Changes in lung ultrasound presentation induced by breath-hold diving in a simulated depth competition at Taiwan

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Abstract
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Introduction: Acute respiratory symptoms after diving are common among competitive breath-hold divers. These symptoms, including shortness of breath, cough, haemoptysis, and chest discomfort, are often linked to immersion pulmonary oedema (IPO) or pulmonary barotrauma. This study aimed to evaluate the incidence, clinical presentation, and risk factors of IPO using portable ultrasound devices in a depth competition for breath-hold divers in Taiwan.
Methods: This observational study was conducted during a competition around Liuqiu Island, Taiwan. Twenty-five breath-hold divers participated. Lung ultrasonography was performed pre- and post-diving, along with measurements of basic vital signs. Symptoms and diving history were recorded. The primary outcome measure was B-line score before and after diving.
Results: Following the dive, 7/25 (28%) of divers reported acute respiratory symptoms, 10/25 (40%) showed ultrasound evidence of increased extravascular lung fluid, and 2/25 (8%) met the clinical criteria for IPO, presenting with both symptoms and hypoxaemia ($SpO_2 \leq 95\%$) alongside positive B-lines. B-line scores significantly increased from a median of 4 (range 1–4) to 7 (range 3–13) ($P = 0.048$). Male sex, higher body mass index, and elevated pre-dive systolic blood pressure were significantly associated with positive ultrasound findings. Among all factors, only diving depth remained statistically significant associated with increased post-dive B-line scores (regression coefficient = 0.046) ($P = 0.007$).
Conclusions: The incidence of post-dive acute respiratory symptoms was 28%, and 8% of participants exhibited clinical features of IPO. Positive lung ultrasound findings were observed in 40% of divers, mostly asymptomatic. Maximum diving depth was significantly associated with increased post-dive B-line scores.

Introduction

Breath-hold diving, also known as freediving, is becoming increasingly popular worldwide and has evolved from a recreational activity into a competitive sport. Acute respiratory symptoms following freediving are commonly reported among divers performing deep dives.[1,2] These symptoms include shortness of breath, cough, haemoptysis, chest discomfort, and may even be accompanied by otolaryngological symptoms such as sputum production and voice changes, or neurological symptoms like fatigue. These clinical features are believed to result primarily from two pathophysiological mechanisms: pulmonary barotrauma, related to lung pressure changes during descent, ascent, breath-hold packing, or diaphragmatic contractions, and immersion pulmonary oedema (IPO) associated with central blood pooling and increased pulmonary capillary pressure.[3–5] Collectively, these manifestations are often referred to as 'lung squeeze' within the freediving community. To better categorise these clinical events, the term freediving-induced pulmonary syndrome (FIPS) has recently been proposed as an umbrella term encompassing both conditions, particularly when the exact aetiology cannot be clearly distinguished.[3]

During immersion, the central distribution of blood leads to pulmonary hypertension.[1] When transpulmonary capillary pressure exceeds the balance between hydrostatic and oncotic forces across the alveolar–capillary membrane, fluid may leak into the alveolar space, impairing gas exchange and compromising the blood–gas barrier.[4,6] Compared to other water-based activities such as scuba diving, snorkelling, or surface swimming, freediving causes profound changes in lung volume due to increasing ambient pressure with depth. As divers descend, the reduction in lung volume may lead to alveolar atelectasis and pulmonary vascular engorgement; mechanisms that may contribute to the development of IPO and associated respiratory symptoms. These events are more likely to occur at depths where lung volume falls below the residual volume, a phenomenon that has been reported to occur in many divers at depths beyond 36 m.[1,7] Involuntary diaphragmatic contractions in the 'struggle phase' of apnoea is also postulated to cause blood shifting from pulmonary capillaries to alveoli by creating negative intrathoracic pressure.[8]

Recent clinical studies have used portable ultrasound devices to evaluate divers. Vertical artifacts, known as B-line artifacts or ultrasound lung comets, increase after diving and may indicate extravascular lung fluid accumulation from IPO.[8–10] To investigate the incidence, clinical presentation, and risk factors of IPO in East Asia, a region with limited research, and to establish a suitable lung ultrasound assessment method for prehospital settings, participants of a competition in Taiwan were evaluated using a portable ultrasound device.

