Pulmonary effects of submerged oxygen breathing: 4-, 6-, and 8-hour dives at 140 kPa

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Shykoff B.E. Pulmonary effects of submerged oxygen breathing: 4-, 6-,and 8-hour dives at 140 kPa. Undersea Hyperb Med; 32(5):351-361.Elevated inspired oxygen partial pressures (P_IO_2) may cause pulmonary oxygen toxicity (PO_2T). However, normal variability and water immersion also cause pulmonary function (PF) changes. In 21 subjects, we measured the variability of flow-volume parameters and diffusing capacity for carbon monoxide (D_LCO) for six weeks without diving. In 24 divers, we compared the effects of air (P_IO_2 = 0.3 atm = 30 kPa) and oxygen (P_IO_2 = 1.4 atm = 140 kPa) during paired resting dives of 4, 6, or 8 hours in a freshwater pool 4.6 m deep. Without diving, median coefficients of variation (CV) were: vital capacity, 3.2%; FEV_1, 3.5%; peak flow, 7.0%; and D_LCO, 5.9%. Measurements within 2.4·CV of baseline were considered unchanged. After 4-, 6-, and 8- hour air dives, PF decreased in one, one, and four subjects, respectively, and three, one, and two, respectively, reported symptoms. After the oxygen dives, PF decreased in two, three, and four subjects, respectively, and two, four, and seven, respectively, reported symptoms. PO_2T persisted for several days after 8-hour oxygen dives.

INTRODUCTION

Oxygen-rich breathing gas provides many advantages for divers. Unfortunately, exposure to high inspiratory partial pressures of oxygen (P_IO_2) also has hazards, some of which (e.g., hyperoxic injury to lung and airway tissue) collectively are called pulmonary oxygen toxicity (PO_2T).

We undertook this study because data were lacking to determine how much decrement in measured pulmonary function after use of high P_IO_2 underwater was related to PO_2T, how much to submersion, and how much to variability in baseline pulmonary function tests. Furthermore, few data were available for pulmonary effects of in-water exposures lasting from four to eight hours.

Reductions in vital capacity have been used to define PO_2T after dry hyperbaric oxygen exposures (1,2). Oxygen injury to the lung, by causing edema, can reduce both vital capacity (VC) and diffusing capacity for carbon monoxide (D_LCO). However, submersion and water immersion can change pulmonary function values or even cause pulmonary edema (3). Fluctuations in hydration, blood pressure, and posture also may affect pulmonary function test results. The normal variability in the general population has been reported (4), but the variability of baselines among physically active divers was not known. Heavy exercise has been reported to change diffusing capacity (5-7), but the short-term effects of moderate physical exercise on pulmonary function, effects that could influence baseline (pre-dive) measurements, were not known.

The goals of this study were to assess the stability of pulmonary function in a physically active population, to separate the pulmonary effects of the physical stress of breathing while submerged from the effects of the chemical stress of high oxygen partial pressures, and to assess acceptable oxygen exposure times for shallow water submersion.

METHODS

To assess the normal variability in pulmonary function among our population, we conducted a six-week non-diving study with 21 subjects, 14 of whom were Navy divers. After that phase was complete, 24 diver-subjects performed pairs of dives, breathing air on the first dive and oxygen on the second. Subject demographics are summarized in Table 1. All subjects gave written, informed consent. Eight of the subjects participated in both the non-diving and the diving studies. All subjects participated in regular physical training.

For one week before the studies, subjects had not dived while breathing air or mixed gas, and in the four weeks preceding the studies, they had not breathed 100% oxygen at any pressure. Apart from the experimental dives, they did not dive during the studies.

