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Breathing at Depth: Physiologic and Clinical Aspects of Diving while Breathing Compressed Gas

Kay Tetzlaff, MD[a,*], Einar Thorsen, MD, PhD[b]

[a]*Department of Sports Medicine, Medical Clinic and Polyclinic, University of Tübingen, Silcherstrasse 5, 72076 Tübingen, Germany*
[b]*Department of Hyperbaric Medicine, Haukeland University Hospital, University of Bergen, 5021 Bergen, Norway*

When diving, human beings are exposed to hazards that are unique to the hyperbaric underwater environment and the physical behavior of gases at higher ambient pressure. Hypercapnia, hyperoxia, carbon monoxide intoxication, inert gas (predominantly nitrogen) narcosis, and decompression illness (DCI) all may lead to impaired consciousness, with a high risk of drowning in this nonrespirable environment. Proper physiologic function and adaptation of the respiratory system are of the utmost importance to minimize the risks associated with compressed gas diving. This article provides an introduction to the diving techniques, the physics, and the pertinent human physiology and pathophysiology associated with this extreme environment. The causes of the major medical problems encountered in diving are described, with an emphasis on the underlying respiratory physiology.

Methods of diving

Diving has become a popular recreational activity and is no longer restricted to military and commercial underwater operations. Although the number of recreational divers is still increasing, the number of professional divers has been more or less the same over the last few decades. It was estimated by the American National Sporting Goods Association [1] that recreational diving ranks third among the fastest growing outdoor activities and that approximately 2.1 million Americans were engaged in this activity in 2001.

Several methods of underwater diving exist. Diving from submerged air-filled diving bells and diving with air supplied from the surface via an umbilical cord allowing a free flow of gas into a diving helmet have been in use from the early nineteenth century. Problems encountered with diving, including decompression sickness (DCS) and barotrauma, were well known early in the twentieth century. The breakthrough for underwater exploration was the development of the open-circuit breathing apparatus by Cousteau and Gagnan in the French Navy in 1943. This self-contained underwater breathing apparatus (scuba) allowed the diver to breathe air supplied from a high-pressure tank carried by the diver and delivered through a pressure regulator that accommodated the changing ambient pressure of the diving environment. This system provided divers with previously unknown freedom and mobility under water.

With bounce diving (where the diver starts the dive from the surface using scuba equipment, spending a limited time at depth before returning to the surface), the exposure to bottom pressure is limited to minimize decompression stress and the risk of DCI. When breathing air, the practical limit is at a pressure corresponding to a depth of 50–60 m of sea water (msw). The narcotic effects of nitrogen, the high gas density, and the decompression stress all contribute to adverse effects on the body beyond that depth range. Some of these effects can be reduced by changing the breathing gas mixture. Mixtures enriched with oxy-

* Corresponding author.
E-mail address: Kay.Tetzlaff@bc.boehringer-ingelheim.com (K. Tetzlaff).

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gen reduce the uptake of inert gas and thereby reduce the risks of decompression, whereas mixtures using added helium reduce the gas density. Increasing the oxygen faction in the gas mixture increases the risk of toxic oxygen effects. Most dangerous is the risk of cerebral oxygen toxicity with sudden unconsciousness, and seizures can occur with exposure to partial pressures of oxygen higher than 150 kPa. Because of the risk of hyperoxic cerebral toxicity, military combat divers who are diving using pure oxygen in a closed-circuit breathing apparatus usually restrict their diving depth range to 0–10 msw.

For diving operations of long duration and deeper than 50–60 msw, the technique of saturation diving was developed in the period from 1960 to 1980. The divers undergo compression in hyperbaric chambers to a pressure equivalent to the diving depth, and they are transferred to the work site in a diving bell. Their body tissues are allowed to become saturated with the gas mixture, which usually is a mixture of helium and oxygen, with a partial pressure of oxygen in the range of 35–70 kPa. Theoretically, they can stay under pressure for an infinite length of time. Most commonly, periods up to 2 weeks are used in diving operations on the offshore oil and gas fields. The divers' effective working time at the work site is not limited by the time constraints of bounce diving. Routine saturation diving operations are typically restricted to depths of 100–150 msw, although an experimental saturation dive to a maximal depth of 701 msw has been performed. In the depth range deeper than 250 msw, there may arise problems, with the pressure effect causing high-pressure nervous syndrome.

The decompression procedures with saturation dives must take into account that body tissues are saturated with the inert gases and the rate of decompression is limited to 25–30 m/d, meaning that some saturation diving operations require that divers stay and live in the hyperbaric chambers for periods up to 30 days or more. Most of the time, the diver is in a dry environment in the hyperbaric chamber, and some operations, such as welding in dry habitats, can be undertaken without the diver having been submerged at all when the diver is transferred from the diving bell to the habitat directly.

Physical and physiologic factors affecting lung function during diving

Diving exposure

Diving is associated with exposure to higher than normal ambient pressure. A dive is typically characterized by compression, isobaric, and decompression phases. The major difference between the diving described in this article and breath-hold diving is that a gas mixture is breathed at increased ambient pressure freely in the atmosphere of a diving bell or a hyperbaric chamber or supplied by an underwater breathing apparatus. Diving usually takes place submerged in water, but some diving operations can be done in a dry environment in a hyperbaric chamber or underwater habitat.

Normal atmospheric pressure or one atmosphere absolute is equivalent to the pressure of a column of 760 mm Hg or 101.3 kPa. One bar corresponds to a pressure of 750 mm Hg, 100 kPa, or 10 msw. For example, at a depth of 30 msw, the diver is exposed to a pressure of 4 bars, and at 100 msw, the diver is exposed to a pressure equivalent of 11 bars.

The fractional concentrations of each gas in a mixture of ideal gases remain the same independent of pressure, and the partial pressure of each component gas is dependent on its fractional concentration and total pressure. The fractional concentration of oxygen in air is 0.21, and at normal atmospheric pressure, the partial pressure of oxygen is 21 kPa. At an ambient pressure of 4 bars or a depth of 30 msw, the fractional concentration of oxygen is still 0.21 but the partial pressure is 84 kPa.

Gases dissolve in fluids proportionately with their partial pressures in the gas phase, which means that the volume of dissolved gases in blood and tissues increases until equilibrium with the gas phase is achieved. The fluid is then saturated with the gas. During the compression and decompression phases of a dive, this process follows first-order exponential functions, with each tissue having its characteristic time constant.

Exposure to factors associated with pressure and gas mixture, such as hyperoxia, decompression stress, and gas density, are known to have acute effects on pulmonary function that may limit ventilatory capacity and exercise tolerance. The effects of hyperoxia and decompression stress may even be toxic or harmful, resulting in acute inflammatory reactions and disease, and possibly long-term residual effects. Other factors associated with the equipment used and the environment in which the diving takes place may impose additional physiologic limitations of the divers' performance.

Hyperoxia

The toxic effects of oxygen on the lung are well known and the dose-response relation and pulmonary tolerance limits have been settled as far as changes in

vital capacity (VC) are concerned [2]. Above a threshold of 50 kPa, there is a reduction in VC dependent on the pressure of oxygen and exposure time. The asymptotic threshold was found to be somewhat lower than 50 kPa [3], and the threshold is definitely lower for changes in lung function variables other than VC. After some saturation dives in which the partial pressure of oxygen has been at or lower than 50 kPa for periods of up to 4 weeks [4,5] and after exposures in which no changes in VC were predicted or demonstrated, there have been reductions in transfer factor for carbon monoxide (Tl_{CO}) and maximal expiratory flow rates at low lung volumes as well as an increase in the slope of phase III of the single breath nitrogen washout test [6].

The toxic effects of oxygen are mediated by reactive oxygen species, and inflammatory changes in the lung parenchyma are induced [7]. First, this process gives rise to symptoms of nonproductive coughing and a retrosternal burning sensation before a reduction in VC takes place. The recovery of VC reductions as large as 20%–30% is usually complete within 1 or 2 weeks.

The toxic effects of oxygen must be accounted for in practical diving and hyperbaric treatment procedures. The unit pulmonary toxic dose (UPTD) is the toxic effect equivalent to the exposure to oxygen at 101 kPa for 1 minute [2]. For a given reduction in VC to take place, there is a hyperbolic relation between the exposure time and partial pressure of oxygen. A dose of 615 UPTDs results in an average 2% decrease in VC, and a dose of 1425 UPTDs results in a 10% decrease. For operational diving activity, a 2% decrease in VC is generally considered acceptable, and for recompression and hyperbaric oxygen therapy for DCI and arterial gas embolism (AGE), a 10% or even larger decrease in VC may be accepted.

Decompression stress and venous gas microembolism

In the decompression phase, blood and tissues are supersaturated with the inert gas of the atmosphere. This provides the pressure gradient for diffusion of gas out of the fluid, but supersaturated fluids are inherently unstable and there is a risk of free gas evolving in gas bubbles. Gas bubbles can form interstitially in the tissues or, probably more commonly, intravascularly in venous blood. Because of the unloading of inert gas in the lung during the decompression phase, bubbles do not form and grow in the arterial circulation. Bubbles can, however, obtain access to the arterial circulation if the pulmonary capillary bed in which the venous bubbles lodge is bypassed. These right-to-left shunts can occur as intracardiac shunts or as intrapulmonary arteriovenous malformations and can contribute to AGE (discussed elsewhere in this article).

By controlled infusion of gas bubbles in the venous circulation in sheep, there is an immediate increase in pulmonary arterial pressure and disturbances in gas exchange function consistent with the mechanical effects of microembolization [8]. Some hours later, there is increased fluid transport across the capillaries, with increased protein content in the lymphatic fluid indicating damage to the capillary endothelium [9]. Inflammatory processes mediated by activated leukocytes contribute to this endothelial damage [10]. A large increase in pulmonary arterial pressure, which can be a result of a large shower of venous gas microemboli (VGM), may facilitate spillover of gas bubbles to the pulmonary veins [11].

VGM are frequently detected by Doppler ultrasound monitoring. They are commonly observed with generally accepted decompression procedures but do not necessarily cause clinical DCS.

Immediately after air bounce dives [12,13] and saturation dives in which VGM were demonstrated during and after the decompression phase, reductions in Tl_{CO} and maximal oxygen uptake correlating with the cumulative load of VGM have been demonstrated.

Gas density and respiratory mechanical loading

For a given gas mixture, density increases proportionately with pressure. Airway resistance is proportional to density with turbulent flow characteristics, and maximal expiratory flow rate is inversely proportional to the square root gas density, which has been shown experimentally for maximal voluntary ventilation and forced expiratory volume in 1 second (FEV_1) as well [14]. When breathing air at a pressure of 4 bars, corresponding to a depth of 30 msw, the gas density is four times normal and maximum voluntary volume (MVV) and FEV_1 are reduced by 50% of normal. The ventilatory capacity is then limiting exercise performance. Because of the increased partial pressure of oxygen in the breathing gas and some carbon dioxide retention, however, tolerated peak oxygen uptake is not significantly reduced in healthy fit subjects.

To reduce the internal resistance of breathing gas mixtures, helium is usually used instead of air when diving deeper than 50–60 msw when saturation diving techniques are preferred. Even hydrogen has been used experimentally but is associated with problems because of its narcotic effects and the danger of fire.

Gas transport in alveoli is by diffusion. The helium and oxygen mixture breathed in deep experimental saturation dives to pressures corresponding to depths of 500–700 msw has a fractional concentration of oxygen of less than 2%, with the rest being helium and, sometimes, some nitrogen. The density can be as high as 8–10 times that of air at atmospheric pressure. There is some alveolar-capillary diffusion limitation of oxygen in this low fraction of inspired oxygen (F_{IO_2}) environment contributing to pulmonary gas exchange limitation in deep diving [15]. Within the depths accessible with today's diving techniques, however, this effect is small and is estimated to depress alveolar oxygen pressure by a few kilopascal only.

Resistance to breathing is further increased by an external breathing apparatus and the effects of static lung loading attributable to submersion. The combination of increased internal and external breathing resistances and static lung loading may facilitate the development of lung edema associated with diving and swimming, particularly in a cold environment and with high exercise intensity [16,17].

Respiratory heat and water loss

Inhaled gas is heated and humidified during its passage through the airways. The energy required to heat the gas is dependent on the physical characteristics of the gas mixture, including temperature, density, and specific heat as well as the physiologic requirement for ventilation. Some of the energy used for heating the inspired gas is recovered in the upper airways during exhalation. The mean temperature of exhaled gas is normally lower than body temperature but higher than ambient temperature. The energy required to humidify the gas is assumed to be independent of pressure, but gas mixtures used for diving are dry so as to prevent icing in the gas supply lines. The specific heat capacity for helium is five times greater than for nitrogen, 5.19 and 1.04 $J/g^{-1}/K^{-1}$, but density is only 0.18 g/L^{-1} for helium and 1.25 g/L^{-1} for nitrogen. Therefore, the respiratory heat loss when diving with air remains higher compared with diving with helium-oxygen mixtures, because it is the product of density and specific heat capacity that determines heat loss. The respiratory heat loss when diving is always larger than at normal atmospheric pressure whatever the gas mixture is, however, and the heat loss as well as the water loss for gas humidification may induce a bronchomotor response [18–20].

The thermal problems related to saturation diving with helium and oxygen gas mixtures are mainly attributable to the increased heat loss over the skin surface in the dry helium oxygen environment, which is a function of heat conductance rather than heat capacity. Heat conductance for helium is 1.51 $W/m^{-1}/K^{-1}$, and for nitrogen, it is 0.26 $W/m^{-1}/K^{-1}$. The range of comfortable temperatures in this environment is usually 27°C–29°C compared with 20°C–22°C in air at atmospheric pressure.

Respiratory effects of single dives

Immediately after dives, changes in pulmonary function can be demonstrated that are the combined effects of all the specific exposure factors associated with the dive. After deep saturation dives to depths of 300 m or more, a reduction in Tl_{CO} of 10%–15% and reduced maximal oxygen uptake have been consistently demonstrated in several studies [21–23]. Exposures to hyperoxia and VGM have been shown to contribute to these effects [4,5,12,13]. Any reduction in VC as a result of oxygen toxicity has, however, not been demonstrated. On the contrary, a small increase in VC has been seen after some dives. This could be caused by the opposing effects of hyperoxia and respiratory muscle training attributable to the effects of increased gas density. The recovery time for the changes in Tl_{CO} is 4–6 weeks.

