Lung function changes in divers after a single deep helium-oxygen dive

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Abstract
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Introduction: This study measured pulmonary function in divers after a single helium-oxygen (heliox) dive to 80, 100, or 120 metres of sea water (msw).
Methods: A total of 26 divers participated, of whom 15, five, and six performed a 80, 100, or 120 msw dive, respectively. While immersed, the divers breathed heliox and air, then oxygen during surface decompression in a hyperbaric chamber. Pulmonary function was measured twice before diving, 30 min after diving, and 24 h after diving.
Results: At 30 min after the 80 msw dive the forced expiratory volume in 1 s (FEV_1)/forced vital capacity (FVC) ratio and the maximum expiratory flow at 25% of vital capacity (MEF_{25}) values decreased (89.2% to 87.1% and 2.57 $L{\cdot}s^{-1}$ to 2.35 $L{\cdot}s^{-1}$, *P* = 0.04, *P* = 0.048 respectively) but FEV_1/FVC returned to the baseline values by 24 h post-dive. Other pulmonary indicators exhibited downward trends at 30 min after the dive, but statistical significance was lacking. Interestingly, though several parameters decreased after the 100 msw dive, statistical significance was not reached. After the 120 msw dive, the FEV_1/FVC and MEF_{75} decreased (90.4% to 85.6% and 8.05 $L{\cdot}s^{-1}$ to 7.46 $L{\cdot}s^{-1}$, *P* = 0.01, *P* = 0.007). The relatively small numbers of subjects who dived to 100 and 120 msw depths may explain the inconsistent results. The subjects diving to 100 and 120 msw were more trained / skilled, but this would not explain the inconsistencies in results between these depths.
Conclusions: We conclude that single deep heliox dives cause a temporary decrease in FEV_1/FEV and MEF_{25} or $MEF_{75,}$ but these changes can recover at 24 h after the dive.

Introduction

Diving is a high-risk operation associated with elevated ambient pressure, altered gaseous characteristics and changes in cardiovascular stress after immersion in water; all impact the lungs.[1] Long-term deep diving (by commercial divers) triggers small airway disease and decreased lung function,[2,3] but such effects have not been found in military or recreational divers.[4–6] If an individual is clinically susceptible, a single dive can change pulmonary function.[7,8] Hyperoxia, venous gas microembolus formation, changes in breathing characteristics, respiratory heating, and water loss are possible adverse effects after a single wet scuba dive.[8,9]

Helium is less soluble and more diffusible than nitrogen. A mixture of helium and oxygen (heliox) serves as the breathing medium during deep dives to avoid the narcotic effects of nitrogen under pressure.[10] Heliox is of lower density than nitrogen and oxygen mixtures (air or nitrox) and facilitates deep diving. The respiratory resistance increases and the dynamic lung volumes decrease as the pressure increases with greater gas density. Breathing of a low-density heliox mixture partially normalises dynamic lung volumes. Heliox breathing reduces airway flow resistance and thus the work of breathing.[11,12] However, high-level respiratory heat loss during heliox diving (due to the physical properties of helium) and the long decompression time under water may negatively affect the human respiratory system. Heat loss from the body surface is greater in a hyperbaric heliox environment than in air.[13] Cold may lead to marked respiratory changes, such as hyperventilation and hypocapnia through neurogenic mechanisms.[14]

A few studies have explored pulmonary effects associated with heliox diving. One reported that a dive to 55 to 80 metres of seawater (msw) breathing trimix (a mixture of helium, nitrogen and oxygen) was associated with accumulation of extravascular lung water and reduced left ventricular contractility.[15] A decrease in the transfer factor for carbon monoxide (TL_{CO}) was observed after eight saturation dives to pressures of 3.1–4.6 MPa.[16] The forced expiratory volume in 1 s (FEV_1)/forced vital capacity (FVC) ratio was reduced after several open-sea, closed-circuit rebreather dives to 90 and 120 msw performed within 4 days; the divers breathed trimix.[17] However, the effect of a single deep heliox dive (to more than 80 msw) on human pulmonary function is unknown. We thus evaluated changes in lung function parameters after single heliox dives to 80, 100, and 120 msw.