Pulmonary function was assessed by forced vital capacity (FVC), slow vital capacity (SVC), and D_LCO. For all tests, each pulmonary function measurement session resulted in three repetitions that met American Thoracic Society standards (8). The Collins CPX and Collins GS Modular Pulmonary Function Testing System instruments (W. R. Collins, Inc.; Braintree, MA) were used. The test gas for single-breath D_LCO measurements contained 0.3% carbon monoxide and 0.3% methane, and results were adjusted for hemoglobin and carboxyhemoglobin concentrations (9), determined by CO-Oximeter (Instrumentation Laboratory; Lexington, MA) analysis of a venous blood sample taken just before testing. The single-breath maneuver

Table 1. Subject Demographics

	Height (cm)	Weight (kg)	Age (yrs)
	Median (Range)	Median (Range)	Median (Range)
DRY			
19 men 2 smokers 14 Navy divers 2 civilians 4 Navy nondivers	180 (170 – 188)	86 (75 – 105)	38 (31 – 53)
2 women nonsmokers nondivers 1 civilian, 1 Navy	163, 165	67, 69	45, 53
DIVING			
4-hr 8 men 3 in dry study 1 smoker	183 (173 – 185)	84 (75 –95)	39 (32 –44)
6-hr 8 men 4 in dry study 0 smokers	183 (175 – 188)	91 (76 – 100)	35 (29 – 46)
8-hr 8 men 1 in dry study 2 smokers	178 (173 –191)	89 (82 – 95)	39 (36 – 49)

sample time and sample volume were adjusted to avoid analyzer transients (10).

Non-diving Stability Study

In seven weeks, subjects in the non-diving portion completed six pulmonary function test sessions at times coordinated with their regular physical training. For each subject, pulmonary function testing sessions were scheduled twice at each of three times: (1) within one hour of completing morning physical training, (2) early in the afternoon about six hours after physical training, and (3) between 6:30 and 9:00 in the morning, before physical training and at least 12 hours after exercise defined by the subject as strenuous. The sequence of the testing was varied among subjects, for about equal numbers in each timing group each week.

Details of general health and of the type and intensity of exercise were recorded on each testing day. Reported exercise is summarized in Table 2. Navy personnel at the Navy Experimental Diving Unit (NEDU) generally perform 30 minutes of group calisthenics followed by 30 minutes of personally chosen physical training (e.g., running, cycling, or weight lifting) on Monday, Wednesday, and Friday mornings, and individual physical training on Tuesday and Thursday mornings. Physical training performed by all subjects was typical for NEDU.

A repeated measures analysis of variance (ANOVA) design was used for the stability study, with the time after physical training as a within-subjects factor. The coefficients of variation of each variable were calculated for each subject.

Diving Study

Diving was conducted in the NEDU test pool in 4.6 m of freshwater. Subjects sat in lounge chairs on the bottom of the test pool, for a depth of about 3.6 m at chest level, and watched movies. Water temperature was 32 °C ± 3 °C (90 °F ± 5 °F), warm water hoses were available, and divers were dressed for comfort.

Divers were assigned arbitrarily and randomly to a 4-, 6-, or 8-hour dive group, each containing eight divers. The random number generator in Excel was used to assign a number to each volunteer. The first eight subjects assigned numbers ending in 1 were placed in the eight-hour group, the first eight given numbers ending in 2 were assigned to the six-hour group, and the first eight with numbers ending in 3 went to the four-hour group. All subjects assigned numbers with invalid last digits, and any diver assigned to a group already filled, were given new numbers until all three groups contained eight divers.

Each subject dived twice for the assigned time, with about one week between dives. To minimize the time required between dives, the order was constant, with air as the breathing gas during the first dives and oxygen during the second. Gas was surface-supplied to the full facemask of a MK 20 open circuit

Table 2. Exercise reported before pulmonary function testing
(Most subjects reported more than one type of exercise at each session.)

Type	Number of subjects	Duration	Subjective intensity
Group or individual calisthenics	11	30 to 105 min	light to hard
Running (including sprints)	12	15 to 80 min	medium to hard
Biking	1	45 to 60 min	medium
Elliptic trainer	1	30 to 40 min	medium
Weight training	4	60 to 90 min	hard

Table 3. Symptoms list

During the dives:	After the dives:
Vision changes	Inspiratory burning
Ringing or roaring in ears	Cough
Nausea	Chest pain or tightness
Tingling or twitching	Shortness of breath
Light-headedness or dizziness	Lowered exercise tolerance
Chest tightness	Unreasonable fatigue
Shortness of breath	
Sensation of rapid shallow breathing	
Burning on inspiration	
Cough	

underwater breathing apparatus. Oxygen was humidified by being passed through bubblers built for the purpose, but the air was not.