After short air bounce dives, small reductions in Tl_{CO} and VC as well as a decrease in airway conductance have also been demonstrated [24,25], but the recovery time after these dives of a short duration (ie, hours) compared with days in saturation is much shorter, only 1–2 days. In these dives, the effects of submergence and static lung loading as well as the effects of respiratory heat and water loss are believed to contribute significantly to the changes in lung function.

Clinical problems

The important clinical problems encountered in diving medicine are listed in Box 1, and are described and discussed here.

Pulmonary barotrauma

Although the lung can withstand considerably high absolute ambient pressures without harm, exposure to abrupt changes in pressure may severely affect the lung at even small pressure differences. The

Box 1. Major clinical problems associated with diving

A. Pulmonary barotrauma
Pneumothorax
Interstitial emphysema
Pneumomediastinum
Pneumoperitoneum
B. DCI
AGE
DCS
- Cutaneous
- Musculoskeletal
- Audiovestibular
- Respiratory disease
- Venous gas embolism
- Paradoxic gas embolism

C. Pulmonary edema

term "pulmonary barotraumas" (PBTs) refers to lung injury that is induced by a change in intrapulmonary pressure relative to ambient pressure. Astronauts, aviators, compressed air workers, and divers are inherently exposed to rapid changes in ambient pressure and are thus at risk of PBT. The following section focuses on diving-related PBTs, which is a feared complication of compressed gas diving and consistently ranks second among all causes for scuba diving fatalities after drowning [26].

Definition and mechanisms

Diving-related PBT may occur during the descent of a breath-hold dive when intrathoracic gas volume falls short of residual volume and intrathoracic pressure becomes negative relative to hydrostatic pressure. This complication, also known as lung squeeze, is rare [27].

PBT during the ascent from a scuba dive, however, is defined as lung rupture that occurs during decompression when ambient pressure decreases [28]. According to Boyle's law, the volume of an enclosed gas expands with decreasing pressure. Expanding intrapulmonary gas during the ascent from a scuba dive eventually must be exhaled properly. If the rate of decrease in pressure during the ascent exceeds the rate at which the expanding gas can escape through the airways, overdistension of the alveoli and bronchi may cause lung rupture. Closure of the upper airways by, for example, breath-holding, airway obstruction attributable to pulmonary pathologic changes, or both, may precipitate this pathophysiology [28]. Unprotected dogs with a closed trachea that were rapidly decompressed from ambient pressures of 306.3 or 612.6 kPa, equivalent to depths of approximately 31 and 62 msw, developed PBT when the intratracheal pressure reached a critical level of approximately 10.7 kPa (80 mm Hg) [29]. This could be prevented by the application of thoracoabdominal binders, despite a rise in intratracheal pressure to levels of 24 kPa (180 mm Hg). Accordingly, experiments with fresh unchilled human cadavers showed that lung barotrauma occurred at intrapulmonary pressures of approximately 9.7–10.7 kPa (73–80 mm Hg) [30]. Binding of the chest and abdomen required much higher pressures of 17.7–25.3 kPa (133–190 mm Hg). It was further observed that rupture of the visceral pleura occurred when basal pleural adhesions were present. Thus, the transpulmonary pressure (ie, the difference between intratracheal and intrapleural pressure) is the critical factor for the development of PBT rather than the absolute level of the intratracheal pressure.

Intrapulmonary air trapping during ascent may occur in any particular region of the lung. Localized overdistension of the lung then results in rising local transpulmonary pressure with subsequent rupture of the alveolar wall [31]. Once rupture occurs, gas is sucked into the peribronchial space and causes pulmonary interstitial emphysema [29]. Gas may track into the tissues by the mechanics of breathing and cause pneumomediastinum with emphysema of the neck. Alternatively, it may dissect toward the lung periphery, rupturing via subpleural blebs into the pleural space, causing pneumothorax, or mediastinal gas may rupture the mediastinal pleura and enter the pleural space. The latter mechanism is supported by observations from experimental animal studies showing that the mediastinum contained dissecting gas in all cases in which there was pneumothorax [29]. Moreover, extra-alveolar gas may pass the diaphragm through the esophageal hiatus into the peritoneal cavity and cause pneumoperitoneum [32,33].

Gas may also track along the perivascular sheaths of the pulmonary arteries and erupt into such an artery or move toward the hilum on expiration and dissect into the thin-walled pulmonary veins. In consequence, the gas may then rapidly enter the systemic circulation and cause AGE, a clinical condition that is associated with high morbidity and mortality [34]. A pressure gradient between the air passages and the left atrium in excess of 8 kPa (60 mm Hg) has been found to enable the transfer of gas into the vasculature [29]. If gas has entered the left side of the heart via the pulmonary veins, it may be distributed into

Table 1
Systematic studies that reported clinical and radiologic evidence of pulmonary barotraumas in case series of divers/submarine escape trainees suffering from PBT with or without arterial gas embolism

First author, year [reference]	No. of subjects	PBT	AGE	Combined PBT/AGE
Elliott, 1978 [71][a]	88	N/A	9	79
Kizer, 1987 [58][b]	42	N/A	1	41
Leitch, 1986 [60]	140	23	59	58
Harker, 1993 [64][b]	31	N/A	15	16
Tetzlaff, 1997 [59]	15	2	10	3

Abbreviation: N/A, not applicable.
[a] Only submarine escape trainees included.
[b] Only divers with clinical diagnosis of AGE included.

nearly all organs, causing embolic occlusion of end arteries. Head position during ascent in relation to the torso, buoyancy of the gas bubbles, and blood flow dynamics favors the distribution of gas bubbles to the brain. Because of the extremely short hypoxia tolerance of the central nervous system, critical injury may occur depending on the absolute quantity of gas and the areas affected. Small gas bubbles may rapidly be absorbed and only briefly interrupt blood flow. Larger gas bubbles, however, may cause severe harm by ischemic cell injury and disruption of the blood-brain barrier. Immediate pathologic changes are characterized by a rise in cerebrospinal fluid pressure, systemic hypertension, cessation of neuronal activity, and changes in vascular permeability [35]. Cellular and humoral responses induced by the effects of gas-blood as well as gas-endothelial interfaces contribute to inflammation that is maintained even after absorption of the gas [34].

In contrast to PBT induced by mechanical ventilation [36], AGE is the most frequent sequel to diving-related PBT (Table 1). The direction and amount of transpulmonary pressure generated by rapid decompression during diving may account for this distinct feature. Often, AGE is combined with pneumomediastinum (Fig. 1), and severe cases of PBT have been reported in which the gas had tracked into the vasculature causing AGE into pleural spaces and the mediastinum [37,38]. In fatal cases of PBT, death may result from obstruction of the heart (pneumocardium) and central circulation after massive AGE [39–41]. The detailed pathophysiologic changes causing death in human beings, however, are not yet entirely understood [40].

PBT may also occur with the use of breathing gases other than air. There are two case reports of PBT with and without AGE in divers using a closed-circuit oxygen rebreathing diving apparatus. Remarkably, the highly elevated oxygen fraction may have accelerated the resorption of extra-alveolar gas in these cases, where symptoms were reported to have resolved rapidly [42,43].

Because of the common misapprehension that diving accidents do not occur in shallow water, it is worth mentioning that the risk for PBT is greatest just below the surface, because the ambient pressure doubles between 0 and 10 msw and the relative change in volume is maximal at that depth range. Accordingly, cases of severe AGE have been reported that occurred during shallow water dives of less than 5 msw and even during swimming [44–46].

Decompression-related PBT is not restricted to scuba diving only. It may occur during the ascent of a commercial airplane when the passenger cabin pressure decreases by approximately 26.7 kPa (200 mm Hg) [47] or during hypobaric chamber training performed for military aircrew members throughout the world [48–50]. Cerebral AGE after PBT has been reported in ground maintenance crew members after cabin pressure tests to approximately 55 kPa (413 mm Hg) [51,52]. Few cases have occurred during hyperbaric oxygen therapy in a hyper-

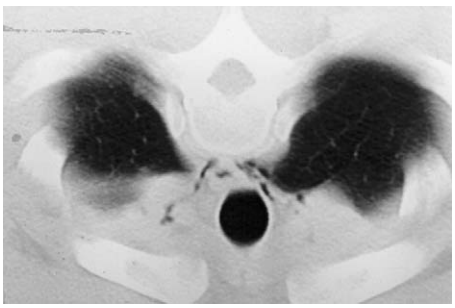

Fig. 1. CT scan of a 23-year-old Navy scuba diver who developed chest pain and nausea while performing free ascent training from a depth of 11 msw. The scan was taken after the first recompression treatment. The chest radiograph was unremarkble. MRI of the neurocranium revealed a large cerebellar infarction.

baric chamber [53–55]. All these exposures have in common the fact that the pressure change during the ascent is of minor magnitude and occurs more slowly when compared with scuba diving ascents. Thus, PBT is infrequent in these occupations. Remarkably, pre-existing lung pathologic findings have been described more often in these cases [47,49,53–55], supporting the concept that air-trapping pulmonary lesions increase the risk of PBT.

Clinical presentation of pulmonary barotrauma

The clinical presentation of diving-related PBT largely depends on feature and localization of injury. Pulmonary symptoms alone may be present in cases with pneumothorax or mediastinal emphysema without concurrent gas embolism. Pneumomediastinum has been detected by chest radiographs in even asymptomatic subjects after buoyant ascents [56]. Hoarseness only or a strange voice with mild chest pain should prompt the physician to consider PBT in the differential diagnosis after scuba dives [43,57]. More prominent pulmonary symptoms reported from larger case series comprised chest discomfort, chest pain or tightness, dyspnea or apnea, and hemoptyses [58–60]. Among these, chest pain and dyspnea were the most frequent and accounted for approximately 25% and 13% of all cases of combined PBT and AGE, respectively.

In most cases, however, neurologic symptoms are present as a consequence of AGE (Table 2). A stroke-like syndrome with unilateral neurologic symptoms has been considered typical for diving-related AGE [28,61]. A less typical presentation with bilateral symptoms may also be seen [62,63]; therefore, AGE is not excluded. Cognitive symptoms and unconsciousness are most frequently present, whereas seizures, focal motor deficits, visual disturbances, vertigo, and sensory changes are also common (see Table 2) [58–60,64,65]. Most importantly, these symptoms appear on or shortly after surfacing within 5 minutes (>90% of cases) [26,59,60]. However, time to onset of symptoms may take longer than 10 minutes [65], and there are case reports with delayed onset after hours up to several days [66,67]. Symptoms generally progress rapidly when not treated, but spontaneous recovery may occur and has been reported even following resuscitation after initial apnea and pulselessness [68]. A small, but important number (approximately 4%) of patients present fatally with immediate unconsciousness and cardiopulmonary arrest [69]. Postmortem radiography in fatal AGE revealed massive gas in cardiac chambers and large thoracic vessels in these cases [39–41,70]. Some fatalities, however, may simply be attributable to drowning subsequent to loss of consciousness under water; thus, the actual incidence of PBT and/or AGE may be underestimated.

Table 2
Most frequent symptoms of arterial gas embolism and pulmonary barotrauma

Symptom	Range (%)
Unconsciousness	17–81
Paraesthesias and/or paralyses	23–77
Dizziness	10–43
Nausea and/or vertigo	9–39
Visual disturbances	13–26
Convulsions	0–31
Headache	0–26

Data from five larger case series published in peer-reviewed literature: Refs. [58–60,64,65].

Risk factors for pulmonary barotrauma

Incident statistics show that the technique of ascent (ie, the decompression procedure that the body is exposed to) is a major risk factor. At depth, the diver inhales gas from the scuba equipment at normal lung volumes. When surfacing from depth during a free ascent (ie, without breathing from the scuba equipment), the expanding gas must be exhaled continuously. Thus, certain diving techniques, such as out-of-air emergency training, buddy-breathing during ascent, or buoyant ascents during submarine escape tank training, pose significantly increased risks to the subjects. Accordingly, reported incidences per number of dives are 0.04%–0.06% for buoyant ascent training [71,72] and 0.005% for military scuba dives [60,73].

Among individual factors contributing to the risk of PBT, conditions that predispose to intrapulmonary air trapping play a major role. An autopsy study on 13 diving fatalities revealed that in the cases with fatal pneumothorax occurring during ascent from depths between 10 and 40 msw, the site of rupture was related to pleural adhesions and lung bullae [74]. Such adhesions were also present in 26% of investigated lungs that were not involved in PBT, however. Poorly ventilated intrapulmonary structures, such as lung bullae or air cysts, may hinder the expanding gas from being exhaled properly or simply be a locus minor resistentiae. Accordingly, flap-valve mechanisms have been described from emphysematous lesions that may support air trapping during expiration [31]. There are case reports of PBT in which plain film radiography revealed evidence of pre-existing large lung cysts [71,75,76] that were considered to be causally related to the injury. Indeed, in one case report of fatal AGE occurring after the

descent of a commercial flight, the rupture of a large pre-existing intrapulmonary air cyst was confirmed by autopsy [47]. More recent studies using CT of the chest [43,77–81] have frequently detected bullae and cysts that had escaped detection by chest radiographs and thus support the hypothesis that in cases of diving-related PBT with normal plain chest radiographs, subtle pre-existing pulmonary lesions may still be potentially implicated in the injury (Fig. 2). Some doubt remains as to whether these bullae detected by postinjury radiology were pre-existing. Their persistence over long-term follow-up may support this assumption [43,62,77].

An analysis of the database of the Royal Navy Institute of Naval Medicine revealed a series of 140 cases of PBT with and without AGE, of which 8% were recurrent incidents [82]. In these cases as well as in another reported case [83], there were no identifiable predisposing findings. A chest CT scan was only available in the latter case, however. We are aware of a 26-year old female diver who asked for consultation after she had suffered twice from unilateral neurologic limb symptoms and nausea after emergency ascents from open water scuba dives within 2 years. Only after the second incident was chest CT was performed, which revealed a subpleural bulla in the right lower lobe [84].

