Sports-related lung injury during breath-hold diving

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ABSTRACT The number of people practising recreational breath-hold diving is constantly growing, thereby increasing the need for knowledge of the acute and chronic effects such a sport could have on the health of participants. Breath-hold diving is potentially dangerous, mainly because of associated extreme environmental factors such as increased hydrostatic pressure, hypoxia, hypercapnia, hypothermia and strenuous exercise.

In this article we focus on the effects of breath-hold diving on pulmonary function. Respiratory symptoms have been reported in almost 25% of breath-hold divers after repetitive diving sessions. Acutely, repetitive breath-hold diving may result in increased transpulmonary capillary pressure, leading to noncardiogenic oedema and/or alveolar haemorrhage. Furthermore, during a breath-hold dive, the chest and lungs are compressed by the increasing pressure of water. Rapid changes in lung air volume during descent or ascent can result in a lung injury known as pulmonary barotrauma. Factors that may influence individual susceptibility to breath-hold diving-induced lung injury range from underlying pulmonary or cardiac dysfunction to genetic predisposition.

According to the available data, breath-holding does not result in chronic lung injury. However, studies of large populations of breath-hold divers are necessary to firmly exclude long-term lung damage.

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Introduction

The breath-hold diving technique has long been used in the pursuit of seafood and pearls. Japanese and Korean "ama" pearl divers specialise in free diving in the cold sea to collect food and pearls in a practice dating back 2000 years; they continue to dive to this day, without any modern diving equipment. The number of people practising recreational breath-hold diving is increasing continuously, with the sport gaining in popularity. Physiological limits achieved in breath-hold diving have been extended progressively in all categories of the sport, due to improvements in the training process and swimming gear (fins, suits and masks). For example, the current world record in the no-limit discipline (passive descent using

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weights and ascent using an inflated balloon) in males is 214 m of sea water, suggesting that these unique athletes can briefly sustain external hydrostatic pressure of ~22 atm, which is considered extreme even for self-contained underwater breathing apparatus (scuba) divers. Breath-hold divers (BHDs) compete in different disciplines such as static and dynamic apnoea, constant weight and no limit. In the static apnoea discipline the diver floats motionless face-down in a pool; during dynamic apnoea, the diver swims underwater to attain maximal distance. In deep diving disciplines such as constant weight, divers swim down as deeply as possible along a vertically suspended rope using fins; the no-limit discipline encompasses passive exposure to high pressure, often using a heavy metal bar grasped by the diver to descend to great depths. During static and dynamic apnoea, divers are exposed to progressively increasing hypoxic hypercapnia at very low hydrostatic pressure, while in constant-weight diving, divers experience progressive hyperoxic hypercapnia during descent and at the bottom. The hypoxic hypercapnia is experienced only at the end of the dive just below the surface (an effect of rapid reduction in surrounding pressure that leads to chest expansion).

Breath-holding, with or without water immersion, results in complex cardiovascular adjustments that occur even before a change in arterial blood gases, and can be summarised as the "diving response". The response includes bradycardia, reduced cardiac output, increased arterial blood pressure and peripheral vasoconstriction [1, 2]. These changes are caused by the simultaneous activation of the sympathetic and parasympathetic nervous system and seem to reduce oxygen consumption in peripheral tissues and ensure sufficient oxygen supply of the vital organs [3]. The only organs that maintain or increase blood flow during prolonged breath-holds are the liver and brain, whereas even myocardial perfusion is reduced by 30% [4]. Hypoxaemia and hypercapnia serve as additional stimuli to increase sympathetic tone [5]. Maximal voluntary apnoea consists of two temporally distinct phases: during the initial or "easy-going" phase no significant chest movement is evident; in the "struggle" phase, the subject feels an ever-growing urge to breathe and shows progressive involuntary breathing movements that last until a breaking-point is reached and the glottis opens [6]. As the reduction of cardiac output occurs during the easy-going phase, involuntary breathing movements in the struggle phase cause waves of negative intrathoracic pressure that act to normalise venous return to the heart [7]. Furthermore, involuntary breathing movements participate in central hemodynamic homeostasis during apnoea by maintaining cardiac output and consequently the cerebral oxygenation throughout the struggle phase [8, 9].