To eat, drink, or void, the subjects were permitted to surface and breathe room air for no more than five minutes per hour. Not all divers took all of their breaks, but most did; the number of missed air breaks was not recorded. Subjects were questioned about specific symptoms (Table 3) once per hour while they were underwater. Pulmonary function tests were performed one working day before a dive (baseline), immediately after diving, and daily for three days afterwards, except for three Thursday dives, when testing occurred on Thursday, Friday, and Monday. Thursday dives were performed by four 8-hour divers with both gases, and by four 6-hour divers with air. Specific questions about symptoms were asked at each pulmonary function measurement session. If pulmonary function had not returned to baseline on day three or four after the dive, it was measured again one week after the dive and tested repeatedly until values no longer differed from baseline.

The diving study was designed for repeated measures ANOVA, with the breathing gas as a within-subject factor and the dive duration as a between-subject factor.

A deficit in a pulmonary function variable after the in-water study was defined as a decrease from baseline of 2.4 times the coefficient of variation found from the stability study, the 95% confidence band. For the subjects who participated in both components of the study, we used the means of the stability study and pre-dive measurement values as the baselines, and the coefficients of variation of all of those values. For the subjects who participated only in the diving study, we used the pre-dive values as baseline and the cross-subject median coefficients of variations from the stability study to define change.

Fisher's Exact Test was used to compare proportions of subjects with or without symptoms or deficits.

RESULTS

Stability of pulmonary function

No detectable differences in pulmonary function were ascribable to time after routine exercise although the statistical power was adequate to reveal meaningful differences. A 5% difference in either vital capacity or diffusing capacity in these data would have been detectable with 95% confidence more than 99% of the time. However, the only differences found were that diffusing capacity per lung volume was 3% greater in the afternoon than in the morning, and that hemoglobin concentration was 3% higher in the morning (highest after exercise) than in the afternoon.

The median and maximum coefficients of

Table 4. Stability of pulmonary function across 6 weeks

Coefficient of variation	Median	Max
VC	3.2 %	5.6 %
FEV_1	3.5 %	8.5 %
Peak flow	7.0 %	29.0 %
Midflow	7.2 %	14.7 %
D_LCO	5.9 %	9.4 %

variation for pulmonary function variables over six weeks are listed in Table 4. A few subjects showed highly variable pulmonary function tests from week to week.

DIVING

Air breathing

After breathing air underwater for eight hours, four subjects showed changes in pulmonary function. For three subjects, these changes were without symptoms: a reduction in peak flow on the second day after diving, a reduction in peak flow on the third day after diving, and a reduction in diffusing capacity on the fourth day after diving. For the fourth diver, reduced peak flow and diffusing capacity on the first day after diving were accompanied by moderate inspiratory burning and cough. A fifth diver experienced mild cough during and immediately after the dive but had no measured decrement in pulmonary function. After breathing air underwater for six hours, one subject showed asymptomatic reductions in peak flow on the day after diving and in diffusing capacity on the fourth day and another subject reported moderate chest tightness on the day after diving. After breathing air underwater for four hours, one subject showed an asymptomatic reduction in diffusing capacity on the third day after diving, while three others reported mild cough immediately after the dive, a symptom that progressed to mild shortness of breath in one diver on the following day. With that one exception, all symptoms and changes in pulmonary function after any air dive had resolved by the next measurement session.

O_2 breathing compared to air breathing

Pulmonary function values before the oxygen dives were no different ($p>0.05$) from what they had been before the air dives, except for D_LCO, which was slightly lower before the 4-hour oxygen dives than before the 4-hour air dives. Values are shown in Table 5.