Methods

This study was approved by the Foundation Institutional Review Board (approval no. 202100900B0) and conducted according to The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.

PARTICIPANTS

A total of 25 breath-hold divers (16 males and 9 females) participated in the study, with a mean age of 31 (standard deviation [SD] 5) years (range 23–41), height of 169 (SD 8) cm, and weight of 61 (SD 10) kg. Among the participants, 23 were Taiwanese, one was Japanese, and one was British. Informed consent was obtained in writing after explaining the study protocol. The competition organiser was also informed and agreed to cooperate during the event.

STUDY SETTING

To minimise disruption, the study was conducted during a 'simulation' competition three days before the formal event. The competition used a floating system with a buoyancy device on top and a weighted descent line in the open ocean near Liuqiu Island in southern Taiwan. A dive boat followed the system and transported participants after their dives. Once onboard, participants were asked to remove their wetsuits. Sonographic and vital sign measurements were taken within 30 minutes of surfacing. Pre-dive measurements were taken hours earlier on land, and participants were prohibited from diving for at least 12 hours beforehand. According to data from the Central Weather Bureau of Taiwan, the average surface water temperature around Liuqiu Island was 25.7°C, with a low of 23.3°C.

MEASUREMENTS

Lung ultrasonography was performed by the same operator (Y-J C) using a Philips Lumify C5-2 curved-array transducer (Amsterdam, Netherlands). The settings included: lung preset, mechanical index 0.7, image depth 11 cm, and gain 36. The 'after-diving' ultrasound was performed within 30 minutes of surfacing. B-lines were defined as wedge-shaped, laser-like vertical hyperechoic signals originating from the pleural line, extending to the bottom of the screen without fading, and moving in synchronisation with lung sliding. We obtained 6–12 lung ultrasound views, depending on areas not covered by the swimsuit (worn underneath the wetsuit), as shown in Figure 1. Views were taken at the mid-clavicular/mid-axillary and paravertebral lines over both the upper and lower portions on each side, with a 10-second video clip recorded for each view. Two experienced ultrasonography physicians, blinded to the divers' conditions, interpreted the clips and reached consensus on the number of B-lines in each view.

B-lines are vertical reverberation artifacts seen on lung ultrasound, generated when fluid accumulates in the interstitial space. This finding can be observed in conditions such as pulmonary oedema, interstitial lung diseases, and interstitial pneumonia.[11] Three or more B-lines in a single-rib interspace in at least two different intercostal spaces or an increase in more than five B-lines from all studied views after diving were defined as positive findings. These findings, indicating increased extravascular lung fluid, were denoted as 'suspect pulmonary oedema'. The B-line score was used to assess the extent of extravascular lung fluid, calculated by adding the number of B-lines in each view, with a score of one for each B-line. The normalised B-line score was calculated as the total number of B-lines detected in all scanned views for each diver, divided by the number of views successfully obtained.

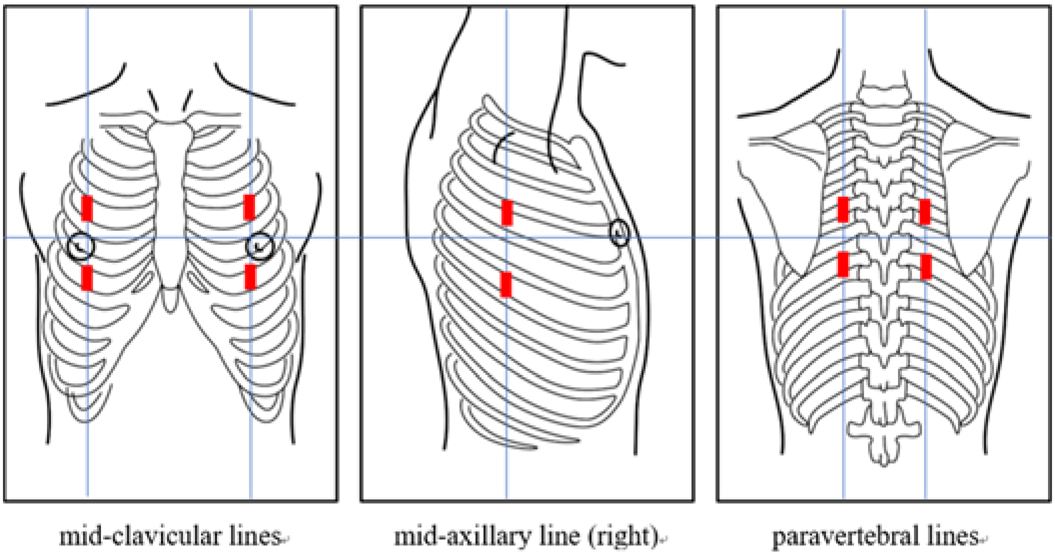
Participants' pulse rate, body temperature, and oxygen saturation were measured before and after diving, while blood pressure was measured prior to diving. Symptoms such as shortness of breath and chest discomfort post-dive were recorded. Divers completed a post-dive questionnaire on underwater conditions and their diving performance. Diving history, illnesses, underlying conditions, and personal history were noted during registration. Training time per month was calculated from the reported training frequency, with 'daily' assumed to be 28 times per month and 'weekly' four times. Adjusted diving experience was calculated by multiplying the diving years by the training frequency factor: (daily × 1, weekly × 0.8, monthly × 0.6, seasonal × 0.4).