BHDs generally comprise a young and athletic population without known chronic ailments. But how does a healthy lung respond when pushed to extremes of physiology? The incidence of lung injuries in BHDs remains unspecified, largely because divers with minor discomfort may not seek medical attention. One study has reported acute respiratory symptoms in nearly 25% of BHDs after repetitive breath-hold diving [10]. However, the question remains whether recurrent minor injuries lead to long-term damage, given the large number of subjects exposed to repetitive apnoeas. Recreational breath-hold diving carries many risks, mainly because of major physiological stressors that arise in the extreme environment, for instance increased hydrostatic pressure, hypoxia, hypercapnia, hypothermia and strenuous exercise. Exposure to moderate to excessive depths may result in severe complications, such as pulmonary barotrauma during ascent or descent, lung collapse, pulmonary oedema with alveolar haemorrhage, cardiac arrest, blackout, nitrogen narcosis, decompression sickness and even death [11]. It is important to bear in mind that relatively shallow repetitive apnoea dives are performed not only by elite BHDs, but also by spear fishermen, underwater hockey and rugby players and synchronised swimmers. Thus, physiological assessments of the acute and long-term effects on the human body may have further reaching importance than in BHDs alone. A single mechanism responsible for the development of lung injury related to diving and immersion has not yet been identified, but a combination of factors is likely to be involved: lung and heart compression (descent) and expansion (ascent), alterations in pulmonary capillary integrity and increased intrathoracic blood volume, cardiac output and pulmonary arterial pressure [12, 13]. Lack of available instruments for monitoring vital physiological parameters while the subject is submerged presents a major limitation in mechanistic investigations of the cause of lung injury in breath-hold diving.

This review focuses solely on the acute and chronic effects of breath-hold diving on lung tissue and function. For other aspects of breath-hold diving physiology and pathophysiology, see other reports [11, 14–16]. A literature search using PubMed was conducted, using the keywords "breath-hold diving" or "apnoea diving" and "lung injury" or "pulmonary oedema" or "haemoptysis". Some of the experimental data were collected in dry conditions, and some in wet conditions during field diving.

Respiratory pathophysiology during and after breath-hold diving

After repetitive breath-hold dives, divers are known to experience symptoms such as cough and a sensation of chest constriction accompanied by various degrees of dyspnoea [17, 18]. These symptoms may occur in scuba divers, swimmers or in athletes otherwise engaged in strenuous activity [19, 20].

For gas exchange to be effective, the pulmonary blood–gas barrier needs to be extremely thin and fine, while keeping its strength and ability to ensure integrity. If the transpulmonary pressure rises to values higher than the membrane can withstand, disruption of the capillary endothelium and alveolar epithelium will occur. Such stress failure may cause increased permeability and protein leakage, or even haemorrhage in more serious cases [21]. A moderate rise of capillary transmural pressure causes leakage of low protein fluid and hydrostatic oedema, while a larger disruption may result in leaks that are high in protein [12]. Therefore, a rise in transpulmonary capillary wall pressure is considered to be a common denominator for development of both noncardiogenic oedema and alveolar haemorrhage with haemoptysis.

Total lung capacity (TLC) is achieved by the respiratory muscles distorting the chest wall to a maximal volume that can be attained in spite of lung recoil. Lowest possible volume, or residual volume (RV), is attained by the respiratory muscles distorting the chest wall toward a minimal volume that is limited by airway closure [22, 23]. For a long time, conventional wisdom taught that the maximal breath-hold depth is limited by the compression of lung volume below RV, leading to "lung squeeze" that could result in lung rupture [24]. Yet world records repeatedly exceed predictions based on this depth-limit model, challenging current respiratory physiological knowledge. Alterations in TLC and RV are possible and can be advantageous to BHDs. They can be achieved through glossopharyngeal breathing, a manoeuvre first described in the 1950s, in post-poliomyelitic patients with severe respiratory muscle weakness. Patients fought the weakness by swallowing air into their lungs, thus increasing their vital capacity and prolonging off-respirator time [25]. Hence, with glossopharyngeal insufflation (GPI), by engulfing additional air into the lung, a new larger maximal volume can be achieved before the dive. Divers are thereby able to reach greater depths, store surplus oxygen and add space for storage of carbon dioxide (CO_2). However, this manoeuvre is not without consequence, and may itself lead to deleterious changes in pulmonary mechanics and even pulmonary barotrauma due to increased permeability of pulmonary capillaries and elevated transpulmonary pressure [16, 26, 27]. Additionally, GPI leads to increased intrathoracic pressure which impedes venous return [28] and consequently decreases cardiac output [4, 27, 29]. These profound haemodynamic changes may result in a prompt drop in systemic arterial blood pressure and syncope, which can easily lead to a fatal outcome if occurring underwater [15, 28, 30]. In contrast, glossopharyngeal exsufflation is used to further decrease RV and reduce lung recoil by constantly deforming the chest to ever-smaller volumes [25].