Methods

The study was conducted according to the guidelines of the Declaration of Helsinki and was approved by the Ethical Committee of the Naval Medical Center (protocol code 202008). All subjects provided written informed consent.

SUBJECTS

Twenty-six healthy male divers were recruited. Of these divers, 15, five, and six performed 80, 100, and 120 msw heliox dives, respectively. Their baseline characteristics are summarised in Table 1. Health status and previous diving experience were self-reported. All divers met "*The Medical Examination Standards for Professional Divers*" (China National Standard, GB 20827-2007, 2007.08.01). Failure to meet the divers' physical examination standards, or a history of upper respiratory tract infection or Eustachian tube dysfunction in the past week were the exclusion criteria. All study subjects were asked not to smoke, exercise vigorously, and drink coffee before diving.

DIVE PROTOCOL

To reduce in-water and total decompression times we employed surface decompression with oxygen (SURDO$_2$). This fulfills all or part of the decompression requirements using a recompression chamber rather than holding the diver in the water. The reduced time in water aims to prevent dangerous reduction in body temperature. Inside the recompression chamber divers are maintained at a constant pressure and are unaffected by the sea-surface conditions. Dive profiles are shown in Figure 1. Prior to the surface decompression, dives took place in open water conditions with a water temperature of 23–24°C. The decompression profiles were prescribed by a Naval Medical Institution algorithm programmed into a dive computer. During descent at 15–20 m·min^{-1} the diver (wearing a wetsuit) was gradually transitioned from air-breathing to heliox-breathing (He:O$_2$ 82:18 v/v) using surface supply open-circuit breathing apparatus (KMB 28B diving mask, Kirby-Morgan, Santa Maria CA, USA). They remained at depth for 15 min, and returned to the first decompression stop at 6 m·min^{-1}. After converting the breathing gas from heliox to air at the first stop, each diver ascended incrementally (Figure 1) to 12 msw where they changed to breathing 100% oxygen. After 30 min at the 12-msw stop, the diver returned to the surface and within 6 min of leaving 12 msw was recompressed to 15 msw depth equivalent in the hyperbaric chamber (breathing 100% oxygen). The time between surfacing and recompression was 5 min. The SURDO$_2$ procedure is shown in Figure 1.

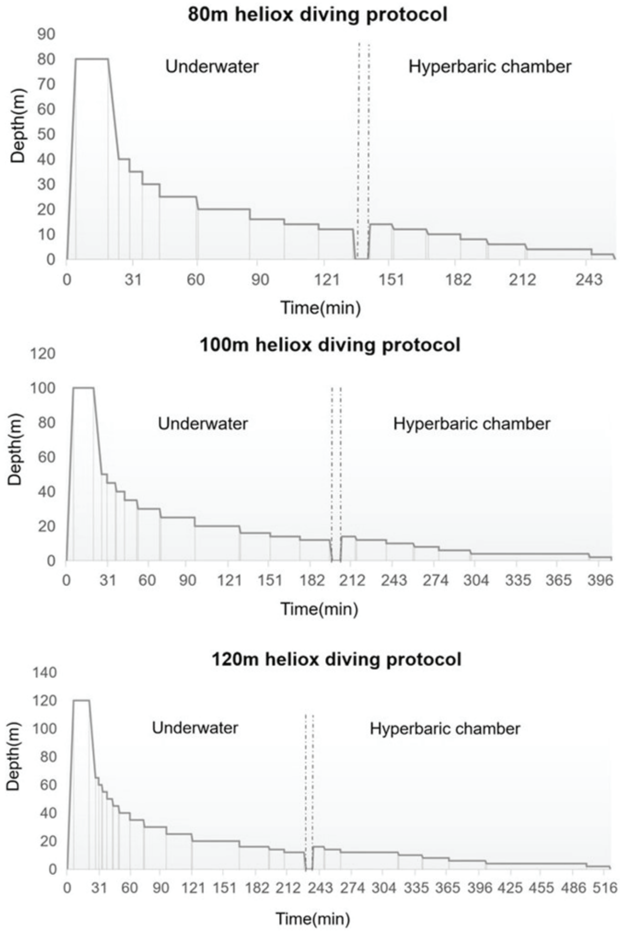
PULMONARY FUNCTION TESTS

For all divers, baseline pulmonary function was measured during the week before diving, at 30 min after completing the SURDO$_2$, and at 24 h after the dive was complete. Pulmonary function tests were recorded using an electronic spirometer (COSMED Inc., Rome, Italy). To reduce variability in the measurement of lung function, all measurements were performed by one person. During the measurement,

