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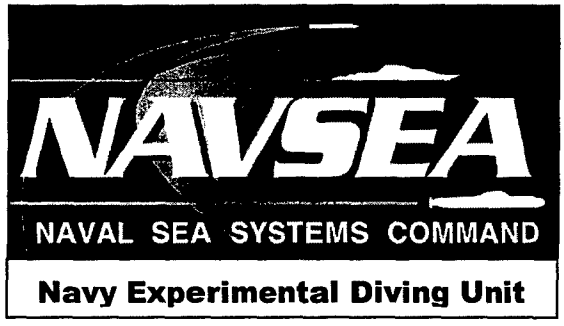
PULMONARY EFFECTS OF SUBMERGED BREATHING OF AIR OR OXYGEN



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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Symptoms and decreased pulmonary function test (PFT) results can occur after oxygen exposure due to pulmonary oxygen toxicity (PO_2T), but effects of air diving on these variables had not been reported. Baseline variability in the Navy setting also had not been established. In 21 subjects, we studied PFT variability during six weeks without diving. In 24 divers, we studied PO_2T after pairs of four-, six-, and eight-hour dives to 15 ft of fresh water, one with oxygen partial pressure (PO_2) of 30 kPa (air) and the other with PO_2 of 140 kPa (oxygen). Divers breathed open circuit, surface-supplied gas. PFTs were measured and respiratory symptoms logged before and daily for four days after dives. Variables measured included vital capacity (VC), peak flow, and diffusing capacity for carbon monoxide (D_LCO). For our population, baseline 95% confidence intervals were ±7% for VC, ±15% for peak flow, and ±12% for D_LCO. Postdiving decreases greater than these resulted in seven subjects after air and in nine after oxygen, proportions that are not different from one another by Fisher's exact test. However, more divers (7 of 8) reported symptoms after eight hours of oxygen than reported them after eight hours of air or after four hours of oxygen (2 of 8 in both cases). Symptoms and PFT deficits were not correlated with each other. Both often persisted for several days, and either could be delayed in onset. Both symptom-days and PFT deficit-days increased with oxygen dive duration (Cochran's p: symptoms <0.001, PFTs: =0.025). Even air diving caused symptoms and PFT deficits. Symptoms were a more sensitive indicator of PO_2T than were changes in PFT results.

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INTRODUCTION

Use of oxygen-rich gas provides many advantages for divers. Unfortunately, exposure to high inspiratory partial pressures of oxygen (P_IO_2) also has its own risks, one of which, possible lung damage, is known as pulmonary oxygen toxicity (PO_2T).

The risks of developing PO_2T are poorly characterized. The current shallow-water exposure limit, four hours breathing oxygen at 25 fsw or less in any 24-hour period, was established somewhat arbitrarily as a known "safe" exposure.[1] It does not represent a tested upper limit before PO_2T develops. However, when the possibility of doubling the shallow water exposure time was explored, many pulmonary symptoms and measurable pulmonary function deficits were seen after seven to eight hours of breathing oxygen underwater.[2] We undertook this study because data were lacking to determine how much decrement in measured pulmonary function was related to PO_2T, how much to submersion, and how much to variability in baseline pulmonary function test results. Further, no pulmonary information was available for exposure times between four and eight hours.

Pulmonary function decrements could result from oxidative injury, because vital capacity (VC) and diffusing capacity for carbon monoxide (D_LCO) are both reduced if there is pulmonary edema; reductions in vital capacity have been used to define PO_2T after dry hyperbaric oxygen exposures.[3,4] However, submersion and water immersion are other documented causes of altered pulmonary function and even lung edema.[5] Water immersion reduces VC because blood is forced into the chest, and breathing gear changes the pressures in the lungs. Additionally, heavy exercise has been reported to change diffusing capacity,[6–8] but the immediate effects of moderate physical exercise on pulmonary function, effects that could influence baseline (predive) measurements, were not known. Fluctuations in hydration, blood pressure, and posture also may effect pulmonary function test results. Normal variability in the general population has been reported,[9] but the variability of baselines among physically fit divers was 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. We measured pulmonary function both immediately after diving and for several days after the diving exposures.