Pulmonary barotrauma

Pulmonary barotrauma is a lung injury induced by rapid changes in intrapulmonary pressures related to surrounding pressure at depth. Even a small pressure difference may result in pulmonary barotrauma and can present as pneumomediastinum, pneumothorax, pneumopericardium, or at worst, arterial gas emboli (AGE). These events may occur during ascent or descent [31] and often occur in divers who perform GPI [26]. For detailed aspects of pulmonary barotrauma see other reports [32].

During descent, as the surrounding water pressure rises, the air in the lungs decreases in volume as far as the rigidity of the thorax permits. Below the RV threshold, the air volume can no longer decrease so the intrathoracic pressure decreases, resulting in lung squeeze and ensuing atelectasis. The external increase in hydrostatic pressure also compresses peripheral leg and abdominal veins, initiating a blood shift towards the chest, with possible rupture of the alveolar capillary membrane and filtration of fluid and blood into the alveolar space [14, 16]. Diving that involves lung squeeze results in reduced dynamic spirometry values [13]. During ascent, lung volume expands and the diver must exhale in order to keep intrapulmonary pressures close or equal to the surrounding pressure. If the diver does not exhale properly, lung volume increases, with overdistention of alveoli and bronchi leading to possible rupture [33]. The usual reason for pulmonary barotrauma is the diver's ascending technique. If the alveolar membrane ruptures, air infiltrates the peribronchial space and causes emphysema, pneumomediastinum, pneumopericardium or pneumothorax. If the gas further penetrates the systemic circulation through disrupted lung vasculature and reaches the brain or heart vasculature it may cause AGE with severe neurological or coronary consequences [34, 35].

In breath-hold diving the individual experiences hyperoxia during descent and hypoxia during ascent. Hypoxic loss of consciousness is a grave effect of breath-hold diving and must be mentioned because of its fatal nature. Hyperventilation prior to the dive lowers the arterial partial pressure of CO_2 and thereby impedes respiratory drive (typically occurring when CO_2 tension rises to 45–60 mmHg) [36]. Even though the diver experiences hyperoxia during descent, if the breath-hold is prolonged by a delayed reappearance of the stimulus to breathe, oxygen decreases due to metabolic consumption and decreasing ambient pressure during ascent. Once the individual's oxygen reserve is exhausted, loss of consciousness ensues, often just a few metres below the water surface, hence the term "shallow water blackout" [37]. Such severe diving accidents are common among spear-fishermen, who perform repetitive deep dives with prolonged breath-hold in order to collect seafood, particularly if they practice diving without a buddy.

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Noncardiogenic oedema and haemoptysis

Swimming-induced pulmonary oedema or immersion pulmonary oedema has been known to occur in otherwise healthy swimmers and divers, sometimes with severe complications and even fatal outcomes [19]. The oedema is often noted in swimmers who are performing strenuous exercise in the water. The exact pathophysiology of the immersion oedema and possible risk factors are still largely unknown. Bronchoalveolar lavage analysis ruled out an inflammatory process as the background for the development of oedema [38]. The prevailing theory claims that several factors, such as increased intrathoracic blood volume and cardiac output, increased pulmonary vasoconstriction and an individually smaller pulmonary lymphatic network contribute to increased hydrostatic pressure that leads to pulmonary capillary stress failure [38, 39]. High pulmonary vascular pressure occurs during immersion as a result of a central blood volume shift, augmented by active vasoconstriction in cold water and the diving reflex [40]. The type of exercise performed during immersion influences the risk of pulmonary oedema, with high-intensity exercise of short duration posing a greater risk than prolonged low-intensity exercise [41]. Exposure to altitude may result in a similar kind of noncardiogenic pulmonary oedema, known as high-altitude pulmonary oedema (HAPE). HAPE is strongly associated with an increase in pulmonary pressure and exercise, comparable to immersion oedema, and is probably caused by stress failure of the pulmonary capillaries [42, 43].