Table 1
Characteristics and baseline lung function of divers engaged in heliox diving to different depths; msw – metres of seawater

Parameter	80 msw depth *n* = 15			100 msw depth *n* = 5			120 msw depth *n* = 6		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Age (years)	24.1	4.6	18–32	29.3	2.8	26–33	27.5	2.7	24–31
Body mass (kg)	71.3	9.6	60–88	72.8	6.0	69–85	66.8	4.2	60–72
Height (cm)	174.3	4.1	170–183	173.3	3.2	168–178	172.0	1.7	170–175
Experience (years)	5.2	2.9	2–12	10.8	3.1	7–15	13.0	2.2	10–16
Lung function	**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	
FVC (Z-score)	-0.50	0.91		-0.30	0.68		-0.06	0.78	
FEV$_1$ (Z-score)	-0.31	0.74		0.11	0.58		0.22	0.42	
FEV$_1$/FVC (Z-score)	0.49	1.50		0.58	0.84		0.62	0.98	
FEF$_{25–75\%}$ (Z-score)	-0.30	1.02		0.05	0.59		-0.18	0.42	
MEF$_{25\%}$ (Z-score)	0.06	1.02		0.36	0.51		0.31	0.42	
FEV$_1$/VCmax% (Z-score)	0.49	1.50		0.58	0.84		0.62	0.98	

Figure 1
Decompression procedures after 80, 100 and 120 msw heliox dives



each diver repeated three blows with full force under the guidance of the surveyor. When collecting the baseline value and the data 24 h after the dive, the collection time was fixed in the morning. The data averages obtained during three reproducible flow-volume loops (Standardization of Spirometry 2019 Update[18,19]) were calculated and compared with the baseline averages (again, of three reproducible values) obtained in the morning.

STATISTICAL ANALYSIS

All statistical analyses were performed using GraphPad Prism software. Paired-sample *t*-tests (two-tailed) and unpaired *t*-tests with Welch's correction were performed (based on the distribution normality, as checked by the Shapiro-Wilk test). Normally distributed data are presented as the mean (standard deviation, SD). A *P*-value < 0.05 was considered to indicate statistical significance.

Results

80 MSW DIVE

Compared with the baseline values, the forced expiratory volume in one second/forced vital capacity ratio (FEV_1/FVC) decreased significantly, from 89.2% (SD 8.4) to 87.1% (7.7), at 30 min after diving ($P = 0.04$), but returned to baseline at 24 h after diving (Figure 2, $P = 0.16$). The maximum expiratory flow at 25% of the vital capacity (MEF_{25}) also decreased at 30 min after diving from 2.57 (0.82) $L \cdot s^{-1}$ to 2.35 (0.67) $L \cdot s^{-1}$, $P = 0.048$. It tended to return to baseline at 24 h after diving, but a significant difference from baseline remained, 2.48 (0.73) $L \cdot s^{-1}$ vs 2.57 (0.82) $L \cdot s^{-1}$, $P = 0.048$. The FEV_1, forced expiratory flow at 25–75% of the forced vital capacity ($FEF_{25-75\%}$), and MEF at 50 and 75% of vital capacity ($MEF_{50\%}$ and $MEF_{75\%}$) slightly decreased immediately after diving (compared with the baseline values), but statistical significance was not attained (Figure 2). No other indicator changed significantly after diving.

100 MSW DIVE

Figure 3 shows that after a 100 msw heliox dive, compared with before the dive, all pulmonary function parameters trended downward but not significantly ($P > 0.05$). The FVC, FEV_1, and FEV_1/FVC returned to the baseline values 24 h after diving, whereas the peak expiratory flow (PEF), $FEF_{25-75\%}$, and $MEF_{25\%}$, $MEF_{50\%}$ and $MEF_{75\%}$ decreased further (Figure 3). However, the changes were not significant.