Some studies investigated the idea that PBT might be predictable by means of pulmonary function testing. In a controlled study of 14 divers who had suffered from PBT that was established clinically or by chest radiography, pulmonary conductance and static recoil pressure were measured, on average, 0.8 years after the injury [85]. It was found that a derived index of lung distensibility was significantly decreased in the PBT group compared with 10 healthy divers and 34 healthy controls. The authors postulated that stresses in peribronchial alveolar tissue would be magnified near total lung capacity if bronchi are relatively stiffer. Limitations to that study

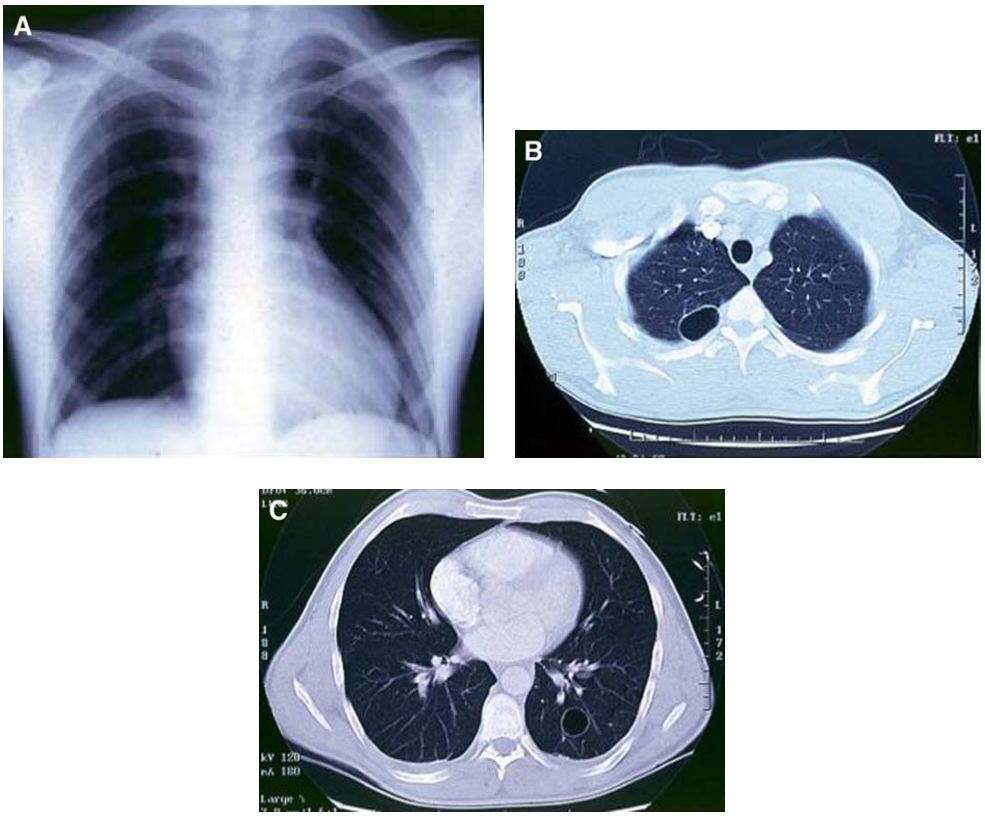

Fig. 2. (*A*) Chest radiograph of a 38-year-old sport scuba diver who complained of sudden leg paralysis and right-sided chest tightness after an uneventful 25-m dive with 20 minutes of bottom time in the Red Sea. The radiograph was taken after the initial treatment for decompression illness and repatriation. Chest CT scan of the same diver shows bilateral lung bullae in the right upper lobe (*B*) and in the left lower lobe (*C*). (Courtesy of Armin Kemmer, MD, Murnau, Germany.)

were the finding of a significant difference in the index of lung distensibility between the control divers and healthy nonsmokers in measurements spanning over a time range of more than 10 years. In a retrospective review of a large series of submarine escape training tank incidents that occurred in the Royal Navy during a 22-year period, there were only six cases in which there was radiologic or clinical evidence of extra-alveolar gas and four additional cases that were considered to be related to PBT for other reasons [86]. Standardized residuals were calculated for FEV_1 and forced vital capacity (FVC) as well as for the quotient of FEV_1/FVC. The authors found significant associations between values of FVC and FEV_1 below those predicted and PBT ($P < .01$ and $P < .05$, respectively) but not for FEV_1/FVC. Surprisingly, these studies revealed some correlation between restrictive lung indices and risk of PBT rather than indices of obstruction. Thus, individuals with small and stiff lungs may be at increased risk of PBT. In another retrospective study of 15 scuba divers who had consecutively suffered from PBT with or without AGE, however, expiratory flows at low lung volumes were found to be less than predicted and significantly less than those values of a control group of divers who had experienced diving injuries other than PBT [59]. Thus, peripheral airflow limitation may have indicated obstructive lung disease in some of these cases. The issue with these latter studies is that the differences from the control populations were rather small (ie, within two times the standard deviation); in fact, there are a large number of subjects diving safely with spirometric indices within that range. In conclusion, there are as yet no convincing data indicating pulmonary function to be predictive for detecting those divers who are at risk of PBT, mostly because of the small samples investigated.

Decompression illness

General features of pathophysiology

Severe injury from scuba diving is predominantly caused by decompression-related pathophysiology. The term ''decompression illness'' has been introduced to encompass those distinct disease entities that may result from tissue damage by excess intracorporeal gas during and after decompression [87]. Included under the broader definition of DCI are AGE, which occurs as a consequence of PBT, and DCS, a multiorgan system disorder that results from micro- or macroscopic nitrogen bubble formation when ambient pressure decreases on surfacing.

As outlined in the section on diving exposure, body tissues become saturated at depth with inert gas molecules as a function of time, the partial pressure of the gas in the breathing mix, and a constant depending on the type of tissue [88]. On ascent from a scuba dive, the sum of tissue gas tensions and vapor pressure may exceed ambient pressure (ie, the body tissues become supersaturated). Dissolved inert gas in the tissue and blood forms a free gas phase to equalize the pressures. Current theories favor the hypothesis that bubbles are predominantly formed by small pre-existing gas nuclei that are commonly contained in body tissues. Spontaneous bubble formation may contribute to this process. Once nucleated, gas bubbles are subject to tissue diffusion and perfusion. The pressure gradient for the partial pressure of the inert gas toward alveolar gas eventually forces the inert gas to leave the tissues. Excess inert gas physiologically reaches the lungs by venous return, where it is trapped in the lung microvasculature and removed by diffusion into the alveolar space [89].

With the introduction of Doppler ultrasound methodology, intravascular gas bubbles have frequently been observed with decompression. Exposure to even mild hyperbaria of 138 kPa ambient pressure (3.8 msw) for 48 hours revealed detectable venous gas emboli a few hours after direct ascent in 20% of asymptomatic subjects, and bubbles were even detectable after 12 hours in subjects who ascended from 4.8 msw [90]. Intravascular gas bubbles are often present in the absence of symptoms after scuba dives [90–93]. These bubbles may elicit acute respiratory responses, such as a decrease in the Tl_{CO} [12,13]. In animal models, intravascular air bubbles have been shown to exert diverse pathophysiologic effects. Hemodynamic changes after venous gas embolism comprised a rise in pulmonary artery pressure and pulmonary vascular resistance and a decrease in arterial oxygen tension [94–96]. Humoral and cellular changes in general concern the activation of the complement system and leukocytes [97,98]. These effects induce proinflammatory cascades that result in hemoconcentration and leakage of the vascular endothelium [9,99]. The magnitude of these changes depends on the amount of venous gas emboli, and smaller bubble numbers are less likely to produce gross hemodynamic or fluid abnormalities. Whether these so-called ''silent bubbles'' cause any long-term effects on the organism is not yet known. Moreover, the factors that determine whether bubble formation becomes pathologic remain to be elucidated.

Clinical features of decompression sickness

The term ''decompression sickness'' refers to a multiorgan system disorder that results from micro- or macroscopic nitrogen bubble formation when

ambient pressure decreases on surfacing. Thus, the presence of these pathologic bubbles per se does not predict the clinical manifestations of DCS but is pivotal for its pathologic diagnosis.

One major clinical presentation of DCS is limited to musculoskeletal or cutaneous symptoms only and is also known commonly by the lay term "the bends." The pathophysiologic basis for these manifestations, which have historically been classified as type I DCS, is still under investigation. It is believed that tendon sheaths or joint capsules may be irritated mechanically by gas bubbles that form within these inhomogeneously perfused tissue compartments. Bubbles may also grow within the bone marrow, causing a rise in intermedullary pressure, or may be delivered by the blood toward these sites. This mechanistic hypothesis is supported by the observation that limb, joint, or muscle pain is immediately responsive to recompression in most cases. The cutaneous manifestation of DCS presents as cutis marmorata with skin itching and rash. In swine, it was shown that the violaceous color of the lesions was presumably attributable to congestion of deeper vessels in the dermis and subcutis, and vascular inflammation was apparent on electron microscopy [100].

More severe DCS historically has been classified as type II and is characterized by neurologic, audiovestibular, or respiratory manifestations. The particular nitrogen saturation and elimination kinetics of neural tissues and their minimal ischemia tolerance favor the development of neurologic symptoms in the presentation of DCS. Neurologic injury is presumed to be attributable to the thrombogenetic effect of venous gas bubbles in the epidural venous plexus surrounding the spinal cord, causing venous stasis and spinal cord ischemia in the thoracic region. There may also be evidence for the in situ generation of so-called "autochthonous bubbles" within the tissue of the spinal cord because of its high solubility for inert gas [101,102]. More recently, however, it was shown in decompressed goats that autochthonous bubbles arise as an artifact and that the nature of the lesion in the spinal cord is a focal infarct or necrosis after events that occurred in local vessels [103]. In swine that underwent a hyperbaric exposure to 612.6 kPa, equivalent to 50 msw, for 24 minutes, 67.2% of animals developed neurologic DCS or died [104]. Histologic examination revealed an association between the hemorrhage within the spinal cord gray matter and increasing disease severity [105]. Brain lesions were present in 23% of pigs, whereas cord lesions, mostly thoracic, were evident in 63% of pigs and in 23% of those clinically unaffected. Using the same animal model for neurologic DCS, another study revealed high rates of microembolic Doppler ultrasound signals in animals that died within 1 hour after a dive [106]. Chest CT performed 20 minutes after a dive showed massive amounts of ectopic gas in the right side of the heart, probably causing death by mechanical outflow obstruction in some of these animals (Fig. 3). In conclusion, these animal experiments confirmed observations from human beings that there is a considerable interindividual range of DCS severity associated with the same decompression stress.

Neurologic DCS may cover a gamut of signs and symptoms depending on localization, the amount of bubbles, and the type of affected tissue. Sensory symptoms, including numbness, tingling, paresthesias, and abnormal sensation, are far more common than more severe neurologic symptoms [26]. Typically, these symptoms develop progressively, beginning with mild paresthesia, followed by regional numbness, weakness, and, occasionally, paresis of the affected limbs. Symptoms usually occur within hours after decompression, but in severe cases, they may present immediately [26]. Thus, a clinical diagnosis of DCS may be difficult to establish, and clinical symptoms may overlap with those of AGE. Furthermore, cases of combined DCS and AGE have been reported [107].

The risk of DCS is considered to be negligible at shallow water depths of 0–10 msw, because the limited gas supply from the scuba equipment prevents the body from a significant inert gas uptake. Beyond that depth, however, the risk proportionally increases with pressure and the time spent at that pressure. The time needed for desaturation on ascent increases accordingly. It has been shown in human beings after

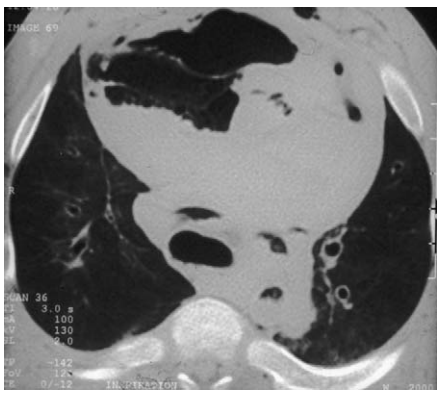

Fig. 3. CT scan of a pig that had been exposed to a hyperbaric chamber depth of 50 msw for 24 minutes. Large amounts of ectopic gas can be seen in the right ventricle.

scuba dives that the presence of intravascular bubbles is correlated with the rate of ascent [91]. In a pig model of DCS, the use of nonlinear ascent profiles with a combined fast/slow ascent was associated with a 30% reduction of the DCS rate [108]. To minimize the risk of DCS, decompression tables and schedules have been established that outline certain gradual decompression profiles. Modern dive computers use algorithms that consider different tissue desaturation kinetics and calculate surface intervals that must be kept before the next dive. Nevertheless, DCS may occur unpredictably even when strictly following decompression requirements. An incidence of 0.003% of "undeserved" DCS (ie, scuba dives with no obvious risk profile) has been reported [73].

There are environmental and individual factors that may place the subject at increased risk. Temperature and exercise influence tissue perfusion and thus may affect the probability of bubble formation. An analysis of accident records of the Royal Navy Institute of Naval Medicine revealed a significant association between the exposure to cold and the occurrence of DCS [109]. Increased pulmonary gas exchange during exercise at depth may be detrimental, because tissues equilibrate more rapidly with increased blood flow. It was recently shown in subjects who performed arm or leg exercise during graded decompression beginning at 9 msw after a 30-minute wet chamber dive at 450 kPa that there were significantly less venous gas bubbles detectable by Doppler ultrasound compared with sedentary control divers [110]. Moreover, in animal models, exercise before diving has been shown to have beneficial effects. In swine, predive exercise conditioning of approximately 20 sessions on a treadmill reduced the rate of DCS by 31% versus that in control animals [111]. Recent data in rats indicate that it is not the aerobic capacity per se but the acute effect of predive exercising that contributes to the risk reduction. Rats that performed a single bout of exercise lasting for 1.5 hours, with 20 hours of rest before the dive, were protected from bubble formation, as were those who had trained regularly for 2 weeks [112]. This effect was recently confirmed in human subjects who underwent two experimental chamber dives to 280 kPa for 80 minutes in a cross-over fashion while performing a single interval exercise 24 hours before one of the dives. There were significantly fewer bubbles and decreased maximum bubble grades detectable after the dives with predive exercise compared with the dives without predive exercise [113]. The reasons for the beneficial effect of a single predive exercise in the rate of diving-related DCS remain speculative. An interesting theory is that the population of gas micronuclei may be depleted by exercise, thus diminishing the chance for gas bubbles to nucleate [114].