DATA ANALYSIS

Continuous variables, such as body height, weight, age, and B-line score, are presented as medians and first to

Figure 1

Ultrasound views for measurement. The upper views are located at the 2nd or 3rd intercostal space along the mid-clavicular lines, the 3rd or 4th intercostal space along the mid-axillary lines, and the 4th or 5th intercostal space along the paravertebral lines. The lower views are at the 4th or 5th intercostal space along the mid-clavicular lines, the 5th or 6th intercostal space along the mid-axillary lines, and the 6th or 7th intercostal space along the paravertebral lines. The percentages shown beneath each view indicate the scan completion rate among all participants. * Views used for subgroup analysis



	Right (pre/post)	Left (pre/post)
Upper	84%/100%*	88%/100%*
Lower	60%/76%	28%/32%

	Right (pre/post)	Left (pre/post)
Upper	88%/92%*	88%/100%*
Lower	56%/64%	52%/64%

	Right (pre/post)	Left (pre/post)
Upper	24%/32%	24%/28%
Lower	80%/88%*	80%/92%*

third quartile (Q1–Q3). Categorical data are presented as numbers and percentages. Linear regression was used to analyse the association between variables and differences in normalised B-line score pre- and post-diving, presented as unstandardised regression coefficients (B) and 95% confidence intervals (CIs).

Results

Among 25 enrolled participants, 23 pre-dive and 25 post-dive lung ultrasound scans were obtained. The median diving experience of these divers was 4.0 years (range 3.0–5.0 years). After adjusting for their frequency of diving (as described above) the adjusted median experience was 3.5 years (range 2.4–4.8 years). The sea conditions and weather during the event were generally calm and warm, although some divers reported encountering currents during their dives. Among the participants, 3/25 (12%) used a monofin for constant-weight dives, 3/25 (12%) did not use any fins, 10/25 (40%) used bi-fins for constant-weight dives, and 9/25 (36%) used the free immersion technique. The median diving depth was 53 m, with a range of 27–77 m and Q1–Q3 = 47–60 m. The median diving time was 109 s (range 98–123 s).

Acute respiratory symptoms, including cough, haemoptysis or bloody sputum, and shortness of breath, were reported in 7/25 (28%) of divers post-dive. Of these seven symptomatic individuals, two presented with both oxygen desaturation ($SpO_2 \le 95\%$) and a marked increase in B-lines on lung ultrasound. When combined with their symptoms, these clinical findings met the operational definition of IPO. Accordingly, the incidence of IPO in this cohort was 8% (2/25 divers).

Lung ultrasonography findings with marked increase in B-lines were observed in 10/25 (40%) of the participants in the post-dive scans. A significant increase was observed in the post-diving B-line score from a pre-dive median of 4 (range 1–4) to 7 post-dive (range 3–13) ($P = 0.048$). Moreover, the normalised B-line score also increased significantly from 0.5 (range, 0.11–0.7) pre-dive to 1.0 (range, 0.44–1.2) post-dive ($P = 0.039$). The difference in the normalised B-line score before and after diving was 0.17 (range, −0.1 to 1), as detailed in Table 2.