120 MSW DIVE

The results after 120 msw heliox dives were similar to those after 80 msw dives. As Figure 4 shows, compared with the pre-dive data, the FEV_1/FVC decreased markedly, from 90.4 (4.3)% to 85.6 (3.1)% at 30 min after diving ($P = 0.01$) but returned to the baseline value at 24 h after diving ($P = 0.47$). The $MEF_{75\%}$ changes followed a similar pattern. The $MEF_{75\%}$ decreased significantly at 30 min after diving compared with the pre-dive value, 7.46 (1.08) $L \cdot s^{-1}$ vs 8.05 (1.17) $L \cdot s^{-1}$, $P = 0.007$, but returned to baseline at 24 h later, 7.52 (0.96) $L \cdot s^{-1}$, $P = 0.3$. No other indicator was affected by diving.

EFFECTS OF DIVING DEPTH

We compared the lung function changes after 80, 100, and 120 msw heliox dives. Table 2 shows that the FVC, PEF, and $MEF_{75\%}$ at 30 min after diving decreased as the dive depth increased, but the differences were not significant (all $P > 0.05$). Table 2 also shows that lung function changes after diving were not affected by the dive depth.

Discussion

We found that a single deep heliox dive temporarily affected lung function, which returned to normal at 24 h after the dive. We found a tendency toward small airway dysfunction after a single 80 msw heliox dive. The FEV_1/FVC and $MEF_{25\%}$ were significantly reduced at 30 min after an 80 msw heliox dive; the FEV_1/FVC returned to normal at 24 h after the dive, but the $MEF_{25\%}$ remained significantly reduced. While in 120 msw heliox dive, the FEV_1/FVC and $MEF_{75\%}$

Figure 2

Changes in pulmonary function parameters at 30 min and 24 h after 80 msw heliox diving (n = 15) compared with the pre-dive ('pre-div') (baseline) data; data are expressed as the mean (SD); *P < 0.05; FVC – forced vital capacity; FEV_1 – forced expiratory volume in one second; PEF – peak expiratory flow; $FEF_{25–75}$ – forced expiratory flow over the middle half of the FVC; MEF_{25} – maximum expiratory flow at 25% of FVC; MEF_{50} – maximum expiratory flow at 50% of FVC; MEF_{75} – maximum expiratory flow at 75% of FVC