Individual factors also contribute to the risk of bubble formation and DCS. Observational studies from diving populations revealed that obesity may be contributory to the occurrence of DCS [115]. In fact, Doppler ultrasound investigations of divers confirmed a significant relation between detected postdive bubble grades and body weight [116]. Moreover, general physical fitness, as indicated by maximal oxygen uptake, does seem to prevent bubble formation in human beings [91]. Age and sex have historically been considered risk factors for DCS [117], but conflicting data have arisen more recently. In a field study monitoring venous gas emboli after recreational open water dives, male and older divers had a higher incidence of high bubble grades by Doppler ultrasound [118]. The investigated divers, however, had a relatively high mean age, and divers were only monitored once. In a retrospective cohort study of recreational diving instructors in Sweden, the incidence of self-reported DCS symptoms among younger divers 18–24 years of age equaled that among those older than 25 years of age [119]. In a survey among recreational divers in the United Kingdom, the physician-confirmed rate of DCS was 0.026% in woman versus 0.016% in men, suggesting a 1.67-fold greater DCS rate in women [120]. When adjusting these rates by diving experience, however, the sex difference became insignificant. The overall DCS rate across male and female divers was 0.02%, which is within the range reported from other sources [26,73,119]. Recent diving accident statistics show a bell-shaped distribution over the complete age range, peaking at the age of 38 years, and the sex distribution of injured divers exactly mirrors the distribution among the total diving population [26]. It is thus less likely that age and sex grossly influence the risk of diving-related DCS.

Remarkably, approximately one quarter of injured divers indicate that they have been exposed to altitude after diving [26], confirming the theoretic concept that further decompression from sea level pressure aggravates bubble formation. A case-control study using recreational dive profiles found that the relative odds of DCS increased with decreased preflight surface intervals [121]. In most divers who developed DCS symptoms during or after the flight, the preflight surface interval was less than 12 hours [26]. This mechanism also applies to those who expose themselves to altitude while driving across mountains after diving. Thus, to be on the safe side, a minimum interval of 24 hours is recommended before flying

when the dive profile did not require decompression stops; otherwise, it should even be longer [122].

Respiratory decompression illness

The respiratory effects of gas bubbles have been well characterized in different animal species. In anesthetized dogs that were decompressed from a 17-minute hyperbaric exposure at 90 msw, pulmonary hypertension, systemic hypotension, hemoconcentration, and hypoxia occurred [123]. Moreover, a decrease in pulmonary compliance but unchanged resistance was measured. Pathologic findings revealed the regular occurrence of pulmonary edema without an elevation of left ventricular end-diastolic pressure. The authors postulated that microvascular permeability was altered by venous bubble emboli formed during decompression. In anesthetized dogs ventilated with oxygen and nitrogen (30%:70% ratio), it was shown that venous gas emboli could remain in the pulmonary vasculature as discrete bubbles for periods lasting up to 43±11 minutes after air infusion at a rate of 0.25 mL/kg^{-1}/min^{-1} and that infused air doses were correlated with bubble residence times [124]. In sheep, it has been shown that the amount of lung microvascular injury could be controlled by the rate of venous gas embolism and was reversible within 1–2 days [99]. In another sheep model of experimental respiratory DCS, animals were exposed to compressed air at 230 kPa for 22 hours, followed by simulated altitude at 76 kPa (570 mm Hg) [125]. In that study, clinical findings were found to be correlated to pathophysiologic changes; an increased mean pulmonary artery pressure after the detection of high precordial bubble grades corresponded with the onset of restlessness, respiratory difficulty, and collapse. Radiography revealed interstitial pulmonary edema in five animals and patchy infiltrates as well as pleural effusions in two. It was concluded that massive embolization of the pulmonary capillary bed precipitates respiratory DCS. These changes are accompanied by impaired endothelial function [126,127] that may be prevented by administration of antibodies to complement factors, such as C5a in rabbits [128].

In diving, however, respiratory DCS is rare, probably because common scuba dive profiles do not exert the significant decompression stress to the lung that is needed for pulmonary manifestations. Clinical symptoms are characterized by increased breathing frequency, cough, cyanosis, and thoracic discomfort or pain. This symptomatology has also been called "the chokes." There is one case report of a 40-year old previously healthy woman who became dyspneic and coughed frothy white sputum immediately after she had made her third dive on the same day [129]. Chest radiography showed bilateral lower lobe airspace consolidation that completely resolved 5 hours after treatment. In contrast to diving, however, incidence of the chokes in altitude DCS has been reported to achieve a rate of 6% [130].

Paradoxic gas embolism

Paradoxic gas embolism may occur when gas that has entered the venous side of the circulation gains access to the systemic arterial circulation. Routes for the transpulmonary passage of venous gas bubbles include the pulmonary capillaries and intra- or extrapulmonary right-to-left shunts.

The lung serves as an excellent filter for microbubbles in the healthy state. Its capacity to effectively filter gas bubbles depends on the size, location, and amount of bubbles trapped in the pulmonary circulation and may be impaired by administration of pulmonary vasodilators, such as aminophylline [131]. The overload threshold of the pulmonary vasculature in dogs could be determined at an infusion rate of 0.3 mL/kg^{-1}/min^{-1} [131]. Higher infusion doses of 0.35 mL/kg^{-1}/min^{-1} resulted in arterial bubbles as detected by Doppler sonography in more than 50% of the dogs. An elevation in pulmonary artery pressure was required before the spillover of venous gas bubbles occurred, with a pressure gradient between pulmonary artery pressure and left atrial pressure of approximately 52 mm Hg [11]. In swine, the breakthrough of bubbles was already apparent at 0.1 mL/kg^{-1}/min^{-1} and occurred in pigs experiencing a substantial reduction in mean arterial pressure and pulmonary artery pressure that had returned to normal at the time of spillover [132]. The time course of changes in mean pulmonary artery pressure in swine after rapid decompression from a 30-minute exposure to 500 kPa was related to the Doppler sonography bubble counts in the pulmonary artery, with a great variation in the degree of bubble formation [133]. In conclusion, these animal models showed that a significant decompression stress is associated with an increased risk of a spillover of venous gas bubbles into the arterial side of the circulation, and the occurrence of arterial gas bubbles seemed to follow the same time course as the venous bubble count in pigs [106,134].

Extrapulmonary right-to-left shunts represent another pathway for paradoxic gas embolism. A patent foramen ovale, as the most common right-to-left shunt, has been demonstrated to be related to otherwise unexplained DCI in divers [135–137]. Normally, the fossa ovalis, a persisting remnant of a physiologic communication between the venous and

arterial sides of the fetal circulation, closes at birth by the postnatal increase in left atrial pressure and fuses within the first 2 years of life. In approximately one third of the population, fusion does not occur, which is not of significance in normal life, because the high left atrial pressure forces the interseptal valve against the septum. In divers, however, the Valsalva maneuver or other procedures that raise intra-abdominal pressure during and after diving lead to a concomitant increase in right atrial pressure and eventually enable the passage of gas bubbles through the foramen ovale. Accordingly, a shunt of venous bubbles could be shown by transcranial Doppler ultrasound in divers with a patent foramen ovale who had developed venous gas emboli after two experimental chamber dives [138]. In a field study investigating recreational divers after scuba dives, arterial microembolic signals were detected by transcranial Doppler ultrasound in 6 of 40 asymptomatic divers who also had significant venous bubbles [93]. In contrast, in another field study using transcranial Doppler ultrasound, no evidence of AGE was detected after multiple dives in commercial divers with a patent foramen ovale [139]. The authors concluded that strict adherence to decompression procedures prevented the divers from significant intravascular bubble formation. The latter studies clearly revealed that it is not the patency of the foramen ovale but the presence of inert gas bubbles that drives the pathologic finding of right-to-left shunts in diving. This concept is supported by the overall incidence of AGE by right-to-left shunting: the prevalence of a patent foramen ovale among the diving population equals that of the total population [93,137,139]. A meta-analysis of three studies that reported incidences for DCI and the echocardiographic presence of a patent foramen ovale in different diving populations revealed a 2.6-fold increase in the risk for DCS, however [140]. The incidence of DCI in that population averaged 0.02%; thus, the absolute increase of risk in the presence of a patent foramen ovale remained small.

Management of decompression illness

As outlined previously, DCI resembles a pattern of diseases that differ fundamentally in their pathophysiology but share, to some extent, the pathologic changes induced by excess intracorporeal gas. There may be a considerable overlap in symptomatology between them [26,141], thus complicating diagnosis.

Evidence has arisen from experimental animal data and experience in human beings that the same treatment algorithms apply for DCI independent of the way in which the excess gas entered the body [142–144]. This is particularly helpful in view of the facts that delay to treatment is inversely related to outcome [26] and time-consuming diagnostic procedures must be postponed until treatment has been initiated.

Diagnosis of DCI mainly relies on careful examination and a detailed medical history, including data on the dive profiles preceding the accident. Other diseases that may mimic DCI, such as cardiovascular or cerebrovascular events, must be considered in view of the present findings. Laboratory and radiographic evaluation should only be applied initially if readily available. Laboratory investigations are useful to assess hemoconcentration and dehydration [145], and an elevated serum creatine kinase level has been shown to be related to the size and severity of AGE [146]. A chest radiograph may be helpful in evaluating the presence of pneumothorax, which must be treated before any recompression therapy is initiated [28]. Costly radiography, such as CT or MRI, may be applied after initial treatment. MRI has been proven useful in further evaluation of neurologic DCI but may be insensitive in some cases [147,148]. For the assessment of further fitness to dive after DCI, it is mandatory to evaluate pulmonary conditions that increase the risk of barotrauma (eg, by chest CT and pulmonary function testing) as well as cardial conditions that predispose to right-to-left shunting.

Effective treatment of tissue damage caused by excess gas includes the fast elimination of the gas phase and the correction of tissue hypoxia. This is best achieved by the application of oxygen at increased ambient pressure, that is, hyperbaric oxygen therapy [149]. It accelerates the elimination of the gas phase by raising the ambient pressure and by creating systemic hyperoxia. Current treatment schedules involve placement of the patient in an environment pressurized at two to three times the sea level pressure while breathing 100% oxygen, which results in arterial oxygen tensions in excess of 2000 mm Hg (267 kPa). The most commonly used treatment algorithm for DCI is the US Navy Table 6, with cycles of oxygen breathing at 18 msw for approximately 75 minutes and at 9 msw for approximately 3 hours, with air pauses in between to minimize adverse oxygen effects [61]. Approximately 40% of injured divers show complete resolution after the first treatment, and only 20% need more than three treatments [26]. If hyperbaric oxygen therapy is not immediately available (eg, at remote locations), early administration of 100% oxygen has been shown to improve clinical outcome significantly [26].

As with any medical emergency, however, cardiopulmonary resuscitation and adjunctive therapies

may be necessary, and transportation of the patient with DCI requires certain prerequisites. A more detailed review on the treatment of DCI exceeds the scope of this article and may be found elsewhere [144,150].

Pulmonary edema

Pulmonary edema has only recently been recognized as a diving-related clinical problem [17,151], probably attributable to the fact that an affected individual may recover spontaneously; therefore, it is largely underreported in scuba diving. Moreover, cases of pulmonary edema may have been misinterpreted as DCI previously [129,152,153].

The first observation was on 11 divers who had developed pulmonary edema while scuba diving in cold British waters. It was assumed that an abnormal increase in vascular resistance to cold exposure may have precipitated edema by raising preload and afterload, because healthy controls did not show the same degree of increase in forearm vascular resistance to experimental cold exposure [17]. Increased oxygen partial pressure at depth might have been contributory, but in 2 divers, episodes of pulmonary edema had occurred even during surface swimming. During follow-up of the divers, most of them had become hypertensive, thus indicating that an abnormal vascular reactivity may be predictive for developing hypertension. A subsequent study reported on four subjects who had developed pulmonary edema while scuba diving or swimming [151]. By distribution of a questionnaire addressing possible symptoms of pulmonary edema, one additional subject (0.22%) of 460 responders was identified as having a positive history of edema. All these subjects who had no history of cardiac or pulmonary disease exhibited no abnormal vascular reactivity when compared with healthy controls. It was thus speculated that a combination of factors, such as immersion and cold exposure, together with an increase in cardiac output, might lead to an excessive increase in pulmonary capillary pressure. Simultaneously, another study reported on a group of eight military subjects who developed hemoptysis and cough while engaged in an open sea swimming competition in warm (23°C) water [154]. The authors suggested that a combination of immersion, exercise, and overhydration had increased pulmonary capillary pressure and eventually caused edema. Subsequently, more cases were reported that occurred during diving in warm waters [155–157], thus diminishing the cold water hypothesis. In Israeli military trainees participating in a 2-month fitness program with distance swims of 2.4 and 3.6 km, there were 29 events of pulmonary edema in 21 individuals (ie, 60% of the study group) [158]. The authors postulated that stress failure of the pulmonary capillary during strenuous swimming precipitated the events and that immersion contributed to this mechanism significantly. In fact, immersion elicits diverse cardiovascular and ventilatory effects that may increase capillary transmural pressure (eg, blood displacement into the lungs, increase in preload, ventilation-perfusion mismatch). The human blood-gas barrier is extremely thin to allow adequate gas exchange to occur by passive diffusion, and its strength to resist higher capillary pressures is mainly provided by the extracellular matrix [159]. It is the type IV collagen matrix that allows intracellular disruptions of the capillary endothelial and alveolar epithelial cells to occur, which are reversible on stress reduction. Pulmonary edema is extremely rare in healthy athletes in a dry environment, albeit there is evidence from animal species that capillary breakage with alveolar bleeding occurs routinely at a high level of exercise. In elite competition cyclists, it could, in fact, be shown that the blood-gas barrier was altered by maximal exercise, whereas it was not changed when exercising at 77% of their maximal oxygen consumption [160,161]. Thus, exhaustive exercise elicits subtle changes to the blood-gas barrier that may become aggravated in the wet environment. Recently, it was reported from the US Naval Medical Center at San Diego that there are more than 20 cases of swimming-induced pulmonary edema annually [162], underlining the high incidence of swimming-induced pulmonary edema during strenuous in-water exercise. Dyspnea and cough are complained of most often and may be accompanied by hemoptyses, hypoxemia, increased breathing frequency, and crackles [163,164]. Radiographic findings, such as Kerley-B lines and airspace consolidation (Fig. 4), usually normalize within 48 hours. Clinical symptoms often improve simply by removal from water and with supportive treatment, so that diuretics are mostly superfluous [163]. Remarkably, in combat swimmers who primarily swim in the lateral decubitus position to allow constant eye contact with the partner and to maintain a low surface profile, it was the dependent submersed lung that was more often affected on chest radiographs [162]. Pulmonary edema has recently been described in an Israeli combat swimmer using a closed-circuit oxygen breathing apparatus [164]. In that case, oxygen may have contributed to the development of edema by its vasoconstrictive effects.