Immersion pulmonary oedema manifests as dyspnoea, cough, expectoration of frothy sputum and hypoxaemia [44]. Auscultation reveals bibasilar rales, with a pulmonary oedema pattern seen on the chest radiograph. The disorder is transient and clears on chest radiography in 7 days [45]. It is common to find decreased forced vital capacity and forced expiratory volume in 1 s, and increased levels of brain natriuretic peptide (indicative of left ventricle strain) after the oedema is resolved [46]. The interstitial pulmonary oedema may be present in its subclinical form and detected by the presence of extravascular lung comets using ultrasound [47]. This sign of extravascular lung water has been shown to vary on several factors, with depth and effort the most prominent [48]. The oedema usually resolves spontaneously within 24 h, which can be accelerated using β_2-adrenergic agonist or diuretic therapy [49].

Haemoptysis due to alveolar haemorrhage induced by breath-hold diving could be explained by the immense cardiovascular changes that happen during apnoea and immersion [14, 50], and can often be interpreted as a sign of underlying pulmonary oedema. Immersion in water along with exposure to a cold environment induces an increase in intrathoracic blood volume and cardiac output [17], as well as pulmonary capillary pressure. The risk of alveolar haemorrhage is further increased by negative pressure that develops inside the alveoli due to involuntary breathing movements during the struggle phase of apnoea with a closed glottis [51]. The ratio between TLC and RV is an important factor in sustaining lung tissue and function at depth. As mentioned earlier, during field diving a redistribution of blood occurs from the periphery towards the intrathoracic vascular compartment. This effect is present during mere head-out immersion, but becomes more pronounced during deep diving. At great depths transthoracic pressure becomes progressively negative, drawing the blood from the periphery into the thorax, on occasion resulting in a blood shift up to 1500 mL [52]. Pulmonary capillaries protrude into the alveolar spaces, replacing air, thus resulting in a decrease of RV and extension of the depth limit. However, this feature further enhances the risk of alveolar haemorrhage by causing the pulmonary capillary pressure to rise [12]. Moreover, it has been noted that divers sometimes use voluntary diaphragmatic contractions as a way to prolong their breath-hold time. Such contractions cause swings of markedly negative intrapulmonary pressure, thus increasing venous return, pulmonary blood volume and pulmonary capillary pressure. Thus, diaphragmatic contraction may act as a contributing factor in the development of haemoptysis after breath-hold diving [18]. Anecdotal evidence from diving research has shown that divers sometimes take aspirin prior to a dive to enhance their performance and alleviate post-diving headache. Caution is needed in such cases, as aspirin may aggravate alveolar haemorrhage through its antiplatelet effect, although it is known that the drug is not likely to cause spontaneous bleeding from intact vessels [17]. Combination of all these factors in diving leads to a great increase in pulmonary capillary pressure, and ultimately may result in a loss of pulmonary capillary membrane integrity.

Individual susceptibility to dive-related lung injury

As lung volume changes during diving, so does transpulmonary pressure. Clinicians routinely avoid airway pressures >30 cmH_2O in order to prevent possible barotrauma or even pleural rupture in mechanically ventilated patients [53]. The ability to tolerate high transpulmonary pressures depends on the structural thickness of the pleura, among other factors. For example, some mammals with thin pleural membranes are often intolerant of high airway pressures, while others with a thicker membrane show greater tolerance of high pressures [23]. In humans, pleural membrane thickness seems to vary between individuals, although it is not clear whether this is an effect of training or natural selection. Some humans are evidently able to tolerate much larger transpulmonary pressures than is expected of general population. Thus, a somewhat thinner pleural membrane could be an additional factor in susceptibility to diving-induced lung injury.

Even though breath-hold diving-induced pulmonary oedema often appears in otherwise healthy people, it is more likely that an older population of divers, some of whom may have undiagnosed cardiac or pulmonary dysfunction, could have a greater risk of developing the illness. Subclinical cardiopulmonary dysfunction can be exacerbated by immersion and strenuous exercise during diving or swimming, thereby increasing the risk of immersion oedema. In addition, valvular dysfunction and hypertension [54], as well as high airway pressure and obesity [44, 49], may augment the likelihood of the development of oedema. Moon *et al.* [19] demonstrated an exaggerated increase in mean pulmonary artery pressure and pulmonary artery wedge pressure in individuals with a history of swimming-induced pulmonary oedema. Therefore, in individuals with a history of immersion pulmonary oedema, there should be an evaluation and search for predisposing conditions, specifically hypertension, valvular heart disease, diabetes, lung disease and silent coronary disease. Since it has been found that individuals who have already experienced immersion pulmonary oedema have a higher potential for recurrence, they should be warned accordingly.