The four subjects who had had changes in pulmonary function after the eight-hour air dives also showed changes after breathing 140 kPa oxygen underwater for eight hours. For one subject, who had reduced diffusing capacity

Table 5. Pulmonary Function Test results before the dives

	8-hour		6-hour		4-hour	
	Pre-air	Pre-O_2	Pre-air	Pre-O_2	Pre-air	Pre-O_2
FVC (L)	5.9 ± 0.3	5.9 ± 0.3	5.7 ± 0.2	5.8 ± 0.2	5.5 ± 0.3	5.5 ± 0.2
FEV_1 (L)	4.2 ± 0.2	4.3 ± 0.2	4.2 ± 0.1	4.2 ± 0.1	4.3 ± 0.2	4.3 ± 0.2
Peak Flow (L/s)	12.0 ± 0.6	11.4 ± 0.5	11.7 ± 0.6	12.0 ± 0.5	12.0 ± 0.5	11.7 ± 0.6
D_LCO [mL/(mmHg ·min)]	40 ± 1	38 ± 2	39.1 ± 0.8	39 ± 1	38 ± 2 *	36 ± 2 *

* $p<0.05$ by Student's paired t-test

immediately after diving, the change was asymptomatic and was gone by the first post-dive day. For the others, symptoms preceded or accompanied the measurable changes: mild chest tightness that began during the third hour of the dive preceded and accompanied large reductions in vital capacity (-17.6%), FEV_1 (-21%), and peak flow (-21%) immediately after diving; mild cough on the first day after diving preceded a reduction in peak flow on the second day after diving; mild inspiratory burning, cough, chest tightness, and fatigue and reduced exercise tolerance, symptoms that lasted for two days, accompanied a reduction in diffusing capacity beginning on the first day after the dive and lasting for three days. The four other divers reported symptoms but showed no decrements in pulmonary function: one diver had moderate inspiratory burning, cough, and chest tightness starting immediately after the dive and continuing through the next day with reduced exercise tolerance; one had mild inspiratory burning, cough and chest tightness immediately after the dive that had resolved by the next day; one had mild cough after the dive that lasted only one day; and the fourth had mild cough and chest tightness starting immediately after the dive and lasting for two days.

After six hours of oxygen breathing (140 kPa), underwater, the subject who had a reduction in peak flow after his air dive showed an asymptomatic reduction in peak flow that disappeared by the next measurement. Two others had asymptomatic changes in pulmonary function, one with reduced diffusing capacity only immediately after the dive, and the other with a large reduction in peak flow (-26%) beginning immediately after the dive and lasting for three days. Three other divers experienced respiratory symptoms without changes in pulmonary function: mild cough immediately after the dive and gone by the next day; mild cough, inspiratory burning, and also reduced exercise tolerance beginning immediately after the dive and lasting throughout the next day; and mild inspiratory burning and cough beginning during the second hour of the dive and continuing with fatigue and reduced exercise tolerance throughout the day after the dive. Another subject reported moderate fatigue but no respiratory symptoms on the day of the dive. Immediately after four hours of oxygen breathing (140 kPa) underwater, one subject showed an asymptomatic reduction in peak flow that lasted for two days and another, who had had a reduction in diffusing capacity three days after the air dive, had an asymptomatic reduction in diffusing capacity immediately after diving, resolved by the next measurement session. One other, who had coughed after his air dive, reported mild cough, inspiratory burning, chest tightness, and shortness of breath immediately after diving but resolved by the next day.

Although some subjects showed distinct pulmonary impairment as described, the average differences in pulmonary function test results after diving were not significant. Median changes from baseline are presented in Table 6.

The numbers of subjects experiencing either post-dive symptoms or reductions in pulmonary function on at least one testing day are shown in Table 7, where neither severity nor duration of symptoms is considered. The number of divers with a detectable pulmonary function test (PFT) deficit on at least one day was not statistically greater after oxygen diving than after air dives, but the number of divers experiencing symptoms after breathing oxygen was significantly greater than the number who did so after breathing air. The incidence of reported symptoms was significantly greater for the 8-hour oxygen exposure than for the 8-hour air exposure, and it was greater after an 8-hour O_2 exposure than after a 4-hour oxygen exposure (Fisher's Exact $p = 0.042$ for both).