Male sex (46.7% vs. 90%, P = 0.040), a higher median body mass index (19.9 vs. 22.4, P = 0.046), and a higher median systolic blood pressure (SBP) before diving (110 vs. 121 mmHg, $P = 0.027$) were significantly associated with positive ultrasound findings. Additionally, deeper diving depths (50 vs 56 m, $P = 0.055$) showed a trend towards significance, suggesting a potential association

Table 1

Clinical characteristics of breath-hold diving contestants (n = 25); data are presented as number (percentage) and median interquartile range (IQR, 25–75%); AIDA – International Association for the Development of Apnea

Parameter	No pulmonary oedema (n = 15)	Suspect pulmonary oedema (n = 10)
Age (years)	30 (28–37)	26 (26–32)
Male sex	7 (46.7%)	9 (90%)
Body height (cm)	165 (159–173)	172 (170–174)
Body weight (kg)	54 (51–67)	66 (60–71)
Body mass index ($kg \cdot m^{-2}$)	19.9 (18.9–22.5)	22.4 (20.6–23.5)
Smoking cigarettes	5 (33.3%)	3 (30%)
Years of smoking	0 (0–0)	0 (0–0)
Training times per month	4 (4–28)	4 (4–4)
Diving experience (years)	5 (3-5)	3.3 (3–5)
Adjusted diving experience	4 (2.4–5.0)	2.8 (2.4–4.0)
Max diving depth (m)	56 (45–70)	68 (55–71)
Max breath-hold time (seconds)	300 (270–330)	289 (255–310)
Diving system and past history		
AIDA	12 (80%)	10 (100%)
Molchanovs	6 (40%)	2 (20%)
Scuba Schools International	4 (26.7%)	1 (10%)
Immersion pulmonary edema	4 (26.7%)	6 (60%)
Blackout or loss of motor control	9 (60%)	4 (40%)
Problems of controlling pressure	4 (26.7%)	5 (50%)
Chronic disease	1 (6.7%)	0 (0%)
Performance category		
Constant weight	2 (13.3%)	1 (10%)
Constant weight without fins	2 (13.3%)	1 (10%)
Constant weight with bi-fins	7 (46.7%)	3 (30%)
Free immersion	4 (26.7%)	5 (50%)
Diving depth (m)	50 (39–60)	56 (50-65)
Diving times (seconds)	109 (83–118)	114 (108–130)
Vital signs before diving		
Peripheral oxygen saturation (%)	98 (97–98)	98 (98–98)
Heart rate ($beats \cdot min^{-1}$)	77 (68–85)	76 (70–88)
Body temperature (°C)	36.5 (36.4–36.8)	36.9 (36.4–36.9)
Systolic blood pressure (mmHg)	110 (100–117)	121 (119–127)
Diastolic blood pressure (mmHg)	72 (70–77)	79 (69–80)
Vital signs after diving		
Peripheral oxygen saturation (%)	98 (96–98)	98 (97–98)
Heart rate ($beats \cdot min^{-1}$)	89 (77–102)	95 (83–109)
Body temperature (°C)	36.3 (36–36.5)	36.6 (36.3–36.6)
Symptoms after diving		
Cough	2 (13.3%)	2 (20%)
Haemoptysis	2 (13.3%)	2 (20%)
Shortness of breath	0 (0%)	1 (10%)