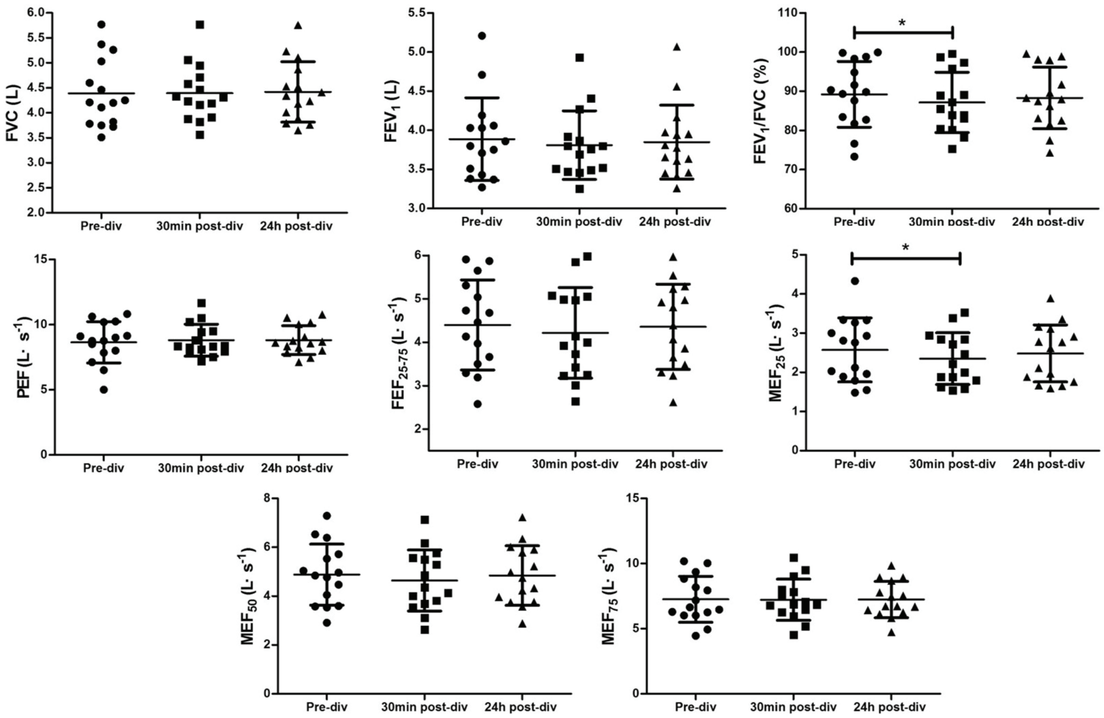


Figure 3

Changes in pulmonary function parameters at 30 min and 24 h after 100 msw heliox diving (n = 5) compared with the pre-dive ('pre-div') (baseline) data; data are expressed as the mean (SD); FVC – forced vital capacity; FEV_1 – forced expiratory volume in one second; PEF – peak expiratory flow; $FEF_{25–75}$ – forced expiratory flow over the middle half of the FVC; MEF_{25} – maximum expiratory flow at 25% of FVC; MEF_{50} – maximum expiratory flow at 50% of FVC; MEF_{75} – maximum expiratory flow at 75% of FVC

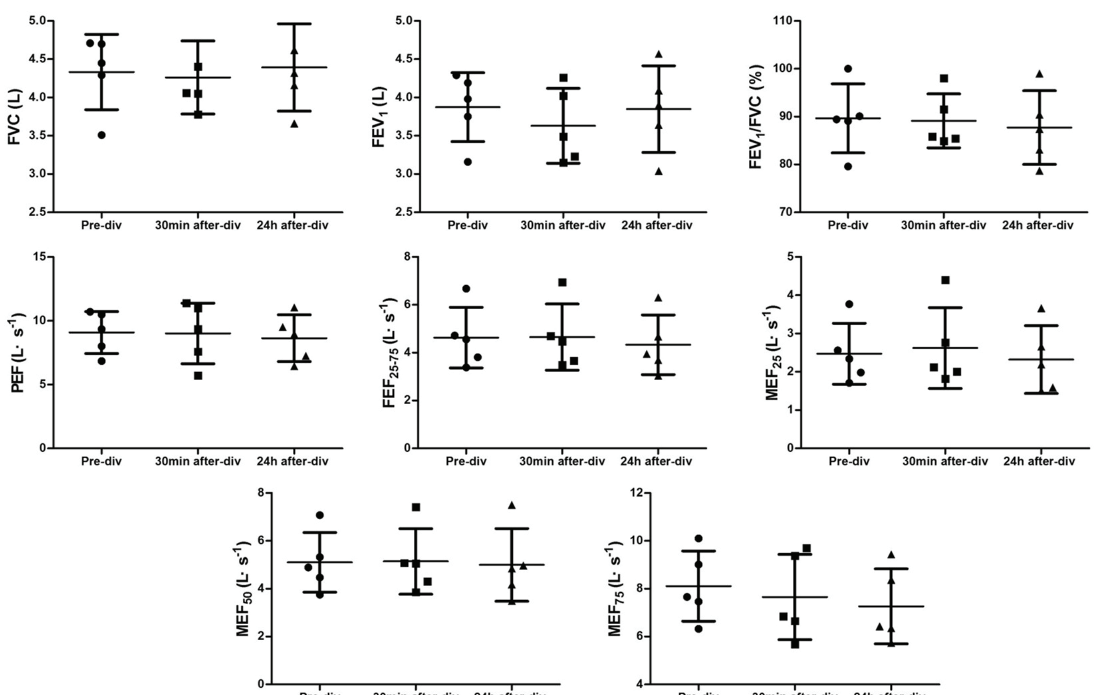
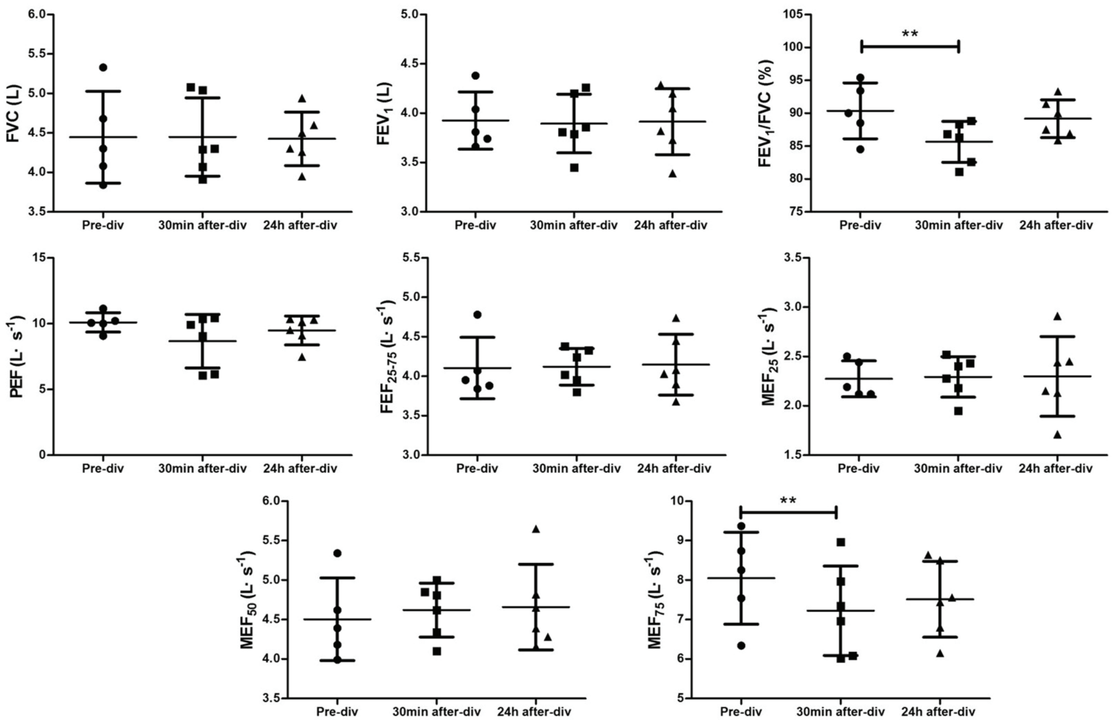