In conclusion, a large variety of different factors may precipitate pulmonary edema during scuba

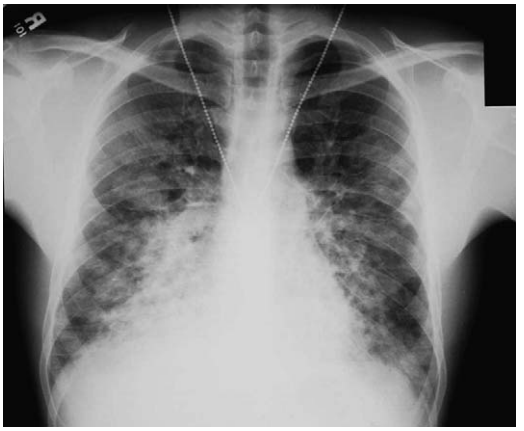

Fig. 4. Chest radiograph of a 28-year-old US Marine who complained of cough and hemoptysis after a 1000-m swim with a wetsuit and fins in the cold (14.4°C [58°F]) Pacific Ocean. (Courtesy of Richard T. Mahon, MD, San Diego, CA.)

diving or swimming, and there is yet no evidence of a single common risk factor. Exertion in the immersed state may be a major causative factor in swimming-induced pulmonary edema, whereas strenuous exercise was only rarely reported in published cases of pulmonary edema during scuba diving [17,151,155–157,165,166]. Remarkably, an advanced age was obvious in the latter subjects (Table 3). It is supposed that individual factors contribute to the development of diving-induced pulmonary edema, because subjects affected once are at risk of further incidents. Thus, these subjects should be advised not to dive again. For those who refuse to accept this advice, the administration of nifedipine (5 mg) before the dive may prevent recurrence [167]. Pulmonary edema during scuba diving or swimming is more frequent than previously thought and must be considered in the differential diagnosis of diving-related injuries.

Fitness to dive with concomitant respiratory diseases

To meet the particular physiologic demands of the underwater environment adequately, a reasonable state of health is required for scuba diving. Certain medical conditions are incompatible with the safety of the individual and his or her diving partner (buddy) and may be made worse by the effects that diving has on health.

The respiratory system is of particular significance in the context of medical fitness to dive. First, exercise capacity at depth is primarily determined by ventilatory capacity because of the excessive work of breathing at higher gas densities [14]. Second, inert gas uptake and elimination are mainly driven by ventilation, gas exchange, and perfusion of the lungs. Any disturbances of these functions may increase the risk of DCI. Third, as the greatest gas-filled body cavity, the lungs are prone to rapid changes in pressure and thus may be subject to barotrauma. Any respiratory abnormalities that are associated with air trapping increase the risk for this potentially life-threatening injury.

When assessing the respiratory system for fitness to dive, a distinct point of view is necessary for recreational scuba diving versus commercial or military diving. In the latter occupations, diving medical examinations are performed to select diving candidates and to survey their health during the occupational exposure [168]. Thus, it is the privilege of the employer to prohibit from diving those individuals who have medical conditions that are associated with a significantly increased risk of diving-related medical complications. In contrast, the responsibility for the recreational dive is with the individual, and the environmental conditions of the dive are self-selected. Recreational divers should consult a physician to get medical advice on any significant

Table 3
Demographics and dive characteristics of cases of pulmonary edema during scuba diving

First author, year [reference]	n	Age (y)	Sex (M/F)	Temperature (°C)	Depth (msw)
Wilmshurst, 1989 [17]	11	45.6 ± 2.6	8/3	<12	N/A
Pons, 1995 [151]	3	30.7 ± 7.2	2/1	4.7–5.6	24–42
Hampson, 1997 [155]	5	43.3 ± 12.9	2/4	12–18	4.5–25
Gnadinger, 2001 [157]	1	52	1/0	25	3.3
Slade, 2001 [156]	8	52.4 ± 5.6	3/5	10–26	4.6–33.8
Hempe, 2003 [165]	1	49	0/1	Cold	8
Halpern, 2003 [166]	1	50	1/0	Mild	12

Figures presented as totals, means ± standard deviation, or ranges.
Abbreviations: F, female; M, male; N/A, not applicable.

associated risks in case there is a medical condition that may affect diving safety. Admittedly, some individuals only aim to get medical clearance. It is therefore important to ensure that the individual acknowledges and understands the associated risks of scuba diving.

In most recreational diving injuries, no preexisting medical problems are apparent [26], and the question has been raised of why people who want to dive should be restricted. Scuba diving has become a popular recreational activity throughout the world, and persons suffering from highly prevalent diseases, such as bronchial asthma, may want to start diving. Increasing data on subpopulations of divers diving safely with certain diseases have emerged, and evidence of significantly increased risks for diving-related injuries in these populations was lacking. This has led to a change in views on diving in persons with respiratory diseases over the past decade. A couple of thoracic societies have published recommendations on respiratory aspects of fitness to dive [169,170]. An increasing number of peer-reviewed articles have addressed the respiratory system and scuba diving in general [171–178] or asthma in particular [172,174,179–182]. For example, a diagnosis of asthma has historically been considered an absolute contraindication to diving [28,61]. A differentiated approach with a trend toward being less restrictive is obvious from more recent recommendations [172,179–182]. The discussion on fitness to dive with respiratory diseases, however, remains controversial, mostly because of the issue that ethical considerations preclude randomized controlled trials in human beings. The analysis of risks therefore largely relies on empirically derived data and anecdotal reports.

Diving with respiratory diseases: epidemiology and clinical considerations

Among possible hazards to subjects diving with respiratory diseases, the risk for DCI is of major concern. Diving accident statistics may help to evaluate whether there is an increased risk. Unfortunately, there is no worldwide database on recreational diving accidents, and many reports rely on estimates or population surveys [73,119,120]. Divers Alert Network (DAN), located at Duke University in Durham, North Carolina, prospectively investigates dive profiles, medical history, and outcome in a growing number of recreational scuba divers in North America [26]. These data now comprise more than 36,000 dives by 3750 divers. The current incidence of DCI is 0.06% of dives, or 0.59% of divers, with one fatality reported (0.03% of divers) [26]. These figures are slightly higher than previous ones that had been obtained from patient surveys and estimates but perfectly match figures reported from single operations in military and/or commercial scuba diving, such as the recovery of Trans World Airways Flight 800, which crashed off the coast of Long Island in 1996. An incidence of 0.05% had been reported for 3992 scuba dives to a mean depth of 35 msw performed by 350 divers [183]. Because most respiratory medical conditions have been considered absolute restrictions for military or commercial diving [168], however, epidemiologic data on subjects diving with respiratory diseases are available for recreational scuba diving only. Previous DAN accident statistics had revealed odds ratios of 1.98 for AGE and 1.16 for DCS in current asthmatics compared with case controls, but the data did not reach statistical significance [184]. Of the injury cases reported annually to the DAN by hyperbaric facilities, there are approximately 6% asthmatics, and asthma was present in less than 0.5% of diving fatalities [26]. Remarkably, there are no data available for other respiratory conditions of similar prevalence, such as chronic obstructive pulmonary disease (COPD), albeit up to 20% of divers do smoke actively [185,186].

Population surveys indicate that divers are diving with respiratory diseases. Whereas 9.7% of subjects diving in Western Australia are reported to have asthma currently, only 0.6% are reported to have COPD [187]. Surveys among sport scuba divers in the United States consistently found that approximately 4% of divers currently had asthma and another 4% had childhood asthma only [188,189]. A survey among British sport divers revealed that there are asthmatics who dive uneventfully, including those reporting daily asthma symptoms [190]. Surprisingly, more than half of the respondents did not know or even ignored the current recommendations for safe diving. In a recent survey among sports divers from continental Europe, 8.7% of the respondents indicated that they dive with current asthma and 42.4% of those with asthma were regularly using drugs to relieve or control their symptoms [186]. In that population, there were subjects who used drugs without bronchodilating activity as prophylaxis before diving and others who reported continued dyspnea but did not use bronchodilators, thus supporting the need for better education and disease management of asthmatic divers.

There are few data on subjects diving with less prevalent respiratory conditions. Population surveys among Australian and European sport divers indicate that there are few subjects diving with a history of

spontaneous or traumatic pneumothorax or chronic bronchitis and that up to 5% of divers reported a history of pneumonia [186,191]. Beyond epidemiology, some curiosities may be found in the literature. There is one case report of a 28-year-old man who dived uneventfully for several months at depths between 3 and 50 msw with pneumothorax [192]. In accordance with what would be expected from the physiology, the diver was described as feeling best while diving, and he even felt better the deeper he went. A 58-year old man was reported to dive well except for the problem of "keeling," or swimming with a buoyancy-related tilt, after a right-sided pneumonectomy for squamous cell carcinoma of the lung [193]. He had been able to counteract the asymmetric buoyancy with weights attached to the left side. There are subjects diving with fibrosing pulmonary diseases, such as sarcoidosis, but no reports are available that provide systematic data on figures and outcomes. One case of a diver with stage III sarcoidosis, who suffered from symptomatology matching that of AGE during decompression from a 50-msw hyperbaric chamber exposure, has been reported [194]. Against medical advice, that diver continued to scuba dive and had a recurrent incident 2 years later after a dive to 30 msw in a lake. Regrettably, residual symptoms remained even after repeated hyperbaric oxygen treatments (Hanjo Roggenbach, MD, personal communication, 2004).

Respiratory assessment of fitness to dive

Because abnormalities of the respiratory system are obviously associated with an increased risk of suffering from underwater hazards, such as DCI or drowning, the investigation of the lung deserves particular attention. The routine assessment should comprise a medical history, physical examination, and spirometry. The need for routine medical examinations has been questioned recently, because conditions preventing subjects from diving were mostly detected by questionnaire [185], but physical examination is useful to document the physical state at the beginning of a diving career and to evaluate possible deviations during follow-up. This may, in fact, have legal implications in the case of residual damage from diving injuries. Spirometry should rule out any ventilatory abnormalities. There is no general consensus on particular limits; however, most reasonably, FEV_1 and FVC should exceed 80% of their respective predicted values [169,170,195]. The quotient of FEV_1/FVC should be greater than 70%, but it must be kept in mind that diving may increase the VC because of respiratory muscle training, and lower than predicted FEV_1/FVC ratios have been found in experienced commercial divers [196,197].

Any history or detection of respiratory abnormalities should prompt further investigation. In fact, approximately 30% of diving candidates are reported to be referred for a specialist opinion because of respiratory conditions [185]. The British Thoracic Society has recently suggested an algorithm for further assessment [170], which recommends a chest radiograph in case of current respiratory symptoms or a history of lung disease or chest trauma. If radiography, in combination with the physical examination and spirometry, is normal, the candidate may be approved unless specific respiratory conditions apply. These conditions may comprise but are not restricted to obstructive airways diseases, such as asthma and COPD, pulmonary fibrosis, sarcoidosis, infectious diseases, and previous chest trauma. Asthma is the most prevalent of these conditions and thus the most important clinical pulmonary condition to be considered in an assessment of fitness to dive; therefore, a differentiated approach to diving eligibility is now recommended [170,180,181]. Table 4 provides recommendations on fitness to dive in asthmatics based on the current severity classification published by the National Institutes of Health [198,199]. Individual factors, such as self-management of the disease and compliance with treatment, must be taken into account when assessing fitness to dive, however, and these recommendations may only guide the physician's advice. The asthmatic diving candidate should be aware of the risks and dive accordingly (ie, avoid fast ascents and exertion). Airway hyperresponsiveness with a significant response to hyperpnea or hypertonic aerosols precludes diving because of the stimuli experienced by the diver, such as hyperpnea of dry gas during exercise and possible aspiration of seawater. Indirect bronchial challenges, such as eucapnic voluntary hyperpnea, are preferred over direct pharmacologic tests, because the latter are less specific for identifying asthma and exercise-induced bronchoconstriction [200]. A history of atopy alone (without respiratory symptoms and with normal lung function) has not been of concern for the evaluation of fitness to dive yet; in fact, there are many subjects diving uneventfully who have a sensitization to common aeroallergens [186,191,201]. One experimental study in human beings indicated postdive pulmonary function changes in asymptomatic subjects with hay fever and airway hyperreactivity to methacholine [202], however, and another study showed an increased postdive response to methacholine challenge in atopic subjects [203].

Table 4
Recommendations regarding fitness to dive for asthmatics

Step	Symptoms (day/night)[a]	PEF or FEV_1 (PEF variability %)[a]	Fitness to dive
Childhood only	None	≥80 <20	Yes
Mild intermittent	≤2 d/wk ≤2 nights/mo	≥80 <20	Yes, if >48 h since last reliever intake
Mild persistent	<Daily	≥80	Yes, if regular controller medication and >48 h since last reliever intake
	>2 nights/mo	20–30	
Moderate persistent	Daily >1 night/wk	<80 >30	No
Severe persistent	Continual Frequent	≤60 >30	No

Abbreviation: PEF, peak expiratory flow.
[a] Clinical features before treatment.

Divers must have a certain aerobic capacity to be able to cope with the increased work of breathing at depth, which may be aggravated by exercise (eg, when swimming against a strong underwater current). Thus, further investigation of diving candidates with a history of respiratory disease or symptoms or abnormalities during routine assessment should include cardiopulmonary exercise testing. Any ventilatory abnormalities or impaired gas exchange during exercise should preclude diving, and a peak oxygen uptake of at least 25 and 27 $mL/kg^{-1}/min^{-1}$ should be achieved in women and men, respectively.