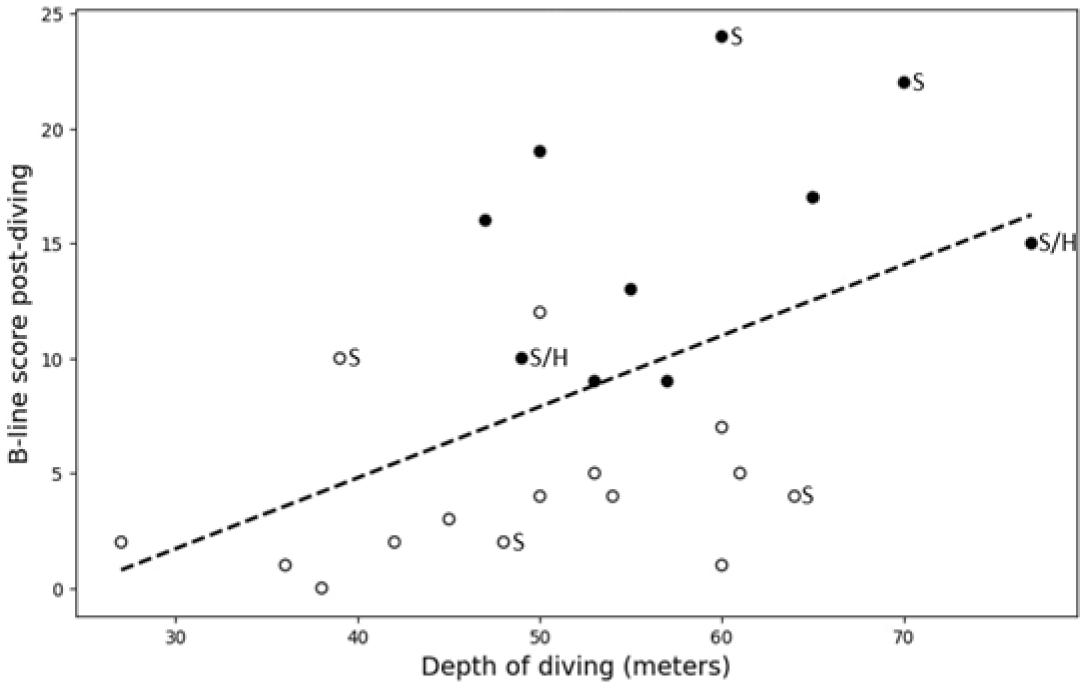
Table 2

Normalised B-line score before and after diving; data are presented as a median interquartile range (IQR 25–75%); * the difference of B-line score and normalised B-line score could be negative if one less B-line is measured after diving

Parameter	Before diving	After diving	P
B-line score	4 (1–7)	7 (3–13)	0.048
Measured views	9 (6–10)	9 (6–10)	0.933
Normalised B-line score	0.5 (0.11–0.7)	1 (0.44–1.2)	0.039
Difference of sonography measurement between before diving and after diving			
Difference of B-line score		2 (-1–8)*	
Difference of normalised B-line score		0.17 (-0.1–1)*	

Figure 2

Scatter plot of post-dive B-line scores versus diving depth; each point represents an individual diver. Suspected pulmonary oedema cases are shown in black. Symptomatic cases are marked with 'S'. Cases with hypoxaemia (SpO_2 ≤ 95%) are marked with 'H'. Cases exhibiting both symptoms and hypoxaemia are labelled 'S/H'



that may become significant with a larger sample size. Linear regression was used to identify the factors associated with increased B-line scores after diving. Among the variables analysed, including sex, body mass index, age, SBP before diving, and diving depth, only diving depth showed a statistically significant association (B = 0.046, *P* = 0.007) (Table 3). Figure 2 shows the relationship between the post-diving B-line score and the diving depth.

A subgroup analysis was conducted on 13 participants to account for variability in the number of ultrasound views obtained. In this subgroup, six specific lung regions were consistently scanned for all participants: the upper mid-clavicular and mid-axillary regions, and the lower paravertebral regions on both the left and right sides, with no missing data. Among these participants, seven were classified as negative and six as suspected for pulmonary oedema. Pre-dive B-line scores did not differ significantly between the two groups (median 3 [range 0–4] vs. 4 [1–7], *P* = 0.385). However, post-dive B-line scores were significantly higher in the suspected pulmonary oedema group (2 [1–3] vs. 8 [6–11], *P* = 0.003), supporting the validity of the simplified six-view protocol in detecting changes related to immersion pulmonary oedema.

Discussion

In European studies, the incidence of IPO among swimmers and divers was 1.1–1.8%.[12,13] The incidence may be underestimated owing to rapid recovery, in which patients might not seek medical assistance if their symptoms subside spontaneously. First-line medical providers may not be familiar with IPO, which may lead to underdiagnosis. In our cohort, the incidence of post-dive respiratory symptoms

Table 3

Linear regression of difference of normalised B-line score between before and after diving; adjusted $R^2 = 0.345$ – proportion of variance in difference of normalised B-line score explained by the multiple linear regression model