Figure 4

Changes in pulmonary function parameters at 30 min and 24 h after 100 msw heliox diving (n = 6) compared with the pre-dive ('pre-div') (baseline) data; data are expressed as the mean (SD); ** $P < 0.01$; FVC – forced vital capacity; FEV_1 – forced expiratory volume in one second; PEF – peak expiratory flow; $FEF_{25–75}$ – forced expiratory flow over the middle half of the FVC; MEF_{25} – maximum expiratory flow at 25% of FVC; MEF_{50} – maximum expiratory flow at 50% of FVC; MEF_{75} – maximum expiratory flow at 75% of FVC



decreased markedly at 30 min but returned to normal at 24 h after the dive.

After the 100 msw dives, the pulmonary parameters tended to decrease at 30 min after diving, but statistical significance was not attained. There are two possible reasons. The first reason is the large inter-individual variability in diver lung function and the small cohort of divers. There were 15 subjects for the 80 msw heliox dives, while there were only five subjects for the 100 msw dives and six for the 120 msw dives. Second, those diving to 100 and 120 msw had more diving experience and were more proficient compared with the shallower divers, which could possibly affect breathing patterns during diving. However, when the diving depth reached 120 msw, statistically significant differences were again apparent, possibly because the dive time becomes significantly longer as the dive depth increases.