Table 6. Median percentage change from baseline in pulmonary function

		Dive day	Day +1	Day +2	Day +3 or +4
FVC					
8 hours	Air	2.2	0.1	-0.5	-2.90
	O_2	3.5	1.3	-0.5	-1.2
6 hours	Air	0. 6	1.8	-1.0	-0.7
	O_2	2. 8	0.5	-0.3	0.4
4 hours	Air	3.6	2.0	0.1	-1.5
	O_2	3.3	1.3	0.3	2.5
Peak flow					
8 hours	Air	-1.9	-3.1	-6.5	-13.3
	O_2	-2.7	-3.5	-8.2	-3.6
6 hours	Air	-3.6	-3.2	1.2	0.3
	O_2	-8.4	-0.7	-2.2	-6.0
4 hours	Air	-2.2	3.9	0.6	3.6
	O_2	0.4	-0.9	4.9	2.3
FEV_1					
8 hours	Air	3.9	1.8	1.0	-4.0
	O_2	2.6	1.4	0.2	-0.2
6 hours	Air	0.5	0.7	-0.3	-0.8
	O_2	1.2	-0.8	0.1	-1.5
4 hours	Air	4.5	1.3	-0.8	-2.3
	O_2	3.0	-0.5	0.0	0.7
D_LCO					
8 hours	Air	-3.6	-5.9	-7.2	-10.8
	O_2	-3.2	-2.9	-5.5	-2.9
6 hours	Air	-0.4	-0.4	-1.2	-3.52
	O_2	-4.5	-2.8	-4.8	-2.4
4 hours	Air	-4.4	-9.0	-4.8	-6.3
	O_2	-0.9	-2.7	-5.1	-1.7

Table 7. Number of subjects with at least one PFT deficit or respiratory symptom on any day after diving

# subjects	**Changed PFT**		**Symptoms**	
Duration	AIR	O_2	AIR	O_2
8 hours	4	4	2	7
6 hours	1	3	1	4
4 hours	1	2	3	2

Table 8: Number of diver-days with pulmonary function deficits or symptoms

Person-days	**Changed PFT**		**Symptoms**	
Duration	AIR	O_2	AIR	O_2
8 hours	4	6	2	11
6 hours	2	4	2	5
4 hours	1	2	4	3

For some subjects, symptoms or deficits in pulmonary function persisted for several days. The numbers of person-days with either symptoms or reduced pulmonary function are recorded in Table 8.

The number of symptom-days increased with the durations of exposure to 1.4 atm (140 kPa) oxygen while submerged (Cochran's $p<0.04$). Pairwise comparison by Fisher's Exact Test showed that 8 hours generated more symptom-days than did 6 hours ($p = 0.014$), while the number of symptom-days after 6 hours of breathing oxygen did not differ from that after 4 hours of breathing oxygen ($p = 0.26$).

Eight hours of breathing 1.4 atm oxygen underwater generated significantly more symptom-days than did 8 hours of breathing air submerged (Fisher's Exact $p = 0.009$). Air-to-oxygen differences in symptom-days after 6- or 4-hour exposures were not significant (exact p values = 0.48 and 1.0). The air-to-oxygen differences in number of pulmonary function test deficit days were not significant after any exposure duration.

The most extreme changes in pulmonary function in individual subjects after eight hours underwater were a decrease in FVC of 17.6% and in FEV_1 of 21% after 140 kPa oxygen-breathing and a decrease in D_LCO of 17% with air.

DISCUSSION

Stability Study

The variability in spirometry results was smaller than that reported for the general population by the American Thoracic Society (ATS) (4). We found median 95% confidence bands of 7.7% in FVC, 8.4% in FEV_1, and 17% in midexpiratory flow. For normal subjects the ATS reports week-to-week variations of 11% in FVC, 12% in FEV_1, and 21% in midexpiratory flow, and within-a-day variabilities of 5% in FVC and FEV_1 and 13% in midexpiratory flow. The somewhat tighter confidence bands we report probably result from having a more homogenous sample in terms of age, general health, physical fitness, and ability to perform respiratory maneuvers. However, even with our better-than-standard reproducibility, we are limited in our ability to detect small changes.

The time after physical exertion did not affect pulmonary function test results in the sample tested. Although pulmonary function is altered after maximum exercise (5-7), our subjects followed their normal fitness routines (Table 2). Because their exercise was moderate relative to their levels of fitness, their pulmonary blood volumes may have returned to normal soon after they completed their physical training. However, our failure to observe an increase in D_LCO immediately after exercise may represent artifactual elevation of all D_LCO values: our subjects held their breaths at maximum lung volume and did not relax against the instrument valve (9). The continued strong inspiratory effort generated by this maneuver draws blood into the lungs during the breath-hold, potentially mimicking at rest the redistribution of blood volume caused by exercise. Nearly all the measured values were greater than 110% of the expected values for a person of similar height, weight, and age.