Variables	B	95% CI	*P*
Male sex	-0.327	(-1.077 to 0.424)	0.368
Age	-0.023	(-0.075 to 0.028)	0.350
Body mass index	0.119	(-0.001 to 0.238)	0.051
Diving depth	0.046	(0.015 to 0.076)	0.007
Systolic blood pressure	-0.013	(-0.046 to 0.020)	0.403
Adjusted $R^2 = 0.345$			

was 28%, which is consistent with a previously reported incidence of 26.4% among freedivers.[1] In the present study, using lung ultrasonography findings, 40% of the divers were found to have increased extravascular lung fluid, with an incidence of IPO during this event of 8%. The higher prevalence observed in our study may be explained by several factors. First, previous reports of IPO prevalence often combined data from swimmers and scuba divers, populations with different diving physiology and potentially different predispositions to pulmonary oedema. Second, because IPO is typically a self-limiting disorder, its prevalence may have been underestimated in retrospective studies, as divers or swimmers who recovered spontaneously may not have sought medical attention. In our study all participants underwent immediate post-dive evaluation with portable lung ultrasound in addition to symptom reporting, which may have increased the detection of cases that would have been missed by recall alone.

Studies have reported subclinical increases in pulmonary fluid among breath-hold divers and ironman athletes, and B-lines observed via lung ultrasound may typically resolve within 24 hours without evident clinical harm.[2,10,14,15] In our investigation, we observed a median pre-dive B-line score of 4, despite participants having rested for at least 12 hours. This score significantly increased to 7 post-dive, suggesting an accumulation and progression of extravascular lung fluid. In the context of depth training, where repeated deep dives are common and safety protocols may be less comprehensive than during official competitions, this subclinical fluid accumulation warrants further attention. However, the clinical threshold at which these subclinical signs may progress to IPO remains unclear. In this study, IPO diagnosis was defined by clinical symptoms, hypoxaemia, and positive lung sonographic findings, following the concepts proposed by Hårdstedt[16] and Ludwig.[17] This study is among the first to focus on Asian-based breath-hold divers, providing insights valuable for the safety and medical preparation of both divers and competition organisers. Based on the 8% incidence of IPO observed in this event, we recognise the importance of adequate on-site preparedness for potential pulmonary complications. Sufficient oxygen supply should be ensured, along with high FiO_2 delivery equipment, such as non-rebreather masks, bag-valve masks, or oxygen regulators,[18] to provide support for multiple affected participants if needed.

Previous studies have identified several factors associated with IPO, including cold-water immersion, strenuous exercise, tight wetsuits, and overhydration. These factors are believed to exacerbate central blood pooling, thereby increasing the risk of IPO.[12,19–21] In this study, none of the divers reported coldness, although some mentioned experiencing mild-to-moderate sea currents during the dive. A positive correlation was observed between higher B-line scores and the male sex, a higher body mass index, depth, and higher SBP before diving. The association between sex and IPO remains unclear. A recent cohort study on breath-hold divers found more B-lines in male divers,[15] which is consistent with our findings. This may be explained by the fact that male divers tend to dive deeper into competition, which may be a risk factor for IPO. Cardiopulmonary risk factors, including hypertension and overweight, have been viewed as predisposing factors for IPO.[22] It should be noted that the divers enrolled in our study were all healthy and young, with no previously reported chronic diseases, and their body mass index was within the normal range. Only diving depth was significantly associated with increased B-line scores in linear regression analysis, suggesting that sex, SBP, and body mass index may be confounding factors.