Smoking is associated with the development of inflammatory airway changes even in the asymptomatic state, and a certain percentage of smokers get COPD [204]. Thus, it is worth questioning whether smokers are fit to dive. A recent analysis of DCI cases in the DAN database from 1989 through 1997 revealed that smokers with DCI tended to present with more severe symptoms than their nonsmoking counterparts [205]. Moreover, significant adjusted odds ratios for the comparison of heavy smokers, as defined by a history of more than 15 pack-years, with those who have never smoked showed some correlation with the severity of DCI in a dose-dependent fashion. It was therefore suggested that a history of smoking per se may justify further pneumatologic evaluation of the diving candidate [206].

Long-term effects of diving on the lung

Diving is associated with exposure to several factors that, independently of each other, have been shown to have effects on pulmonary function. Some of these, such as hyperoxia and VGM filtered in the pulmonary circulation, may induce inflammatory reactions in the lung, whereas others, such as increased breathing resistance and blood and/or fluid redistribution during immersion, may induce mechanical or physiologic stress only without tissue damage.

Studies of some experimental dives have provided insights into the mechanisms of changes in pulmonary function associated with diving and the time course of the changes attributable to different exposure factors. Such studies are not suitable for predicting long-term effects, however, because the effects of subsequent dives add to the effects of the experimental dives. It is easy to monitor the exposure in a well-controlled experimental dive, but one of the great challenges in epidemiologic studies is to define a measure of cumulative diving exposure over time to which any outcome measure can be related.

The basic physical parameters characterizing any dive are pressure, time, and gas mixture. These parameters are independent of the method of diving and form the basis for calculation of diving exposure, including oxygen exposure, decompression stress, and respiratory mechanical load. Differences between diving methods are quantitative rather than qualitative. In epidemiologic studies, there are difficulties in obtaining accurate estimates of cumulative exposure, even in prospective longitudinal studies. The number of dives encountered by different diving methods, number of days in saturation, or only the number of years as a diver is what has been achieved with some accuracy in the epidemiologic studies that have been reported to date. These simple measures of exposure are related to the basic physical parameters of the

dives, however, and reflect the cumulative exposure to the more specific exposure factors in some way.

The first studies characterizing pulmonary function in divers showed that divers had larger than predicted VCs [196,197,207]. There was a significant correlation between FVC and the maximal depth ever dived to up to the age of 30 years [208], consistent with an effect of respiratory muscle training. After the age of 30 years, FVC declined despite continued diving. The FEV_1 was, however, not increased in proportion to the FVC, resulting in a lower than predicted FEV_1/FVC ratio. Initially this was not considered to be a result of airway obstruction, but the same studies did show lower than predicted maximal expiratory flow rates at low lung volumes. Later cross-sectional studies have shown lower FEV_1 and maximal expiratory flow rates at low lung volumes in divers compared with matched control groups and that the reductions in these variables are related to cumulative diving exposure in saturation divers as well as in air bounce divers [209–211].

The large VC in divers can be a result of the selection of subjects with large lungs [212] or that of adaptation to the hyperbaric environment with an increased load of breathing and respiratory muscle training. In a study on a group of apprentice divers, the FVC at the beginning of a diving education was larger than predicted [213] without a difference between subjects who had and subjects who did not have diving experience at the start of their education. There was a further small increase in FVC in the first year only of their professional career, with no further increase after 3 years.

The results of the 6-year longitudinal follow-up up of these apprentice divers confirm the results from the cross-sectional studies in that FEV_1 and maximal expiratory flow rates were reduced in the divers over the follow-up period when compared with a control group of policemen and that the reduction was related to diving exposure [214].

Other longitudinal studies included small groups of selected divers only but support the findings of the study in apprentice divers. After experimental saturation dives to 300 msw or more, 26 divers were followed for 4 years and compared with 28 saturation divers who had not taken part in deep dives to depths of 180 m or more. One year after the deep dive, there was a significant reduction in FEV_1 and maximal expiratory flow rates at low lung volumes, after which the rates of change were not different between the two groups [215]. The reduction in FEV_1 as a consequence of exposure to hyperoxia only, which was the same as in a deep saturation dive, has been shown to persist for 3 years in subjects who did not take part in any diving activity during the follow-up period [216]. That study indicated the exposure to hyperoxia contributes significantly to the short-term as well as long-term effects of diving on lung function.

There are few studies on lung function variables other than FVC, FEV_1, and the maximal expiratory flow rates, but there seems to be a reduction in transfer factor for carbon monoxide as well, which is related to cumulative diving exposure [209,214,217]. Exercise capacity and peak oxygen uptake do not seem to be reduced in divers, but when compared with control groups, divers have larger ventilatory equivalents for oxygen uptake and carbon dioxide output [207,218]. These changes and the reduction in Tl_{CO} may indicate small gas exchange abnormalities.

The long-term changes, although small and hardly influencing the quality of life of active professional divers who were subjected to the studies, may have some consequences, however. A reduced FEV_1 is associated with a reduced ventilatory capacity, even more so when gas density is increased under pressure, encroaching on the diver's underwater exercise capacity. A reduced FEV_1 may increase the risk of PBT as well, at least theoretically.

The epidemiologic studies have been conducted in professionally active divers. If the reduction in FEV_1 persists into retirement, the prevalence of respiratory symptoms is expected to increase by aging. In a group of retired Norwegian divers working in the North Sea before 1990 and experiencing saturation as well as mixed gas bounce diving, the prevalence of respiratory symptoms and spirometric airflow limitation, with a FEV_1/FVC ratio less than 70% and an FEV_1 less than 80% of predicted, was almost double that in the general population, and it was not related to smoking habits, atopy, or other occupational activities like welding [219]. The mean age of these retired divers was 52 years only, and mean time since retiring from diving was 12 years. Further follow-up of other groups of divers into retirement thus seems necessary.

References

[1] National Sporting Goods Assocation. Available at: http://www.nsga.org. Accessed June 22, 2005.
[2] Clarke JM. Pulmonary limits of oxygen tolerance in man. Exp Lung Res 1988;14:897–912.
[3] Harabin AL, Homer LD, Weathersby PK, et al. An analysis of decrements in vital capacity as an index of pulmonary oxygen toxicity. J Appl Physiol 1987;63:1130–5.

[4] Suzuki S. Probable lung injury by long term exposure to oxygen close to 50 kilopascals. Undersea Hyperb Med 1994;21:235–43.
[5] Thorsen E, Segadal K, Reed JW, et al. Contribution of hyperoxia to reduced pulmonary function after deep saturation dives. J Appl Physiol 1993;75:657–62.
[6] Clark JM, Jackson RM, Lambertsen CJ, et al. Pulmonary function in men after oxygen breathing at 3.0 ATA for 3.5 hours. J Appl Physiol 1991;71: 878–85.
[7] Fracica PJ, Knapp MJ, Piantadosi CA, et al. Responses of baboons to prolonged hyperoxia: physiology and qualitative pathology. J Appl Physiol 1991; 71:2352–62.
[8] Hlastala MP, Robertson HT, Ross BK. Gas exchange abnormalities produced by venous gas emboli. Respir Physiol 1979;36:1–17.
[9] Albertine JJ, Wiener-Kronish JP, Koike K, et al. Quantification of damage by air emboli to lung microvessels in anesthetized sheep. J Appl Physiol 1984; 57:1360–8.
[10] Flick MR, Perel A, Staub NC. Leukocytes are required for increased lung microvascular permeability after microembolization in sheep. Circ Res 1981; 48:344–51.
[11] Butler BD, Katz J. Vascular pressures and passage of gas emboli through the pulmonary circulation. Undersea Biomed Res 1988;15:203–9.
[12] Thorsen E, Risberg J, Segadal K, et al. Effects of venous gas microemboli on pulmonary gas transfer function. Undersea Hyperb Med 1995;22:347–53.
[13] Dujic Z, Eterovic D, Denoble A, et al. Effect of a single air dive on pulmonary diffusing capacity in professional divers. J Appl Physiol 1993;74:55–61.
[14] Maio DA, Farhi LE. Effect of gas density on mechanics of breathing. J Appl Physiol 1967;23:687–93.
[15] Van Liew H, Thalmann ED, Sponholtz DK. Hindrance to diffusive gas mixing in the lung in hyperbaric environments. J Appl Physiol 1981;51:243–7.
[16] Thorsen E, Skogstad M, Reed JW. Subacute effects of inspiratory resistive loading and head-out water immersion on pulmonary function. Undersea Hyperb Med 1999;26:137–41.
[17] Wilmshurst PT, Nuri M, Crother A, et al. Cold-induced pulmonary oedema in scuba-divers and swimmers and subsequent development of hypertension. Lancet 1989;1:62–5.
[18] O'Cain CF, Dowling NB, Slutsky AS, et al. Airway effects of respiratory heat loss in normal subjects. J Appl Physiol 1980;49:875–80.
[19] Burnet H, Lucciano M, Jammes Y. Respiratory effects of cold-gas breathing in humans under hyperbaric environment. Respir Physiol 1990;142:413–24.
[20] Rønnestad I, Thorsen E, Segadal K, et al. Bronchial response to breathing dry gas at 3.7 MPa ambient pressure. Eur J Appl Physiol 1994;69:32–5.
[21] Cotes JE, Davey IS, Reed JW, et al. Respiratory effects of a single saturation dive to 300 m. Br J Ind Med 1987;44:76–82.
[22] Suzuki S, Ikeda T, Hashimoto A. Decrease in the single breath diffusing capacity after saturation dives. Undersea Biomed Res 1991;18:103–9.
[23] Thorsen E, Segadal K, Påsche A, et al. Pulmonary mechanical function and diffusion capacity after deep saturation dives. Br J Ind Med 1990;47:242–7.
[24] Skogstad M, Thorsen E, Haldorsen T, et al. Divers' pulmonary function after open-sea bounce dives to 10 and 50 meters. Undersea Hyperb Med 1996;23: 71–5.
[25] Tetzlaff K, Friege L, Koch A, et al. Effects of ambient cold and depth on lung function in humans after a single scuba dive. Eur J Appl Physiol 2001;85: 125–9.
[26] Divers Alert Network. Report on decompression illness, diving fatalities and project dive exploration. The DAN annual review of recreational scuba diving injuries and fatalities based on 2001 data. Durham, NC: Divers Alert Network; 2003.
[27] Strauss MB, Wright PW. Thoracic squeeze diving casualty. Aerosp Med 1971;42:673–5.
[28] Strauss RH. Diving medicine. Am Rev Respir Dis 1979;119:1001–23.
[29] Schaefer KE, McNulty WP, Carey C, et al. Mechanisms in development of interstitial emphysema and air embolism on decompression from depth. J Appl Physiol 1958;13:15–29.
[30] Malhotra MS, Wright HC. The effects of a raised intrapulmonary pressure on the lungs of fresh unchilled cadavers. J Pathol Bacteriol 1961;82: 198–202.
[31] Liebow AA, Stark JE, Vogel J, et al. Intrapulmonary air trapping in submarine escape training casualties. US Armed Forces Med J 1959;10:265–89.
[32] Schriger DL, Rosenberg G, Wilder RJ. Shoulder pain and pneumoperitoneum following a diving accident. Ann Emerg Med 1987;16:1281–4.
[33] Oh ST, Kim W, Jeon HM, et al. Massive pneumoperitoneum after scuba diving. J Korean Med Sci 2003;18:281–3.
[34] Muth CM, Shank ES. Gas embolism. N Engl J Med 2000;342:476–82.
[35] Dutka AJ. A review of the pathophysiology and potential application of experimental therapies for cerebral ischemia to the treatment of cerebral arterial gas embolism. Undersea Biomed Res 1985;12: 403–21.
[36] Zwillich CW, Pierson DJ, Creagh CE, et al. Complications of assisted ventilation: a prospective study of 354 consecutive episodes. Am J Med 1974;57: 161–70.
[37] Broome CR, Jarvis LJ, Clark RJ. Pulmonary barotrauma in submarine escape training. Thorax 1994;49: 186–7.
[38] Friehs I, Friehs M, Friehs GB. Air embolism with bilateral pneumothorax after a five-meter dive. Undersea Hyperb Med 1993;20:155–7.
[39] Hamad A, Alghadban A, Ward L. Seizure in a scuba diver. Chest 2001;119:285–6.