DIVING

Air breathing

The dives during which subjects breathed surface-supplied air were intended to quantify pulmonary effects of breathing underwater without elevated oxygen partial pressures. We saw both pulmonary symptoms and measurable deficits in pulmonary function after those dives. The oxygen partial pressure was approximately 0.3 atm (30 kPa), less than the 0.5 atm (51 kPa) threshold reported for PO_2T in dry conditions (2).

A similar hydrostatic pressure difference exists between the mouth and the chest with head-out water immersion and with use of a demand regulator while totally submerged and seated. Blood volume shifts to the lung from the abdomen and extremities, and external water pressure supports the abdominal contents, pushing the diaphragm higher into the thorax (11). Other investigators (12) did not find changes in flow–volume parameters or diffusing capacity after 40 minutes of head-out immersion of eight subjects in thermoneutral water, but did measure a mean decrease of 7.3% in diffusing capacity when an inspiratory resistive load was added. The scattered symptoms and decrements in pulmonary function following the air-breathing dives probably resulted from these mechanical sources than from low-dose PO_2T. We were unable to find a sensible relation that would collapse the data from the air and oxygen exposures onto the same curve.

The air supply to the divers mistakenly was not passed through the bubblers. However, other investigators have shown that, although FEV_1 was slightly reduced after breathing dry gas underwater at high pressures, differences in pulmonary effects of dry or humid gas were not significant for divers at 135 kPa doing moderate to light work for four hours (13).

Oxygen breathing

The pulmonary effects of diving were very different among subjects. Seven of eight divers reported symptoms after the 8-hour exposure to oxygen at 1.4 atm, while only four — including the one without symptoms — showed pulmonary function deficits. Four subjects reported symptoms after the 6-hour dives with oxygen, and three showed pulmonary function deficits, but none of the subjects with symptoms also had reduced pulmonary function. Two subjects reported symptoms after the 4-hour oxygen exposure, and two subjects showed asymptomatic changes in pulmonary function.

Although the presence of respiratory symptoms without a deficit in pulmonary function is relatively easy to explain, the converse, though reported by other investigators (2), is more puzzling. The presence of measurable pulmonary function deficits without symptoms may suggest that a subject failed to report a symptom that he considered "normal after diving" — or that deficits in pulmonary function were truly asymptomatic. However, symptoms are likely to be more sensitive indicators of the effects of PO_2T than are changes in pulmonary function. For example, one of the pathological effects of oxygen is to damage the pulmonary capillary endothelium (14) and thereby increase the permeability of the pulmonary capillary membranes (15). Increased membrane permeability contributes to interstitial edema, and coughing results from nerve stimulation if even a small volume of liquid builds up within the tissues. However, changes in membrane permeability cause measurable changes in VC only when liquid enters alveolar air spaces, as the maximum possible increase in interstitial membrane thickness is 15% to 20% (15), a rate corresponding to a VC decrease of less than 50 mL, within the error of measurement. Diffusing capacity decreases as much as 13 to 17% if the membrane thickens to that extent without a change in blood distribution, but the measurement may vary by 14% from day to day. A subject with interstitial edema might have normal VC and D_LCO but a marked cough.

Once liquid begins to accumulate in the interstitial spaces of the alveolar-capillary membrane, it drains rapidly into the more compliant spaces around blood vessels and airways (15). However, the regions where liquid can accumulate outside the blood vessels connect to lymph ducts, and lymphatic drainage can increase ten-to-fifteen fold in the face of increased membrane permeability (15). Only if the lymphatic drainage is overwhelmed will fluid enter the alveoli, when measurable changes in vital capacity and D_LCO can be expected. Accumulation of fluid around the airways may increase airway resistance by forming liquid-filled cuffs around them; in a small airway with laminar flow, a 2% decrease in the radius changes peak flow about 8% if the driving pressure does not change. Thus, only a relatively severe increase in permeability reduces VC, intermediate levels of injury may appear as D_LCO or peak flow decrement, and even mild injury may be manifest as a cough.