METHODS

GENERAL

This study had two components: a six-week non-diving stability study, and matched air and oxygen diving tests. We recruited 20 subjects for the non-diving portion and 24 subjects to dive. Eight of the subjects participated in both components.

Subjects in the non-diving portion completed six pulmonary function test sessions in seven weeks. Pulmonary function testing of forced VC, slow VC, D_LCO, and the variables associated with those maneuvers was coordinated with regularly scheduled physical training (PT).

Subjects in the diving portion of the study performed pulmonary function tests before the test dive, within 30 minutes of leaving the water, and repeatedly for three to four days after the test dives. The dives, which were conducted in the Navy Experimental Diving Unit (NEDU) test pool at a depth of fifteen feet of fresh water, were controlled and supervised by qualified NEDU personnel. Divers were assigned arbitrarily and randomly, using the random number generator in Microsoft Excel, to a 4-hour, 6-hour or 8-hour dive group, with eight divers in each group. Each subject dove twice, with about one week between dives. Subjects breathed air during the first dive and humidified oxygen during the second.

EXPERIMENTAL DESIGN AND ANALYSIS

Before the study, subjects had not been diving while breathing air or mixed gas for one week or while breathing oxygen for four weeks. Except for the experimental dives, they refrained from diving throughout the study. Smoking behavior and a history of respiratory allergies were noted for each subject. General health and use of medications were recorded during the studies. Each pulmonary function measurement session involved three successful repeats of each test according to the American Thoracic Society standards.[10]

A repeated measures analysis of variance (ANOVA) design was used for the stability study, with the time after PT as a within-subjects factor. Pulmonary function testing sessions were scheduled twice at each of three times: 1) within one hour of completing morning PT, 2) early in the afternoon about six hours after PT, and 3) on a morning without or before PT, at least 12 hours after strenuous exercise. Details of general health and of the type and intensity of exercise were recorded on each testing day. The coefficients of variation of each variable were calculated for each subject.

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. Divers were questioned about specific symptoms (Table 1) once per hour while they were underwater. Pulmonary function tests were performed one working day before a dive, immediately after a dive, and daily for three days following the dive (only on Friday and Monday when dives were on Thursday). If pulmonary function was not back to baseline on day three or four after the dive, it was measured again one week after the dive and tested repeatedly until values were no longer different from baseline. Specific questions (Table 1) were asked about symptoms at each pulmonary function measurement session.

Table 1: 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	
Rapid shallow breathing	
Burning on inspiration	
Cough	

EQUIPMENT AND INSTRUMENTATION

The Collins CPX and Collins GS Modular Pulmonary Function Testing System instruments (W.R. Collins, Inc.; Braintree, MA) were used for both components of the study. To measure D_LCO the equipment uses a test gas containing 0.3% carbon monoxide and 0.3% methane. Carboxyhemoglobin and hemoglobin concentrations were determined from a venous blood sample (CO-Oximeter, Instrumentation Laboratory; Lexington, MA).

The divers used surface-supplied gas and the MK 20 open circuit underwater breathing apparatus with communication units. Oxygen was humidified by passing it through bubblers built for the purpose.

PROCEDURES

To record VC, a subject wearing nose clips breathed on a mouthpiece. The subject exhaled into the spirometer, inhaled fully, then exhaled fully and inhaled fully again. For SVC measurements, the subject chose a comfortable, not forced, rate of gas flow. For FVC measurements, the initial exhalation was leisurely, but the subject then inhaled rapidly before exhaling as fast as possible and continuing the expiratory effort until no more air could be exhaled. Measurements of forced expired volume in one second (FEV_1) and some other variables were read from the FVC data.