[40] Neuman TS, Jacoby I, Bove AA. Fatal pulmonary barotrauma due to obstruction of the central circulation with air. J Emerg Med 1998;16:413–7.
[41] Roobottom CA, Hunter JD, Bryson PJ. The diagnosis of fatal gas embolism: detection by plain film radiography. Clin Radiol 1994;49:805–7.
[42] Carstairs S. Arterial gas embolism in a diver using a closed-circuit oxygen rebreathing apparatus. Undersea Hyperb Med 2001;28:229–31.
[43] Tetzlaff K, Neubauer B, Reuter M, et al. Pulmonary barotrauma of a diver using an oxygen rebreathing diving apparatus. Aviat Space Environ Med 1996;67: 1198–200.
[44] Raymond LW. Pulmonary barotrauma and related events in divers. Chest 1995;107:1648–52.
[45] Benton PJ, Woodfine JD, Westwood PR. Arterial gas embolism following a 1-meter ascent during helicopter escape training: a case report. Aviat Space Environ Med 1996;67:63–4.
[46] Weiss LD, Van Meter KM. Cerebral air embolism in asthmatic scuba divers in a swimming pool. Chest 1995;107:1653–4.
[47] Zaugg M, Kaplan V, Widmer U, et al. Fatal air embolism in an airplane passenger with a giant intrapulmonary bronchogenic cyst. Am J Respir Crit Care Med 1998;157:1686–9.
[48] Rudge FW. Altitude-induced arterial gas embolism: a case report. Aviat Space Environ Med 1992;63: 203–5.
[49] Cable GG, Keeble T, Wilson G. Pulmonary cyst and cerebral arterial gas embolism in a hypobaric chamber: a case report. Aviat Space Environ Med 2000;71: 172–6.
[50] Rios-Tejada F, Azofra-Garcia J, Valle-Garrido J, et al. Neurological manifestation of arterial gas embolism following standard altitude chamber flight: a case report. Aviat Space Environ Med 1997;68:1025–8.
[51] Lee CT. Cerebral arterial gas embolism in air force ground maintenance crew—a report of two cases. Aviat Space Environ Med 1999;70:698–700.
[52] Hickey MJ, Zanetti CL. Delayed-onset cerebral arterial gas embolism in a commercial airline mechanic. Aviat Space Environ Med 2003;74:977–80.
[53] Unsworth IP. Pulmonary barotraumas in a hyperbaric chamber. Anaesthesia 1973;28:675–8.
[54] Wolf HK, Moon RE, Mitchell PR, et al. Barotrauma and air embolism in hyperbaric oxygen therapy. Am J Forensic Med Pathol 1990;11:149–53.
[55] Mueller PHJ, Tetzlaff K, Neubauer B, et al. Pulmonary barotrauma during hyperbaric oxygen therapy: a case report [abstract]. Undersea Hyperb Med 1998; 25(Suppl):34.
[56] James RE. Extra-alveolar air resulting from submarine escape training: a post-training roentgenographic survey of 170 submariners. Report No. 550. Groton, CT: US Naval Submarine Medical Center; 1968.
[57] Yanir Y, Abramovich A, Beck-Razi N, et al. Telephone diagnosis of a strange voice. Chest 2003;123: 2112–4.
[58] Kizer KW. Dysbaric cerebral air embolism in Hawaii. Ann Emerg Med 1987;16:535–41.
[59] Tetzlaff K, Reuter M, Leplow B, et al. Risk factors for pulmonary barotrauma in divers. Chest 1997;112: 654–9.
[60] Leitch DR, Green RD. Pulmonary barotrauma in divers and the treatment of cerebral arterial gas embolism. Aviat Space Environ Med 1986;57:931–8.
[61] Melamed Y, Shupak A, Bitterman H. Medical problems associated with underwater diving. N Engl J Med 1992;326:30–5.
[62] Collins JJ. An unusual case of air embolism precipitated by decompression. N Engl J Med 1962; 266:595–8.
[63] Tirpitz D, Schipke JD. Delayed recompression after scuba diving-induced pulmonary barotraumas: a case report. Aviat Space Environ Med 1996;67: 266–8.
[64] Harker CP, Neuman TS, Olson LK, et al. The roentgenographic findings associated with air embolism in sport scuba divers. J Emerg Med 1993;11: 443–9.
[65] Dick APK, Massey EW. Neurologic presentation of decompression sickness and air embolism in sport divers. Neurology 1985;35:667–71.
[66] Krzyzak J. A case of delayed-onset pulmonary barotrauma in a scuba diver. Undersea Biomed Res 1987;14:553–61.
[67] Moloff AL. Delayed onset arterial gas embolism. Aviat Space Environ Med 1993;64:1040–3.
[68] Clarke D, Gerard W, Norris T. Pulmonary barotrauma-induced cerebral arterial gas embolism with spontaneous recovery: commentary on the rationale for therapeutic recompression. Aviat Space Environ Med 2002;73:139–46.
[69] Neuman TS. Arterial gas embolism and decompression sickness. News Physiol Sci 2002;17:77–81.
[70] Williamson JA, King GK, Callanan VI, et al. Fatal arterial gas embolism. Detection by chest radiography and imaging before autopsy. Med J Aust 1990;153: 97–100.
[71] Elliott DH, Harrison JAB, Barnard EEP. Clinical and radiological features of 88 cases of decompression barotrauma. In: Shilling CW, Beckett MW, editors. Proceedings of the VI Symposium on Underwater Physiology. Bethesda (MD): FASEB; 1978. p. 527–35.
[72] Lindemark C, Adolfson J. Lung rupture as a complication in free escape. In: Örnhagen H, Carlsson AL, editors. Proceedings of the XI Annual Meeting of the European Undersea Biomedical Society. Bromma (Sweden): Kugel Tryckeri AB; 1985. p. 81–4.
[73] Arness MK. Scuba decompression illness and diving fatalities in an overseas military community. Aviat Space Environ Med 1997;68:325–33.
[74] Calder IM. Autopsy and experimental observations on factors leading to barotrauma in man. Undersea Biomed Res 1985;12:165–82.
[75] Saywell WR. Submarine escape training, lung cysts

and tension pneumothorax. Br J Radiol 1989;62: 276–8.
[76] Mellem H, Emhjellen S, Horgen O. Pulmonary barotrauma and arterial gas embolism caused by an emphysematous bulla in a scuba diver. Aviat Space Environ Med 1990;61:559–62.
[77] Reuter M, Tetzlaff K, Warninghoff V, et al. Computed tomography of the chest in diving-related pulmonary barotrauma. Br J Radiol 1997;70:440–5.
[78] Le Vot J, Solacroup JC, Muyard B, et al. Le thorax de l'accidente de plongée. J Radiol 1989;70:357–63.
[79] Toklu AS, Kiyan E, Aktas S, et al. Should computed chest tomography be recommended in the medical certification of professional divers? A report of three cases with pulmonary air casts. Occup Environ Med 2003;60:606–8.
[80] Heritiér F, Schaller MD, Fitting JW, et al. Manifestations pulmonaires des accidents de plongée. Schweiz Z Sportmed 1993;41:115–20.
[81] Jego C, Berard H, Moulin P, et al. Des bulles qui ne doivent plus plonger. Rev Mal Respir 2003;20: 144–6.
[82] Leitch DR, Green RD. Recurrent pulmonary barotrauma. Aviat Space Environ Med 1986;57:1039–43.
[83] Carpenter CR. Recurrent pulmonary barotrauma in scuba diving and the risks of future hyperbaric exposures: a case report. Undersea Hyperb Med 1997; 24:209–13.
[84] Tetzlaff K, Reuter M, Warninghoff V, et al. Dive-related pulmonary barotrauma in the differential diagnosis of pneumologic outpatients. Pneumologie 1996;50:902–5.
[85] Colebatch HJ, Ng CK. Decreased pulmonary distensibility and pulmonary barotrauma in divers. Respir Physiol 1991;86:293–303.
[86] Benton PJ, Francis TJR, Pethybridge RJ. Spirometric indices and the risk of pulmonary barotraumas in submarine escape training. Undersea Hyperb Med 1999;26:213–7.
[87] Moon RE, Vann RD, Bennett PB. The physiology of decompression illness. Sci Am 1995;273:70–7.
[88] Doolette DJ, Mitchell SJ. The physiological kinetics of nitrogen and the prevention of decompression sickness. Clin Pharmacokinet 2001;40:1–14.
[89] Butler BD, Hills BA. The lung as a filter for microbubbles. J Appl Physiol 1979;47:537–43.
[90] Eckenhoff RG, Olstad CS, Carrod G. Human dose-response relationship for decompression and endogenous bubble formation. J Appl Physiol 1990;69: 914–8.
[91] Carturan D, Boussuges A, Vanuxem P, et al. Ascent rate, age, maximal oxygen uptake, adiposity, and circulating venous bubbles after diving. J Appl Physiol 2002;93:1349–56.
[92] Glen SK, Georgiadis D, Grosset DG, et al. Transcranial Doppler ultrasound in commercial air divers: a field study including cases with right-to-left shunting. Undersea Hyperb Med 1995;22:129–35.
[93] Gerriets T, Tetzlaff K, Liceni T, et al. Arteriovenous bubbles following cold water sport dives: relation to right-to-left shunting. Neurology 2000; 55:1741–3.
[94] Bove AA, Hallenbeck JM, Elliott DH. Circulatory responses to venous air embolism and decompression sickness in dogs. Undersea Biomed Res 1974;1: 207–20.
[95] Neuman TS, Spragg RG, Wagner PD, et al. Cardiopulmonary consequences of decompression stress. Respir Physiol 1980;41:143–53.
[96] Peterson BT, Grauer SE, Hyde RW, et al. Response of pulmonary veins to increased intracranial pressure and pulmonary air embolization. J Appl Physiol 1980;48:957–64.
[97] Levin LL, Stewart GJ, Lynch PR, et al. Blood and blood vessel wall changes induced by decompression sickness in dogs. J Appl Physiol 1981;50:944–9.
[98] Ward CA, McCullough D, Fraser WD. Relation between complement activation and susceptibility to decompression sickness. J Appl Physiol 1987;62: 1160–6.
[99] Ohkuda K, Nakahara K, Binder A, et al. Venous air emboli in sheep: reversible increase in lung microvascular permeability. J Appl Physiol 1981;51: 887–94.
[100] Buttolph TB, Dick EJ, Toner CB, et al. Cutaneous lesions in swine after decompression: histopathology and ultrastructure. Undersea Hyperb Med 1998;25: 115–21.
[101] Francis TJ, Pezeshkpour GH, Dutka AJ, et al. Is there a role for the autochthonous bubble in the pathogenesis of spinal cord decompression sickness? J Neuropathol Exp Neurol 1988;47:475–87.
[102] Francis TJ, Griffin JL, Homer LD, et al. Bubble-induced dysfunction in acute spinal cord decompression sickness. J Appl Physiol 1990;68:1368–75.
[103] Palmer AC. Nature and incidence of bubbles in the spinal cord of decompressed goats. Undersea Hyperb Med 1997;24:193–200.
[104] Broome JR, Dick EJ. Neurological decompression illness in swine. Aviat Space Environ Med 1996;67: 207–13.
[105] Dick EJ, Broome JR, Hayward IJ. Acute neurologic decompression illness in pigs: lesions of the spinal cord and brain. Lab Anim Sci 1997;47:50–7.
[106] Reuter M, Tetzlaff K, Brasch F, et al. Computed chest tomography in an animal model for decompression sickness: radiologic, physiologic, and pathologic findings. Eur Radiol 2000;10:534–41.
[107] Neuman TS, Bove AA. Combined arterial gas embolism and decompression sickness following no-stop dives. Undersea Biomed Res 1990;17:429–36.
[108] Broome JR. Reduction of decompression illness risk in pigs by use of non-linear ascent profiles. Undersea Hyperb Med 1996;23:19–26.
[109] Broome JR. Climatic and environmental factors in the aetiology of decompression sickness in divers. J R Nav Med Serv 1993;79:68–74.
[110] Jankowski LW, Nishi RY, Eaton DJ, et al. Exercise

during decompression reduces the amount of venous gas emboli. Undersea Hyperb Med 1997;24:59–65.
[111] Broome JR, Dutka AJ, McNamee GA. Exercise conditioning reduces the risk of neurologic decompression illness in swine. Undersea Hyperb Med 1995;22:73–85.
[112] Wisløff U, Brubakk AO. Aerobic endurance training reduces bubble formation and increases survival in rats exposed to hyperbaric pressure. J Physiol 2001; 537:607–11.
[113] Dujic Z, Duplancic D, Marinovic-Terzic I, et al. Aerobic exercise before diving reduce venous gas bubbles formation in humans. J Physiol 2004;555:637–42.
[114] Doolette DJ. Exercise fizzy-ology. J Physiol 2001; 537:330.
[115] Dembert ML, Jekel JF, Mooney LW. Health risk factors for the development of decompression sickness among US Navy divers. Undersea Biomed Res 1984;11:395–406.
[116] Carturan D, Boussuges A, Burnet H, et al. Circulating venous bubbles in recreational diving: relationships with age, weight, maximal oxygen uptake and body fat percentage. Int J Sports Med 1999;20:410–4.
[117] Vann RD. Mechanisms and risks of decompression. In: Bove AA, editor. Bove and Davis' diving medicine. 3rd edition. Philadelphia: WB Saunders; 1997. p. 146–58.
[118] Dunford RG, Vann RD, Gerth WA, et al. The incidence of venous gas emboli in recreational diving. Undersea Hyperb Med 2002;29:247–59.
[119] Hagberg M, Örnhagen H. Incidence and risk factors for symptoms of decompression sickness among male and female dive masters and instructors—a retrospective cohort study. Undersea Hyperb Med 2003;30:93–102.
[120] St Leger Dowse M, Bryson P, et al. Comparative data from 2250 male and female sports divers: diving patterns and decompression sickness. Aviat Space Environ Med 2002;73:743–9.
[121] Freiberger JJ, Denoble PJ, Pieper CF, et al. The relative risk of decompression sickness during and after air travel following diving. Aviat Space Environ Med 2002;73:980–4.
[122] Sheffield PJ. Flying after diving guidelines: a review. Aviat Space Environ Med 1990;61:1130–8.
[123] Catron PW, Flynn ET, Yaffe Y, et al. Morphological and physiological responses of the lungs of dogs to acute decompression. J Appl Physiol 1984;57: 467–74.
[124] Butler BD, Luehr S, Katz J. Venous gas embolism: time course of residual pulmonary intravascular bubbles. Undersea Biomed Res 1989;16:21–9.
[125] Atkins CE, Lehner CE, Beck KA, et al. Experimental respiratory decompression sickness in sheep. J Appl Physiol 1988;65:1163–71.
[126] Nossum V, Koteng S, Brubakk AO. Endothelial damage by bubbles in the pulmonary artery of the pig. Undersea Hyperb Med 1999;26:1–8.
[127] Nossum V, Hjelde A, Brubakk AO. Small amounts of venous gas embolism cause delayed impairment of endothelial function and increase polymorphonuclear neutrophil infiltration. Eur J Appl Physiol 2002; 86:209–14.
[128] Nossum V, Hjelde A, Bergh K, et al. Anti-C5a monoclonal antibodies and pulmonary polymorphonuclear leukocyte infiltration—endothelial dysfunction by venous gas embolism. Eur J Appl Physiol 2003;89:243–8.
[129] Zwirewich CV, Müller NL, Abboud RT, et al. Noncardiogenic pulmonary edema caused by decompression sickness: rapid resolution following hyperbaric therapy. Radiology 1987;163:81–2.
[130] Wirjosemito SA, Touhey JE, Worman WT. Type II altitude decompression sickness (DCS): US Air Force experience with 133 cases. Aviat Space Environ Med 1989;60:256–62.
[131] Butler BD, Hills BA. Transpulmonary passage of venous air emboli. J Appl Physiol 1985;59:543–7.
[132] Vik A, Brubakk AO, Hennessy TR, et al. Venous air embolism in swine: transport of gas bubbles through the pulmonary circulation. J Appl Physiol 1990;69: 237–44.
[133] Vik A, Jenssen BM, Eftedal O, et al. Relationship between venous bubbles and hemodynamic responses after decompression in pigs. Undersea Hyperb Med 1993;20:233–48.
[134] Vik A, Jenssen BM, Brubakk AO. Arterial gas bubbles after decompression in pigs with patent foramen ovale. Undersea Hyperb Med 1993;20:121–32.
[135] Moon RE, Camporesi EM, Kisslo JA. Patent foramen ovale and decompression sickness in divers. Lancet 1989;1:513–4.
[136] Wilmshurst PT, Byrne JC, Webb-Peploe MM. Relation between interatrial shunts and decompression sickness in divers. Lancet 1989;2:1302–6.
[137] Germonpré P, Dendale P, Unger P, et al. Patent foramen ovale and decompression sickness in sports divers. J Appl Physiol 1998;84:1622–6.
[138] Ries S, Knauth M, Kern R, et al. Arterial gas embolism after decompression: correlation with right-to-left shunting. Neurology 1999;52:401–4.
[139] Glen SK, Georgiadis D, Grosset DG, et al. Transcranial Doppler ultrasound in commercial air divers: a field study including cases with right-to-left shunting. Undersea Hyperb Med 1995;22:129–35.
[140] Bove AA. Risk of decompression sickness with patent foramen ovale. Undersea Hyperb Med 1998;25: 175–8.
[141] Wilmshurst P, Bryson P. Relationship between the clinical features of neurological decompression illness and its causes. Clin Sci 2000;99:65–75.
[142] Moon RE, Sheffield PJ. Guidelines for treatment of decompression illness. Aviat Space Environ Med 1997;68:234–43.
[143] Moon RE, Dear G de L, Stolp BW. Treatment of decompression illness and iatrogenic gas embolism. Respir Care Clin N Am 1999;5:93–135.
[144] Tetzlaff K, Shank ES, Muth CM. Evaluation and