Many previous studies have measured pulmonary function only immediately after the end of the oxygen exposure. If we had documented pulmonary function changes and symptoms only on the days of the dives, we would have concluded that two, rather than four, of eight subjects showed decreased pulmonary function and that five, rather than seven, of eight subjects reported symptoms after the 8-hour oxygen exposures. After the 6- and 4-hour oxygen exposures, we would have missed all pulmonary function changes and two of the five reports of respiratory symptoms after air exposures. Tissue damage from oxygen toxicity, like that from sunburn, is not complete because an exposure is over. Damaged tissues subsequently trigger an inflammatory response. Symptoms or changes in pulmonary function

during the days following oxygen exposure indicate that tissue damage has occurred during that exposure.

After the 8-hour oxygen exposure, pulmonary function decreased in 50% of the subjects, and 87.5% reported symptoms. In a comparable experiment when divers breathed oxygen from the LAR V at 20 feet of seawater (162 kPa), 73% of them had changes in pulmonary function (16). However, when our baseline variability criteria (Table 2) are applied to those data, the proportion of divers with detectable alterations in pulmonary function drops to between 23% and 40%, similar to what we report here. Five of our eight subjects reported symptoms during or immediately after the dive, and two other subjects reported symptoms the next day. In the LAR V study, 45% of the divers reported symptoms (16).

The unit pulmonary toxic dose (1) (UPTD) calculated for the 8-hour oxygen dives would range from 842 with seven air breaks to 908 with none. For the 6-hour oxygen dives, the range is 634 with five air breaks to 681 with none, and for the 4-hour exposures, from 426 with three air breaks to 454 with none. Unit pulmonary toxic dose cannot be calculated for P_IO_2 less than 0.5 atmospheres absolute (ATA). The Harabin minimized model for dry exposures with these UPTDs predicts median VC changes of -4.4% for the 8-hour exposure, -3.3% for the 6-hour exposure, and -2.2% for the 4-hour exposure (1). The median change in VC immediately after the 8-hour exposures was +3.5% (range -17.6% to +5.9%), after the 6-hour exposure was +2.8% (-1.6% to +6.9%), and after the 4-hour exposures was +3.3% (-6.9% to +7.0%). The mean changes in VC were 0.6% (standard deviation sd 7.6%) after the 8-hour exposure, +1.9% (sd 4.2%) after the 6-hour exposure, and +2.7% (sd 4.5%) after the 4-hour exposure, none of which was statistically significant. For comparison, in nine subjects exposed to 100% oxygen at 1.5 ata in a dry chamber, the mean change in VC was -4.2% (sd 5.2%) after eight hours and -1.1% (sd 2.9%) after four hours, also not statistically significant (17). The Harabin model, which was developed from data for long exposures in dry chambers, appears to be a poor predictor for short or in-water exposures. Because the average changes did not differ statistically from zero for either our study or the dry chamber study at 1.5 atm, we cannot comment on the apparent differences between exposures in water and in gas.

We cannot rule out effects of the air breaks. Although it is difficult to imagine that much recovery can occur in five minutes, short air breaks do increase the tolerable duration of human exposure to elevated oxygen partial pressures; at 2 atm absolute, five minutes of normoxic gas after every twenty minutes of oxygen approximately doubled the time until the development of pulmonary toxicity (18). However, divers in the LAR V study who did not have air breaks experienced respiratory symptoms and changes in pulmonary function at rates similar to those in this study. Given this basic similarity, it seems unlikely that a 5:55 ratio of air exposure to higher P_IO_2 exposure times changed the outcomes.

Pulmonary function test results were less variable in our experimental population than in the general population, but the 95% confidence bands remained wide: at ±7.7% for VC, ±8.4% for FEV_1, ±16.8% for peak flow, and ±14.2% for diffusing capacity. Although very large-scale trials find diurnal variations in pulmonary function (19, 20), neither the effect of time of day nor the effect of routine exercise was measurable in individuals.

Breathing underwater was associated with some pulmonary insult. However, the effects were greater when P_IO_2 = 1.4 atm than with air. The incidence of symptoms increased with dive duration. We conclude that a single 4-hour underwater exposure to P_IO_2 = 1.4 atm is no worse than one to P_IO_2 = 0.3 atm. A 6-hour

exposure to P_1O_2 = 1.4 atm warrants further investigation with more subjects, while an 8-hour underwater oxygen exposure to that P_1O_2 causes mild to moderate pulmonary insult that does not resolve for a few days.