The relationship between diving depth and IPO varies depending on the type of immersion activity. For example, depth is not considered a major risk factor for IPO in scuba diving.[12] However, in our study, we found a positive correlation between diving depth and IPO in freediving, which is consistent with previous reports.[10,15] During freediving, the volume of the thoracic cage decreases more slowly than that of the lungs. This volume mismatch exacerbates intrapleural negative pressure,[23] increasing the hydrostatic pressure gradient. This phenomenon is more prominent in dives where the diver's lung volume falls below residual volume, increasing the risk of lung injury due to greater blood shift.[24] Lung atelectasis at greater depths has recently been reported in underwater ultrasound studies.[25] Due to the unique pathophysiology and epidemiology of IPO after freediving, the concept of "*depth-induced pulmonary oedema*" was proposed.[15] To account for the broader spectrum of clinical presentations seen in breath-hold divers, the term freediving-induced pulmonary syndrome (FIPS) has recently been adopted.[3] In a recent study, Yu et al. proposed a classification of FIPS into several distinct phenotypes, including alveolar oedema, interstitial oedema, mixed oedema, alveolar barotrauma, airway barotrauma, and severe FIPS. These subtypes can be differentiated based on clinical findings and symptomatology.[26] In our cohort, IPO was defined by a combination of acute respiratory symptoms, hypoxaemia, and positive B-line findings on lung ultrasound. These features align with the phenotype classified as mixed oedema and severe FIPS. By contrast, divers who exhibited only respiratory symptoms without imaging abnormalities or desaturation may correspond to the airway barotrauma phenotype. However, confirming this diagnosis is challenging in a field setting without appropriate structural evaluation tools, such as laryngoscopy, bronchoscopy, or computed tomography. Although IPO following freediving and other water-based activities may share similar clinical features and partially overlapping mechanisms, the evaluation of fitness to return to diving should differ. The recent SPUMS / UKDMC position statement advises against resuming compressed gas diving after IPO without a comprehensive cardiovascular evaluation.[27] Applying the same criteria to freedivers may not be appropriate, as the pathophysiological context and physical demands of breath-hold diving differ significantly from scuba diving. Finally, while depth remains an important contributing factor, individual variability among divers plays a substantial role. In our study, eight divers who reached depths greater than 50 m showed no symptoms and no ultrasound evidence of pulmonary fluid accumulation. Parameters considering individual factors, such as dive discipline, smoking history, diving experience, and frequency, were evaluated; however, no statistically significant correlations were found.

The lung ultrasound protocol employed in this study was intentionally simplified to facilitate rapid assessment in field conditions. Sonographic images were acquired from six to 12 views along the bilateral mid-clavicular, mid-axillary, and paravertebral lines. Participants were scanned in an upright position, which enabled completion of the examination within 30 minutes after surfacing, even in the confined space of a diving cabin. In earlier ultrasound studies on IPO, researchers typically acquired 28 to 61 intercostal views per participant, with subjects in supine or sitting positions.[10,12,15] Despite the reduced number of scanning sites in our protocol, the B-line counts per view were comparable to those in previously published data, suggesting that the selected views were representative. Additionally, in our subgroup analysis of 13 participants, we observed a similar trend in B-line scores using only six views, specifically the upper mid-clavicular, mid-axillary, and lower paravertebral regions. This supports the feasibility and clinical utility of a six-view lung ultrasound approach. A recent study employed a comparable six-view approach, scanning the bilateral anterior, lateral, and posterior chest regions to record the highest number of B-lines per view (up to three), with a total possible score of 18.[26] Our subgroup findings align with this methodology and offer additional validation. We recommend that future researchers and medical providers consider adopting the six-view protocol, as it offers a practical balance between diagnostic value and operational feasibility, especially in space-limited settings such as diving platforms or boats, while still enabling timely and informative assessments.

This study has some limitations. Firstly, it was a small observational study. Studies with more participants are needed to better clarify the impact of different factors on the presence of B-lines and IPO, as well as to minimise confounders from individuals. The number of B-lines in the pre-test was higher than expected, possibly due to self-performed dive training in the days prior to the study. This suggests that a 12-hour resting period may not be sufficient. Although post-dive lung ultrasound was performed as soon as feasible, unavoidable delays of up to 30 minutes may have reduced B-line detection and led to underestimation of post-dive pulmonary changes. Oxygen inhalation after diving was not limited; hence, the participants may have freely inhaled oxygen regardless of whether they needed it, resulting in a potential overestimation of the oxygen saturation values. In addition, a high fraction of inspired oxygen may promote absorption atelectasis, which could in turn increase the number of B-lines observed on lung ultrasound. Since divers may exert less effort and suffer less mentally and physically in simulation competitions than in formal competitions, the occurrence of IPO may be lower.

Conclusions

The post-dive incidence of acute respiratory symptoms was 28%, and the incidence of IPO, defined by the combination of positive lung ultrasound findings and hypoxaemia, was 2/25 (8%) in this cohort. Positive ultrasound findings indicating increased extravascular lung fluid were observed in 40% of participants. Maximum diving depth was significantly associated with a higher number of post-dive B-lines.

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