A single deep saturation dive to a depth of 300 m or more reduces lung function.[20,21] A mean reduction in the TL_{CO} of 10–15% is the most consistent finding; some studies reported reductions in peak oxygen uptake (VO_2 peak values). Changes in lung function appear to be, at least partially, reversible at 6–8 weeks after diving. However, some studies found that repeated saturation and compressed air diving caused long-term effects.[1,22] Long-term diving reduces the FEV_1/FVC ratio.[23] This reduction may be due to a selective increment of FVC or decrement in FEV_1 in divers after long-term diving. However, in the present study investigating single dives, FVC values did not change significantly after the 80 msw dive, while FEV_1 showed a small downward trend 30 minutes after the dive (no statistical difference). Some authors have suggested that changes found in FVC or FEV_1 less than 5% are attributable to intra-individual variation and not suggestive of a pathological process.[24] In our study, the changes in FVC and FEV_1 after diving at 80 msw were around 5%, and the maximum change was 11%. Therefore, it is possible that a single heliox dive may not cause pathological changes, but it does not mean that these changes are meaningless. Of course, this part of the conclusion needs further investigation.

Oxygen toxicity may be one cause of changes in lung function, but it is not the only cause. We calculated the 'unit pulmonary toxic dose' (UPTD) values of for the dives in this study. In the $SURDO_2$ phase of the 80, 100 and 120 msw dives, the UPTD values were 208, 344 and 527, respectively. In an earlier study,[25] persons were exposed to continuous oxygen breathing at 152, 203 and 253 kPa (1.5, 2.0 and 2.5 atmospheres absolute [atm abs]) for average durations of 17.7, 9.0 and 5.7 h, respectively. Lung flow-volume and spirometric measurements were performed before, during, and after oxygen exposure. When subjects were exposed to 152 kPa (1.5 atm abs) oxygen for 3.8 hours, that is, when the UPTD value was 724, compared with the control group, FVC decreased by 1.1%, FEV_1 decreased

Table 2

Comparison of difference in lung function (△ values) at 30 min and 24 hours after diving versus baseline in heliox dives to different depths. Data are mean (SD) or median (range). FVC – forced vital capacity; FEV_1 – forced expiratory volume in one second; PEF – peak expiratory flow; $FEF_{25–75}$ – forced expiratory flow over the middle half of the FVC; MEF_{25} – maximum expiratory flow at 25% of FVC; MEF_{50} – maximum expiratory flow at 50% of FVC; MEF_{75} – maximum expiratory flow at 75% of FVC

Parameter	△80 msw depth Baseline vs 30 min	△100 msw depth Baseline vs 30 min	△120 msw depth Baseline vs 30 min	△80 msw depth Baseline vs 24 h	△100 msw depth Baseline vs 24 h	△120 msw depth Baseline vs 24 h
FVC (L)	0.01 (0.29)	-0.07 (0.40)	-0.12 (0.20)	0.03 (0.15)	0.06 (0.41)	-0.06 (0.24)
FEV_1 (L)	-0.08 (0.22)	-0.24 (0.52)	-0.09)0.12)	-0.04 (0.11)	-0.10 (-0.12–0.28)	-0.07 (0.12)
FEV_1/FVC (%)	-2.05 (3.5)	-0.52 (4.62)	-4.1 (1.98)	-0.30 (-8.60–1.40)	-1.92 (7.10)	-0.10 (-9.50–2.4)
PEF ($L{\cdot}s^{-1}$)	-0.40 (-1.33–6.65)	-0.07 (0.73)	-0.08 (-3.90–0.15)	-0.06 (-0.60–2.11)	0.16 (-1.56–0.39)	-0.22 (0.42)
$FEF_{25–75}$ ($L{\cdot}s^{-1}$)	-0.18 (0.61)	-0.02 (0.22)	-0.01 (0.29)	-0.02 (-0.64–0.24)	-0.30 (0.65)	-0.08 (0.45)
MEF_{25} ($L{\cdot}s^{-1}$)	-0.22 (0.40)	0.15 (0.44)	0.04 (0.21)	-0.09 (0.16)	-0.15 (0.59)	-0.10 (0.31)
MEF_{50} ($L{\cdot}s^{-1}$)	-0.24 (0.65)	0.04 (0.25)	0.16 (-0.49–0.23)	-0.04 (0.37)	-0.11 (0.61)	-0.04 (0.63)
MEF_{75} ($L{\cdot}s^{-1}$)	-0.33 (-2.20–6.00)	-0.46 (0.49)	-0.58 (0.26)	-0.17 (-1.10–3.00)	-0.85 (1.04)	-0.26 (0.49)