Inspired by similar changes occurring in populations living at high altitude [55], Cialoni *et al.* [56] proposed involvement of endothelial nitric oxide synthase, otherwise associated with regulation of peripheral vascular tone and blood flow. It has been suggested that there is a specific relationship between the susceptibility to breath-hold diving-induced haemoptysis and polymorphism of several genes involved in the regulation of vascular resistance, notably pulmonary haemodynamics. Cialoni *et al.* searched for differences in genetic variants of the investigated polymorphism (angiotensin-converting enzyme gene insertion/deletion, endothelial nitric oxide synthase G894T and T786C) between BHDs who had previously experienced haemoptysis after diving, and those who did not. Individuals prone to developing HAPE showed reduced production of nitric oxide and TT genotypes of the G894T polymorphism [56]. In the subjects that were not prone to breath-hold diving-induced haemoptysis, the same allele was found as in populations that had lived at very high altitudes for millennia. These genotypes evidently increase tolerance to a hypoxic environment and reduce the possibility of the development of pulmonary oedema [57]. Hence, the pathogenesis of diving-induced haemoptysis may well be correlated to the enzymes responsible for vasomotor tone.

It is necessary to test pulmonary function using conventional spirometry and by determining expiratory flow rates in order to assess fitness to dive. The goal is to detect possible airway obstruction that may augment the risk of pulmonary barotrauma. Tetzlaff *et al.* [58] found a lower pre-injury mid-expiratory flow rate at 25% of vital capacity (indicative of small airways disease) in divers who suffered barotrauma. Other factors that may contribute to the risk of pulmonary barotrauma include a history of respiratory disease (asthma or chronic obstructive lung disease), pre-existing lung cysts, acute infections and rapid ascent without exhaling [59, 60].

Long-term effects of breath-hold diving

Data on the long-term effects of breath-hold diving are rather scarce. No prospective lung function studies have been reported regarding pathophysiological effects in elite competitive BHDs, but it has been speculated that performing GPI could be damaging to the lung tissue and carries the risk of developing chronic pulmonary hypertension [61]. Extremely elevated transpulmonary pressures that occur with GPI could lead to parenchymal changes in the lung tissue, similar to barotrauma after mechanical ventilation [62]. Furthermore, the voluntary hyperinflation manoeuvre results in an acute impairment of pulmonary circulation, similar to pulmonary arterial hypertension [63]. However, in one study, 3-year follow-up measurements for three divers constantly performing dives with GPI showed no lung damage and no changes in lungs distensibility. In contrast, mean ventilator volumes increased over time, which can probably be attributed to an intensive training effect [64]. In cases where GPI had caused chronic damage to the airways and lung tissue, a decline in forced expiratory volumes would be expected. Thus, it seems that the stress on lung tissue is transient and reversible. Along with increased spirometry functions in the long term, BHDs demonstrate excellent CO_2 tolerance, which is probably a training-induced adaptation to frequent hypercapnia [65] rather than an inherited phenomenon [66]. In another study, breath-hold diving has been associated with favourable adaptations in arterial elasticity and wave reflection [67]. However, the effect of very deep diving on pulmonary function remains unknown, although a correlation has been established between maximum diving depth and pulmonary damage. Ultimately, studies with larger numbers of subjects and a variety of field diving conditions are needed in the future to confirm or dispute these findings.

Conclusion

Acute lung injury in BHDs can present as pulmonary barotrauma, noncardiogenic pulmonary oedema or haemoptysis. Pulmonary barotrauma is a result of rapid changes in intrapulmonary pressures related to surrounding pressure at depth, while noncardiogenic pulmonary oedema and haemoptysis have a common set of contributing factors and develop in response to negative intrathoracic or alveolar pressure, leading to increased transcapillary pressure and fluid extravasation into the alveoli. Lung injury is usually transient, and currently there is no evidence of long-term damage. Furthermore, no cardiac or pulmonary

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abnormalities were found in individuals who suffer from lung injury after breath-hold diving, although individual variation in susceptibility is likely to contribute to the development of lung injury.

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