D_LCO was measured using the single-breath technique: the subject exhaled as far as possible, inhaled as much of the test gas as possible, and then held his or her breath for 10 seconds. The variables used to obtain D_LCO were calculated from the gas concentrations before and after the breath-hold. Adjustments were made for carboxyhemoglobin and hemoglobin concentrations.[11] The volume expired before the gas concentrations were measured and the volume of gas over which the concentrations were averaged were adjusted to correct for instrument errors as explained in a previous report.[12]

During the stability study, on mornings when subjects were tested after PT, pulmonary function tests were performed within the hour after PT. On mornings when subjects were tested without PT, pulmonary function tests were conducted at the same time of day as on PT mornings. On days when subjects were tested in the afternoons, tests were given between six and seven hours after the subjects had finished exercise. At each measurement session, subjects responded to a questionnaire about general health, exercise type, and intensity, and we collected venous blood samples to measure their hemoglobin and carboxyhemoglobin.

The diver subjects for the underwater study entered the water at 15-minute intervals, under the direction of the dive supervisor. During the dives, subjects on the bottom of the test pool relaxed in lounge chairs to watch movies. To eat, drink, or void, the subjects were permitted to surface and breathe room air for not more than five minutes per hour. Water temperature was 90 °F ± 5 °F (32 °C ± 3 °C), and warm water hoses were available. Divers wore wet suits. The subjects were questioned about specific symptoms (Table 1) once per hour while they were underwater.

Test methods before and after the dives were the same as those of the stability study. However, blood samples were drawn only on the day before the dive, on the day of the dive, and on the day following the dive. Blood values from the day following the dive were used with the diffusing capacity data for the later measurements.

After the in-water study, a deficit in a pulmonary function variable was defined as a decrease from baseline of 2.4 times the coefficient of variation found from the stability study. For subjects who participated in both components of the study, this magnitude of decrease defined the 95% confidence band. For the subjects from whom we had the data we used the mean of stability study and pre-diving values for the subject as his or her baseline and the coefficients of variation determined for that subject. For the subjects for whom we had measurements on only one day before diving we used the subjects' predive values as baselines but the median of the coefficients of variations from all the subjects in the stability study.

Using Fisher's exact test, we compared prevalences of symptoms or deficits, because the numbers were too small for a chi-squared statistic to be valid.

RESULTS

STABILITY OF PULMONARY FUNCTION

No detectable differences in pulmonary function were ascribable to time after exercise, although the power should have been adequate to reveal meaningful differences. A 2% difference in vital capacity in these data would have been detectable with 95% confidence 70% of the time, and a 5% difference more than 99% of the time. Similarly, a 2% difference in diffusing capacity would have been detectable 30% of the time, and a

5% difference 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 mornings (highest after exercise) than in the afternoons.

The median and maximum coefficients of variation for pulmonary function variables over six weeks are listed in Table 2. A few subjects showed highly variable pulmonary function tests from week to week.

Table 2: 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 %
Mid flow	7.2 %	14.7 %
D_LCO	5.9 %	9.4 %

DIVING

Pulmonary function values before the oxygen dives were not different ($p>0.05$) from what they had been before the air dives, with the exception of D_LCO, which was slightly lower before the 4-hour oxygen dives than before the 4-hour air dives. Values are shown in Table 3.

Table 3: 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
FEV1 (L)	4.2±0.2	4.3±0.2	4.16±0.07	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

Isolated decreases in pulmonary function were seen after both air and oxygen dives, and symptoms were reported after both dive series. However, although some subjects showed distinct pulmonary impairment, the average differences in pulmonary function test results after diving were not statistically significant. Median changes are presented in Table 4.