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REFERENCES

1. Harabin AL, Homer LD, Weathersby PK, Flynn ET. Predicting pulmonary oxygen toxicity: A new look at the unit pulmonary toxicity dose. Naval Medical Research Institute, NMRI 86-52, December 1986.
2. Clark JM, Lambertsen CJ. Rate of development of pulmonary O_2 toxicity in man during O_2 breathing at 2.0 ATA. *J Appl Physiol* 1971; 30(5):739–752.
3. Shupak A, Weiler-Ravell D, Adir Y, Daskalovic Y, Ramon Y, Kerem D. Pulmonary oedema induced by strenuous swimming: A field study. *Respiratory Physiology* 2000; 12(1):25–31.
4. American Thoracic Society. Lung function testing: Selection of reference values and interpretive strategies. *Am Rev Respir Dis* 1991; 144:1202–1219.
5. Manier G, Moinard J, Stoïcheff H. Pulmonary diffusing capacity after maximal exercise. *J Appl Physiol* 1993; 75(6):2580–2585.
6. McKenzie DC, Lama IL, Potts JE, Sheel AW, Coutts KD. The effect of repeated exercise on pulmonary diffusing capacity and EIH in trained athletes. *Med Sci Sports Exerc* 1999; 31(1):99–104.
7. Hanel B, Teunissen I, Rabøl A, Warberg J, Secher NH. Restricted postexercise pulmonary diffusion capacity and central blood volume depletion. *J Appl Physiol* 1997; 83(1):11–17.
8. American Thoracic Society. Standardization of spirometry 1994 update. *American Journal of Respiratory and Critical Care Medicine* 1995; 52:1107–1136.
9. Instruction Manual for the Collins Comprehensive Pulmonary Laboratory (CPL). Braintree, MA: Collins Medical, 2000.
10. Shykoff BE, Measurement of diffusing capacity for carbon monoxide (DLCO). Navy Experimental Diving Unit, TR 02-04, May 2002.
11. Lundgren CEG. Immersion Effects. In: Lundgren CEG, Miller JN, eds. The Lung at Depth. New York: Marcel Dekker,1999:91–128.
12. Thorsen E, Skogstad M, Reed JW. Subacute effects of inspiratory resistive loading and head-out water immersion on pulmonary function. *Undersea Biomed Res* 1999;26(3):137-141.
13. Thorsen E, Rønnestad I, Segedal K, Hope A. Respiratory effects of warm and dry air at increased ambient pressure. *Undersea Biomed Res* 1992; 19(2):73-83.
14. Crapo JD, Freeman BA, Barry BE, Turrens JF, Young SL. Mechanisms of hyperoxic injury to the pulmonary microcirculation. *The Physiologist* 1983; 26(3):170–176.
15. Taylor AE, Rehder K, Hyatt RE, Parker JC. Clinical respiratory physiology. Philadelphia, PA: WB Saunders, 1989:179–189.
16. Marienau KJ, Maurer J. The pulmonary effects of exposure to high PO_2 during prolonged LAR V / MK 25 dives. Navy Experimental Diving Unit, TM 97-14, November 1997.
17. Clark JM, Lambertsen CJ, Gelfand R, Flores ND, Pisarello JB, Rossman MD, Elias JA. Effects of prolonged oxygen exposure at 1.5, 2.0, or 2.5 ATA on pulmonary function in men (Predictive Studies V). *J Appl Physiol* 1999; 86(1):243-259.
18. Hendricks PL, Hall DA, Hunter WL Jr, Haley PJ. Extension of pulmonary O_2 tolerance in man at 2 ATA by intermittent O_2 exposure. *J Appl Physiol* 1977; 42(4):593-599.
19. Guberan E, Williams MK, Walford J, Smith MM. Circadian variation of F.E.V. in shift workers. *Brit J Industr Med* 1969; 26:121–125.
20. Hetzel MR, Clark TJH. Comparison of normal and asthmatic circadian rhythms in peak expiratory flow rate. *Thorax* 1980; 35:732–738