ann Emerg Med* 41: 251–256, 2003.
60. **Lundgren CE.** Immersion effects. In: *The Lung at Depth*, edited by Lundgren CE, Miller JN. New York: Dekker, 1999, p. 91–128.
61. **Lundgren CEG, Miller JN.** Carbon dioxide retention. Enhancement of inert gas narcosis by carbon dioxide. In: *Lung Biology in Health and Disease: The Lung at Depth*. New York: Dekker, 1999, p. 219–222.
62. **Lundgren CEG, Miller JN.** Carbon dioxide retention. Identification of CO_2 retainers. In: *Lung Biology in Health and Disease: The Lung at Depth*. New York: Dekker, 1999, p. 229.
63. **Lundgren CEG, Miller JN.** Carbon dioxide retention. Increased work of breathing. In: *Lung Biology in Health and Disease: The Lung at Depth*. New York: Dekker, 1999, p. 225–226.
64. **Mahon RT, Kerr S, Amundson D, Parrish JS.** Immersion pulmonary edema in special forces combat swimmers. *Chest* 122: 383–384, 2002.
65. **Maio DA, Farhi LE.** Effect of gas density on mechanics of breathing. *J Appl Physiol* 23: 687–693, 1967.
66. **McMahon TJ, Moon RE, Luschinger BP, Carraway MS, Stone AE, Stolp BW, Gow AJ, Pawloski JR, Watke P, Singel DJ, Piantadosi CA, Stamler JS.** Nitric oxide in the human respiratory cycle. *Nature Med* 8: 711–717, 2002.
67. **Mead J.** Measurement of inertia of the lungs at increased ambient pressure. *J Appl Physiol* 9: 208–212, 1956.
68. **Miyamoto Y, Niizeki K.** Ventilatory responses during incremental exercise in men under hyperoxic conditions. *Jpn J Physiol* 45: 59–68, 1995.
69. **Miyamura M, Folgering HT, Binkhorst RA, Smolders FD.** Ventilatory response to CO_2 at rest and during positive and negative work in normoxia and hyperoxia. *Pflügers Arch* 364: 7–15, 1976.
70. **Morrison JB, Florio JT, Butt WS.** The effect of insensitivity to carbon dioxide on the respiratory response to exercise at 4 ATA. *R Naval Physiol Lab Rep* 2/76, January 1976.
71. **Morrison JB, Florio JT, Butt WS.** Effects of CO_2 insensitivity and respiratory pattern on respiration in divers. *Undersea Biomed Res* 8: 209–217, 1981.
72. **Morrison JB, Taylor NA.** Measurement of static and dynamic pulmonary work during pressure breathing. *Undersea Biomed Res* 17: 453–467, 1990.
73. **Mulkey DK, Henderson RA, 3rd Putnam RW, Dean JB.** Hyperbaric oxygen and chemical oxidants stimulate CO_2/H^+-sensitive neurons in rat brain stem slices. *J Appl Physiol* 95: 910–921, 2003.
74. **Mummery HJ, Stolp BW, Dear GdL, Doar PO, Natoli MJ, Boso AE, Archibald JD, Hobbs GW, El-Moalem HE, Moon RE.** Effects of age and exercise on physiological dead space during simulated dives at 2.8 ATA. *J Appl Physiol* 94: 507–517, 2003.
75. **Norfleet WT, Hickey DD, Lundgren CE.** A comparison of respiratory function in divers breathing with a mouthpiece or a full face mask. *Undersea Biomed Res* 14: 503–526, 1987.
76. **Otis AB, Fenn WO, Rahn H.** Mechanics of breathing in man. *J Appl Physiol* 2: 592–607, 1950.
77. **Paiva M, Engel LA.** Theoretical studies of gas mixing and ventilation distribution in the lung. *Physiol Rev* 67: 750–796, 1987.
78. **Pedersen MEF, Fatemian M, Robbins PA.** Identification of fast and slow ventilatory responses to carbon dioxide under hypoxic and hyperoxic conditions in humans. *J Physiol* 521: 273–287, 1999.