by 0.6%, and FEV_1/FVC did not change significantly. In the present study, the UPTD for the 80 msw dive was about 200, but the FEV_1 decreased by 2%, FVC increased by 0.1%, and the FEV_1/FVC decreased by 2.3%. The UPTD value of the 120 msw dive was about 600, but the FEV_1 decreased by 2.3%, the FVC decreased by 2.8%, and the FEV_1/FVC decreased by 4.5%. Based on this comparison, the changes in pulmonary function parameters after the present helium-oxygen dives were significantly greater than those caused by simple exposure to oxygen. Therefore, we believe that oxygen toxicity is not the only cause of changes in lung function. This conclusion is consistent with other research. One study[26] found that exposures to an inspired PO_2 of approximately 130 kPa caused changes in pulmonary function parameters whether the exposure was in a dry chamber or underwater. However, the incidence and individual severity of pulmonary oxygen toxicity was exacerbated in underwater oxygen exposure that included moderate aerobic exercise for half the time. Another study found that the TL_{CO} and forced mid-expiratory flow rate decreased markedly after deep saturation dives.[27]

A decrease in $MEF_{25–75\%}$ is common in subjects with obstructive and restrictive airway disorders, as well as those with diffuse small airway lesions. The pulmonary function changes of professional divers in their first three years of diving are mainly manifested as changes in small airways conductance.[2] Long-term diving increased the FVC and induced obstructive ventilation.[28] A cross-sectional study on 180 healthy male divers and 34 healthy male controls revealed that the divers had a lower mid-expiratory flow ($MEF_{25–50\%}$). The changes were inversely related to the number of years of diving, indicating that diving exerts long-term effects on respiratory function.[22]

A single dive can change the expiratory flow and volume and the lung diffusion capacity. The FVC, FEV_1, $MEF_{25–75\%}$, and spirometric data did not change after a simulated deep dive.[29] However, the FVC, FEV_1, and $MEF_{75\%}$ decreased significantly after a cold-water dive (4°C, 25 min, 10 m).[30] Thus, the results are affected by the diving environment and methods. In the study by Thorsen et al., 4–15 divers performed 17 different saturation dives to depths of 5–450 msw. The decrease in the TL_{CO} after diving was correlated with the cumulative hyperoxic exposure and the level of venous gas microembolism. The decrease in the forced mid-expiratory flow rate was correlated with the cumulative hyperoxic exposure.[31] Hyperoxia, hyperbaria, and venous gas microembolism may all contribute to changes in pulmonary function after a single saturation dive. In the present study, the decreased $MEF_{25–75\%}$ indicates that a single deep heliox dive compromises small airway function, but this is transient, recovering after 24 h. The possible causes of the decrease in $MEF_{25–75\%}$ are as follows. First, as mentioned above, oxygen toxicity is one possibility. One study reported that 90 min at 0.25 MPa once a day over 10 days led to a significant decrease in $MEF_{50\%}$ (-15%) and $MEF_{25\%}$ (-33%) of FVC.[32] However, these repetitive exposures are difficult to compare with the single exposure reported here. The early effects of breathing oxygen with partial pressures between 50 and 300 kPa include a decrease in FEV_1, FVC and maximal expiratory flow rates.[25] Second, when divers inhale oxygen in the hyperbaric chamber, they tend to complain that the gas is dry, associated with a high exhalation resistance. However, further experiments are needed to explore the possible relevance of these factors.

This study has some limitations. The number of subjects is small, particularly in the 100 and 120 msw dive groups. In addition, as divers must be rapidly transferred to a hyperbaric oxygen chamber (to complete surface decompression after ascent), we did not measure lung function before $SURDO_2$. This would have allowed comparison of the changes in lung function before diving, after ascending to the surface and after $SURDO_2$ to determine whether oxygen toxicity or deep diving is the main cause of the changes in lung function. We also did not measure the levels of decompression-induced microbubbles after diving.

Conclusions

A single deep heliox dive can trigger transient changes in pulmonary function. Specifically, it causes a decrease in FEV_1/FVC and $MEF_{25\%}$ or $MEF_{75\%}$ after diving, but these changes recover at 24 h after the dive.

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