management of decompression illness—an intensivists' perspective. Intensive Care Med 2003;29: 2128–36.
[145] Smith RM, Van Hoesen KB, Neuman TS. Arterial gas embolism and hemoconcentration. J Emerg Med 1994;12:147–53.
[146] Smith RM, Neuman TS. Elevation of serum creatine kinase in divers with arterial gas embolization. N Engl J Med 1994;330:19–24.
[147] Warren LP, Djang WT, Moon RE, et al. Neuroimaging of scuba diving injuries to the CNS. Am J Radiol 1988;151:1003–8.
[148] Reuter M, Tetzlaff K, Hutzelmann A, et al. MR imaging of the central nervous system in diving-related decompression illness. Acta Radiol 1997;38: 940–4.
[149] Tibbles PM, Edelsberg JS. Hyperbaric-oxygen therapy. N Engl J Med 1996;334:1642–8.
[150] Moon RE, Gorman DF. Treatment of the decompression disorders. In: Brubakk AO, Neuman TS, editors. Bennett and Elliott's physiology and medicine of diving. 5th edition. Philadelphia: WB Saunders; 2003. p. 600–50.
[151] Pons M, Blickenstorfer D, Oechslin E, et al. Pulmonary oedema in healthy persons during scuba-diving and swimming. Eur Respir J 1995;8:762–7.
[152] Balk M, Goldman JM. Alveolar hemorrhage as a manifestation of pulmonary barotrauma after scuba diving. Ann Emerg Med 1990;19:930–4.
[153] Harris JB, Stern EJ, Steinberg KP. Scuba diving accident with near drowning and decompression sickness. Am J Radiol 1995;164:592.
[154] Weiler-Ravell D, Shupak A, Goldenberg I, et al. Pulmonary oedema and haemoptysis induced by strenuous swimming. BMJ 1995;311:361–2.
[155] Hampson NB, Dunford RG. Pulmonary edema of scuba divers. Undersea Hyperb Med 1997;24:29–33.
[156] Slade JB, Hattori T, Ray CS, et al. Pulmonary edema associated with scuba diving. Chest 2001;120: 1686–94.
[157] Gnadinger CA, Colwell CB, Knaut AL. Scuba diving-induced pulmonary edema in a swimming pool. J Emerg Med 2001;21:419–21.
[158] Shupak A, Weiler-Ravell D, Adir Y, et al. Pulmonary oedema induced by strenuous swimming: a field study. Respir Physiol 2000;121:25–31.
[159] West JB. Invited review: pulmonary capillary stress failure. J Appl Physiol 2000;89:2483–9.
[160] Hopkins SR, Schoene RB, Martin TR, et al. Intense exercise impairs the integrity of the pulmonary blood-gas barrier in elite athletes. Am J Respir Crit Care Med 1997;155:1090–4.
[161] Hopkins SR, Schoene RB, Henderson WR, et al. Sustained submaximal exercise does not alter the integrity of the lung blood-gas barrier in elite athletes. J Appl Physiol 1998;84:1185–9.
[162] Mahon RT, Kerr S, Amundson D, et al. Immersion pulmonary edema in special forces combat swimmers. Chest 2002;122:383–4.
[163] Lund KL, Mahon RT, Tanen DA, et al. Swimming-induced pulmonary edema. Ann Emerg Med 2003; 41:251–6.
[164] Shupak A, Guralnik L, Keynan Y, et al. Pulmonary edema following closed-circuit oxygen diving and strenuous swimming. Aviat Space Environ Med 2003;74:1201–4.
[165] Hempe S, Lierz P. Akutes Lungenödem bei einer Taucherin. Anasthesiol Intensivmed Notfallmed Schmerzther 2003;38:648–50.
[166] Halpern P, Gefen A, Sorkine P, et al. Pulmonary oedema in scuba divers: pathophysiology and computed risk analysis. Eur J Emerg Med 2003;10:35–41.
[167] Wilmshurst P. Cardiovascular problems in divers. Heart 1998;80:537–8.
[168] Elliott DH. Medical evaluation for commercial diving. In: Bove AA, editor. Bove and Davis' diving medicine. 3rd edition. Philadelphia: WB Saunders; 1997. p. 361–71.
[169] Jenkins C, Anderson SD, Wong R, et al. Compressed air diving and respiratory disease. Med J Aust 1993; 158:275–9.
[170] British Thoracic Society Fitness to Dive Group. A subgroup of the British Thoracic Society Standards of Care Committee. British Thoracic Society guidelines on respiratory aspects of fitness for diving. Thorax 2003;58:3–13.
[171] Heritiér F, Russi E. Scuba diving: barotrauma, decompression sickness, pulmonary contraindications. Schweiz Med Wochenschr 1993;123:161–5.
[172] Neuman TS, Bove AA, O'Connor RD, et al. Asthma and diving. Ann Allergy 1994;73:344–50.
[173] Twarog F, Weiler JM, Wolf SI, et al. Discussion of risk of scuba diving in individuals with allergic and respiratory diseases. J Allergy Clin Immunol 1995; 96:871–3.
[174] Anderson AD, Brannan J, Trevillion L, et al. Lung function and bronchial provocation tests for intending divers with a history of asthma. SPUMS J 1995; 25:233–48.
[175] Heritiér F. Lungs and underwater diving. Rev Med Suisse Romande 1997;117:475–8.
[176] Russi EW. Diving and the risk of barotrauma. Thorax 1998;53(Suppl 2):S20–4.
[177] Tetzlaff K, Reuter M. Pneumologische Aspekte der Tauchmedizin. Pneumologie 1998;52:489–500.
[178] Dillard TA, Ewald FW. The use of pulmonary function testing in piloting, air travel, mountain climbing, and diving. Clin Chest Med 2001;22: 795–816.
[179] Krieger BP. Diving: what to tell the patient with asthma and why. Curr Opin Pulm Med 2001;7:32–8.
[180] Coëtmeur D, Briens E, Dassonville J, et al. Asthme et pratique de la plongée sous-marine. Contre-indication absolue pour quells asthmas? Rev Mal Respir 2001; 18:381–6.
[181] Tetzlaff K, Muth CM, Waldhauser LK. A review of asthma and scuba diving. J Asthma 2002;39: 557–66.

[182] Koehle M, Lloyd-Smith R, McKenzie D, et al. Asthma and recreational scuba diving. Sports Med 2003;33:109–16.
[183] Leffler CT, White JC. Recompression treatments during the recovery of TWA Flight 800. Undersea Hyperb Med 1997;24:301–8.
[184] Corson KS, Dovenbarger JA, Moon RE, et al. Risk assessment of asthma for decompression illness [abstract]. Undersea Biomed Res 1991;18(Suppl): 16–7.
[185] Glen S, White S, Douglas J. Medical supervision of sport diving in Scotland: reassessing the need for routine medical examinations. Br J Sports Med 2000; 34:375–8.
[186] Tetzlaff K, Muth CM. Demographics and illness prevalence of scuba diving asthmatics [abstract]. Eur Respir J 2003;22(Suppl 45):418s.
[187] Cresp R, Grove C, Lalor E, et al. Health status of recreational scuba divers in Western Australia. SPUMS J 2000;30:226–30.
[188] Bove AA, Neuman T, Kelsen S, et al. Observation on asthma in the recreational diving population [abstract]. Undersea Biomed Res 1992;19(Suppl):18.
[189] Hanson E, Fleisher J, Jackman R, et al. Demographics and illness prevalence in a recreational scuba diver population: fitness to dive [abstract]. Undersea Hyperb Med 1999;26(Suppl):48.
[190] Farrell PJS, Glanvill P. Diving practices of scuba divers with asthma. BMJ 1990;300:166.
[191] Taylor DM, O'Toole KS, Ryan CM. Experienced, recreational scuba divers in Australia continue to dive despite medical contraindications. Wilderness Environ Med 2002;13:187–93.
[192] Ziser A, Väänänen A, Melamed Y. Diving and chronic spontaneous pneumothorax. Chest 1985;87:264–5.
[193] Robinson LA, Rolfe MW. Keeling syndrome—a late complication of pneumonectomy. N Engl J Med 1996;335:1074.
[194] Tetzlaff K, Reuter M, Kampen J, et al. Hyperbaric chamber-related decompression illness in a patient with asymptomatic pulmonary sarcoidosis. Aviat Space Environ Med 1999;70:594–7.
[195] South Pacific Underwater Medicine Society. The SPUMS recreational diving medical. Reprinted December 1999. Available at: http://www.spums.org.au/SPUMS_Medical_1999_web.pdf. Accessed June 22, 2005.
[196] Crosbie WA, Clarke MB, Cox RAF, et al. Physical characteristics and ventilatory function of 404 commercial divers working in the North Sea. Br J Ind Med 1977;34:19–25.
[197] Crosbie WA, Reed JW, Clarke MC. Functional characteristics of the large lungs found in divers. J Appl Physiol 1979;46:639–45.
[198] National Asthma Education and Prevention Program. Expert panel report 2. Guidelines for the diagnosis and management of asthma. National Institutes of Health Publication No. 97–4051. Bethesda (MD): National Institutes of Health; 1997.
[199] National Asthma Education and Prevention Program. Expert panel report 2. Guidelines for the diagnosis and management of asthma. Update on selected topics 2002. National Institutes of Health Publication No. 02–5074. Bethesda (MD): National Institutes of Health; 2003.
[200] Holzer K, Anderson SD, Douglass J. Exercise in elite summer athletes: challenges for diagnosis. J Allergy Clin Immunol 2002;110:374–80.
[201] Tetzlaff K, Neubauer B, Reuter M, et al. Atopy, airway reactivity and compressed air diving in males. Respiration (Herrlisheim) 1998;65:270–4.
[202] Tetzlaff K, Staschen CM, Struck N, et al. Respiratory effects of a single dive to 50 meters in sport divers with asymptomatic respiratory atopy. Int J Sports Med 2001;22:85–9.
[203] Cirillo I, Vizzaccaro A, Crimi E. Airway reactivity and diving in healthy and atopic subjects. Med Sci Sports Exerc 2003;35:1493–8.
[204] Bohadana A, Teculescu D, Martinet Y. Mechanisms of chronic airway obstruction in smokers. Respir Med 2004;98:139–51.
[205] Buch DA, El Moalem H, Dovenbarger JA, et al. Cigarette smoking and decompression illness severity: a retrospective study in recreational divers. Aviat Space Environ Med 2003;74:1271–4.
[206] Dillard TA, Ewald FW. Should divers smoke and vice versa? Aviat Space Environ Med 2003;74: 1275–6.
[207] Davey IS, Cotes JE, Reed JW. Relationship of ventilatory capacity to hyperbaric exposure in divers. J Appl Physiol 1984;56:1655–8.
[208] Watt S. Effect of commercial diving on ventilatory function. Br J Ind Med 1985;42:59–62.
[209] Thorsen E, Segadal K, Kambestad B, et al. Divers' lung function: small airways disease? Br J Ind Med 1990;47:519–23.
[210] Tetzlaff K, Friege L, Reuter M, et al. Expiratory flow limitation in compressed air divers and oxygen divers. Eur Respir J 1998;12:895–9.
[211] Dmitrouk AI, Gulyar SA, Ilyin VN, et al. Physiological mechanisms of adaptation of divers to the condition of deepwater in the Antarctic. In: Sterk W, Geeraedts L, editors. Proceedings of 16th Annual Meeting of the European Biomedical Society. Amsterdam; 1990. p. 311–9.
[212] Bouhuys A, Beck GJ. Large lungs in divers? J Appl Physiol 1979;47:1136–7.
[213] Skogstad M, Thorsen E, Haldorsen T. Lung function over the first 3 years of a professional diving career. Occup Environ Med 2000;57:390–5.
[214] Skogstad M, Thorsen E, Haldorsen T, et al. Lung function over six years among professional divers. Occup Environ Med 2002;59:629–33.
[215] Thorsen E, Segadal K, Kambestad BK, et al. Pulmonary function one and four years after a deep saturation dive. Scand J Work Environ Health 1993; 19:115–20.
[216] Thorsen E, Kambestad BK. Persistent small air-

ways dysfunction after exposure to hyperoxia. J Appl Physiol 1995;78:1421–4.

[217] Bermon S, Lapoussiere JM, Dolisi C, et al. Pulmonary function of a firemen-diver population: a longitudinal study. Eur J Appl Physiol 1994;69:32–5.

[218] Thorsen E, Segadal K, Kambestad B. Characteristics of the response to exercise in professional saturation divers. Undersea Biomed Res 1991;18:93–101.

[219] Thorsen E, Irgens Å, Grønning M, et al. Prevalence of obstructive lung disease among retired North Sea divers [abstract]. Undersea Hyperb Med 2003; 30(Suppl):223.