79. **Pedley TJ, Sudlow MF, Milic-Emili J.** A non-linear theory of the distribution of pulmonary ventilation. *Respir Physiol* 15: 1–38, 1972.
80. **Pendergast DR, Lindholm P, Wylegala J, Warkander D, Lundgren CE.** Effects of respiratory muscle training on respiratory CO_2 sensitivity in SCUBA divers. *Undersea Hyperb Med* 33: 447–453, 2006.
81. **Peterson RE, Wright WB.** Pulmonary mechanical functions in man breathing dense gas mixtures at high ambient pressures-Predictive Studies III. In: *Underwater Physiology V: Proceedings of the Fifth Symposium on Underwater Physiology*, edited by Lambertsen CJ. Bethesda, MD: FASEB, 1976, p. 67–77.
82. **Pirnay F, Marechal R, Dujardin R, Lamy M, Deroanne R, Petit JM.** Exercise during hyperoxia and hyperbaric oxygenation. *Int Z Angew Physiol* 31: 259–268, 1973.
83. **Prefaut C, Dubois F, Roussos C, Amaral-Marques R, Macklem PT, Ruff F.** Influence of immersion to the neck in water on airway closure and distribution of perfusion in man. *Respir Physiol* 37: 312–323, 1979.
84. **Prefaut C, Ramonatxo M, Boyer R, Chardon G.** Human gas exchange during water immersion. *Respir Physiol* 34: 307–318, 1978.
85. **Ray AD, Pendergast DR, Lundgren CE.** Respiratory muscle training improves swimming endurance at depth. *Undersea Hyperb Med* 35: 185–196, 2008.
86. **Reeves RB, Morin RA.** Pressure increases oxygen affinity of whole blood and erythrocyte suspensions. *J Appl Physiol* 61: 486–494, 1986.
87. **Robertson CHJ, Engle CM, Bradley ME.** Lung volumes in man immersed to the neck: dilution and plethysmographic techniques. *J Appl Physiol* 44: 679–682, 1978.
88. **Sahn SA, Zwillich CW, Dick N, McCullough RE, Lakshminarayan S, Weil JV.** Variability of ventilatory responses to hypoxia and hypercapnia. *J Appl Physiol* 43: 1019–1025, 1977.
89. **Saltzman HA, Salzano JV, Blenkarn GD, Kylstra JA.** Effects of pressure on ventilation and gas exchange in man. *J Appl Physiol* 30: 443–449, 1971.
90. **Salzano J, Rausch DC, Saltzman HA.** Cardiorespiratory responses to exercise at a simulated seawater depth of 1,000 feet. *J Appl Physiol* 28: 34–41, 1970.
91. **Salzano JV, Camporesi EM, Stolp BW, Moon RE.** Physiological responses to exercise at 47 and 66 ATA. *J Appl Physiol* 57: 1055–1068, 1984.
92. **Sapoval B, Filoche M, Weibel ER.** Smaller is better–but not too small: a physical scale for the design of the mammalian pulmonary acinus. *Proc Natl Acad Sci USA* 99: 10411–10416, 2002.
93. **Sherman D, Eilender E, Shefer A, Kerem D.** Ventilatory and occlusion-pressure responses to hypercapnia in divers and non-divers. *Undersea Biomed Res* 7: 61–74, 1980.
94. **Shupak A, Guralnik L, Keynan Y, Yanir Y, Adir Y.** Pulmonary edema following closed-circuit oxygen diving and strenuous swimming. *Aviat Space Environ Med* 74: 1201–1204, 2003.
95. **Shupak A, Weiler-Ravell D, Adir Y, Daskalovic YI, Ramon Y, Kerem D.** Pulmonary oedema induced by strenuous swimming: a field study. *Respir Physiol* 121: 25–31, 2000.