Table 4: Median percentage change in pulmonary function

		Dive day	Day +1	Day +2	Day +3 or +4
FVC					
8 hours	Air	2.30	0.04	-0.47	-3.69
	O_2	1.91	1.09	-0.40	-2.07
6 hours	Air	-0.01	0.17	-1.79	-0.87
	O_2	0.58	-0.87	0.23	-0.99
4 hours	Air	0.01	-1.27	-2.24	-4.11
	O_2	0.41	-1.21	-0.61	0.31
Peak flow					
8 hours	Air	-1.91	-3.12	-6.54	-13.31
	O_2	-1.35	-0.71	-8.19	-1.55
6 hours	Air	2.97	7.45	3.05	7.46
	O_2	3.85	5.43	1.76	3.52
4 hours	Air	-1.85	4.70	-2.39	3.33
	O_2	2.92	4.72	4.03	3.13
FEV1					
8 hours	Air	3.93	1.80	0.98	-5.23
	O_2	0.78	0.50	0.16	-1.03
6 hours	Air	-1.06	0.53	-1.87	-3.84
	O_2	-0.36	-1.92	-0.43	-2.12
4 hours	Air	2.33	0.26	-1.52	-2.54
	O_2	1.20	-1.13	-0.28	-0.39
D_LCO					
8 hours	Air	-1.51	-5.46	-0.25	-8.58
	O_2	-3.18	-3.52	-5.50	-3.56
6 hours	Air	-1.35	0.48	-1.19	-1.91
	O_2	-1.97	-2.88	-3.89	-0.50
4 hours	Air	-2.97	-7.97	-4.32	-5.93
	O_2	-0.88	-0.96	-2.28	-0.48

The numbers of people experiencing postdive symptoms or reductions in pulmonary function on at least one testing day are shown in Table 5. In this table, neither severity nor duration of symptoms is considered. The number of divers with a detectable PFT deficit on at least one day was not greater after oxygen diving than after air dives, but more divers experienced symptoms after breathing oxygen than after breathing air. The incidence of reported symptoms was significantly greater for the 8-hour oxygen exposure than for 8-hour air exposure, and was greater after an 8-hour oxygen exposure than after a 4-hour oxygen exposure (Fisher's exact $p = 0.042$ for both).

Table 5: Number of subjects with one or more PFT deficits or symptoms on one or more days after diving

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

The incidence of symptoms or measured decreases in pulmonary function did not differ significantly with the duration of the dives when subjects breathed air.

The number of days a subject has some deficit after diving may be operationally more important than whether a person experiences any symptoms or decreases in pulmonary function. 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 listed in Table 6.

Table 6: 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

The number of symptom-days increased with the duration of exposure to 1.4 ATA 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 oxygen underwater generated significantly more symptom-days than did 8 hours of breathing air (Fisher's exact $p = 0.009$). Differences, air to oxygen, in symptom-days after 6- or 4-hour exposures were not significant (exact p values = 0.48 and 1). The differences in number of pulmonary function test deficit days, air to oxygen, were not significant after any exposure duration.

Details of symptoms, pulmonary function changes, and time to resolution of the symptoms or the changes are given for each subject in Table 7.

Table 7: Details of results, by subject

a) Eight-hour dives

Smoker? Yrs diving		First symptom		Max intensity		Resolved by		First PFT changes		Resolved by	
		air	O_2	air	O_2	air	O_2	air	O_2	air	O_2
n	19y	-	H2 t	-	1	-	+1	+3 f	IP-S v,f,v1	+4	+3
n	12y	-	+1 c	-	1	-	+2	+2 f	+2 f	+3	+3
n	20y	H4,c IP,c	IP i,c,t,e	1	2	H5, +1	+2	-	-	-	-
y	13y	+1 i,c	+1 i,c,t, e,f	2	2	+2	+3	+1 f,d	+1 d	+2	+7
n	20y	-	IP i,c,t	-	1	-	+1	-	-	-	-
y	21y	-	-	-	-	-	-	+4 d	IP d	+7	+1
n	16y	-	IP c	-	1	-	+1	-	-	-	-
n	16y	-	IP c,t	-	1	-	+2	-	-	-	-

First column: y = smoker, n = nonsmoker; Number of years diving.

First reported/ resolved by/ First PFT changes: H = hour during the dive. IP = immediately post, +1 = one day after the dive, etc.

Maximum intensity (of symptoms): 1 = mild, 2 = moderate.

First PFT changes: S = severe.

Symptoms: i = inspiratory burning, c = cough, t = chest tightness or pain, s = shortness of breath, e = reduced exercise tolerance, f = unreasonable fatigue.