96. **Slade JB Jr, Hattori T, Ray CS, Bove AA, Cianci P.** Pulmonary edema associated with scuba diving: case reports and review. *Chest* 120: 1686–1694, 2001.

97. **Slutsky AS.** Gas mixing by cardiogenic oscillations: a theoretical quantitative analysis. *J Appl Physiol* 51: 1287–1293, 1981.
98. **Smith RM, Hong SK, Dressendorfer RH, Dwyer HJ, Hayashi E, Yelverton C.** Hana Kai II: a 17-day dry saturation dive at 18.6 ATA. IV. Cardiopulmonary functions. *Undersea Biomed Res* 4: 267–281, 1977.
99. **Spaur WH, Raymond LW, Knott MM, Crothers JC, Braithwaite WR, Thalmann ED, Uddin DF.** Dyspnea in divers at 49.5 ATA: mechanical, not chemical in origin. *Undersea Biomed Res* 4: 183–198, 1977.
100. **Stolp BW, Moon RE, Salzano JV, Camporesi EM.** 2,3 DPG levels during saturation diving to 650 msw (Abstract). *Undersea Biomed Res* 12, *Suppl*: 21, 1985.
101. **Stolp BW, Moon RE, Salzano JV, Camporesi EM.** P-50 in divers decompressing from 650 msw. In: *Underwater Physiology VIII: Proceedings of the Eighth Symposium on Underwater Physiology*, edited by Bachrach AJ and Matzen MM. Bethesda, MD: Undersea Medical Society, 1984, p. 315–326.
102. **Tabakin BS, Hanson JS.** Response to ventilatory obstruction during steady-state exercise. *J Appl Physiol* 15: 579–582, 1960.
103. **Taunton JE, Banister EW, Patrick TR, Oforsagd P, Duncan WR.** Physical work capacity in hyperbaric environments and conditions of hyperoxia. *J Appl Physiol* 28: 421–427, 1970.
104. **Taylor NA, Morrison JB.** Effects of breathing-gas pressure on pulmonary function and work capacity during immersion. *Undersea Biomed Res* 17: 413–428, 1990.
105. **Taylor NA, Morrison JB.** Static and dynamic pulmonary compliance during upright immersion. *Acta Physiol Scand* 149: 413–417, 1993.
106. **Taylor NA, Morrison JB.** Static respiratory muscle work during immersion with positive and negative respiratory loading. *J Appl Physiol* 87: 1397–1403, 1999.
107. **Thalmann ED, Sponholtz DK, Lundgren CE.** Effects of immersion and static lung loading on submerged exercise at depth. *Undersea Biomed Res* 6: 259–290, 1979.
108. **Thorsen E, Hjelle J, Segadal K, Gulsvik A.** Exercise tolerance and pulmonary gas exchange after deep saturation dives. *J Appl Physiol* 68: 1809–1814, 1990.
109. **Thorsen E, Segadal K, Kambestad BK.** Mechanisms of reduced pulmonary function after a saturation dive. *Eur Respir J* 7: 4–10, 1994.
110. **Thorsen E, Segadal K, Reed JW, Elliott C, Gulsvik A, Hjelle JO.** Contribution of hyperoxia to reduced pulmonary function after deep saturation dives. *J Appl Physiol* 75: 657–662, 1993.
111. **Thorsen E, Skogstad M, Reed JW.** Subacute effects of inspiratory resistive loading and head-out water immersion on pulmonary function. *Undersea Hyperb Med* 26: 137–141, 1999.
112. **Van Liew HD, Thalmann ED, Sponholtz DK.** Diffusion-dependence of pulmonary gas mixing at 5.5 and 95 ATA. *Undersea Biomed Res* 6: 251–258, 1979.
113. **Van Liew HD, Thalmann ED, Sponholtz DK.** Hindrance to diffusive gas mixing in the lung in hyperbaric environments. *J Appl Physiol* 51: 243–247, 1981.
114. **Vorosmarti J, Bradley ME, Anthonisen NR.** The effects of increased gas density on pulmonary mechanics. *Undersea Biomed Res* 2: 1–10, 1975.
115. **Wagner PD.** Insensitivity of $\dot{V}O_{2max}$ to hemoglobin-P50 as sea level and altitude. *Respir Physiol* 107: 205–212, 1997.
116. **Wagner PD, Laravuso RB, Uhl R, West JB.** Continuous distributions of ventilation-perfusion ratios in normal subjects breathing air and 100 percent O_2. *J Clin Invest* 54: 54–68, 1974.
117. **Warkander DE, Nagasawa GK, Lundgren CE.** Effects of inspiratory and expiratory resistance in divers' breathing apparatus. *Undersea Hyperb Med* 28: 63–73, 2001.
118. **Warkander DE, Norfleet WT, Nagasawa GK, Lundgren CE.** CO2 retention with minimal symptoms but severe dysfunction during wet simulated dives to 6.8 atm abs. *Undersea Biomed Res* 17: 515–523, 1990.
119. **Warkander DE, Norfleet WT, Nagasawa GK, Lundgren CE.** Physiologically and subjectively acceptable breathing resistance in divers' breathing gear. *Undersea Biomed Res* 19: 427–445, 1992.
120. **Weibel ER, Sapoval B, Filoche M.** Design of peripheral airways for efficient gas exchange. *Respir Physiol Neurobiol* 148: 3–21, 2005.
121. **Weiler-Ravell D, Shupak A, Goldenberg I, Halpern P, Shoshani O, Hirschhorn G, Margulis A.** Pulmonary oedema and haemoptysis induced by strenuous swimming. *BMJ* 311: 361–362, 1995.
122. **Whalen R, Saltzman H, Holloway D, McIntosh HD, Sieker HO, Brown IW Jr.** Cardiovascular and blood gas responses to hyperbaric oxygenation. *Am J Cardiol* 15: 638–646, 1965.
123. **Wilmshurst PT, Nuri M, Crowther A, Webb-Peploe MM.** Cold-induced pulmonary oedema in scuba divers and swimmers and subsequent development of hypertension. *Lancet* 1: 62–65, 1989.
124. **Wilson BA, Welch HG, Liles JN.** Effects of hyperoxic gas mixtures on energy metabolism during prolonged work. *J Appl Physiol* 39: 267–271, 1975.
125. **Wood LD, Bryan AC.** Effect of increased ambient pressure on flow-volume curve of the lung. *J Appl Physiol* 27: 4–8, 1969.
126. **Wood LD, Bryan AC.** Exercise ventilatory mechanics at increased ambient pressure. *J Appl Physiol* 44: 231–237, 1978.
127. **Wood LD, Bryan AC, Bau SK, Weng TR, Levison H.** Effect of increased gas density on pulmonary gas exchange in man. *J Appl Physiol* 41: 206–210, 1976.
128. **Wood WB.** Ventilatory dynamics under hyperbaric states. In: *Proceedings of the Second Symposium on Underwater Physiology*, edited by Lambertsen CJ, Greenbaum LJ, Jr. Washington, DC: National Academy of Sciences-National Research Council (Publication 1181), 1963, p. 108–123.
129. **Wright WB, Crothers JR.** Effects of immersion and high pressures on pulmonary mechanical functions in man (Abstract). In: *Proceedings of the Aerospace Medical Association Annual Scientific Meeting*. Aerospace Medical Association, 1973, p. 39.
130. **Wylegala JA, Pendergast DR, Gosselin LE, Warkander DE, Lundgren CE.** Respiratory muscle training improves swimming endurance in divers. *Eur J Appl Physiol* 99: 393–404, 2007.
131. **Yang QH, Kaplowitz MR, Lai-Fook SJ.** Regional variations in lung expansion in rabbits: prone vs supine positions. *J Appl Physiol* 67: 1371–1376, 1989.
132. **Zechman F, Hall FG, Hull WE.** Effects of graded resistance to tracheal air flow in man. *J Appl Physiol* 10: 356–362, 1957.