PFT changes: f = reduced peak flow, v = reduced vital capacity, d = reduced diffusing capacity, v1 = reduced FEV_1.

b) Six-hour dives

Smoker?	Yrs diving	First Reported		Max intensity		Resolved by		First PFT changes		Resolved by	
		air	O_2	air	O_2	air	O_2	air	O_2	air	O_2
n	18y	-	-	-	-	-	-	+1,f +4,d	IP f	+2 +7	+1
n	26y	-	IP c	-	1	-	+1	-	-	-	-
n	12y	-	IP i,c,e	-	1	-	+2	-	-	-	-
n	9y	+1 f,e	H3 I,c,f,e	1	1	+2	+2	-	-	-	-
n	4y	-	-	-	-	-	-	-	IP d	-	+1
n	10y	-	-	-	-	-	-	-	-	-	-
n	16y	-	IP f	-	2	-	+1	-	-	-	-
n	23y	+1 t,e	-	2	-	+2	-	-	IP-S f	-	+3

First column: y = smoker, n = nonsmoker; Number of years diving.
First reported/ resolved by/ First PFT changes: H = hour during the dive. IP = immediately post, +1 = one day after the dive, etc.
Maximum intensity (of symptoms): 1 = mild, 2 = moderate.
First PFT changes: S = severe.
Symptoms: i = inspiratory burning, c = cough, t = chest tightness or pain, s = shortness of breath, e = reduced exercise tolerance, f = unreasonable fatigue.
PFT changes: f = reduced peak flow, v = reduced vital capacity, d = reduced diffusing capacity.

c) Four-hour dives

Smoker?	Yrs diving	First Symptoms		Max intensity		Resolved by		First PFT changes		Resolved by	
		air	O_2	air	O_2	air	O_2	air	O_2	air	O_2
n	11y	IP c	-	1	-	+1	-	-	-	-	-
n	25y	-	-	-	-	-	-	-	-	-	-
n	12y	-	-	-	-	-	-	-	-	-	-
n	15y	-	-	-	-	-	-	-	-	-	-
n	19y	IP i	-	1	-	+1	-	-	IP f	-	+2
n	12y	IP c +1 s	IP i,c,t,s	1	1	+2	+2	-	-	-	-
n	17y	-	IP f	-	+1	-	-	-	-	-	-
y	13y	-	-	-	-	-	-	+3 d	IP d	+7	+1

First column: y = smoker, n = nonsmoker; Number of years diving.
First reported/ resolved by/ First PFT changes: H = hour during the dive. IP = immediately post, +1 = one day after the dive, etc.
Maximum intensity (of symptoms): 1 = mild, 2 = moderate.
First PFT Changes: S = severe.
Symptoms: i = inspiratory burning, c = cough, t = chest tightness or pain, s = shortness of breath, e = reduced exercise tolerance, f = unreasonable fatigue.
PFT changes: f = reduced peak flow, v = reduced vital capacity, d = reduced diffusing capacity.

DISCUSSION

STABILITY STUDY

The variability in spirometric test results was smaller than that reported by the American Thoracic Society (ATS) for the general population.[9] We found median 95% confidence bands of 7.7% in FVC, 8.4% in FEV1, and 17% in mid-expiratory flow. For normal subjects the ATS reports a week-to-week variation of 11% in FVC, 12% in FEV_1, and

21% in mid-expiratory flow, and within-a-day variability of 5% in FVC and FEV_1 and 13% in mid-expiratory flow. The somewhat tighter confidence bands we report probably result from a having a more homogenous population 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 population tested. Although pulmonary function is altered after maximum exercise, [6-8] our subjects followed their normal fitness routines. That their exercise was moderate, in combination with their general high level of physical training, may have meant that pulmonary blood volume was back to normal soon after they completed PT. However, our failure to observe an increase in D_LCO immediately after exercise also may represent experimental artifact. Nearly all of the measured D_LCO values were more than 110% of the expected value for a person of similar height, weight, and age. We corrected D_LCO for hemoglobin and carboxyhemoglobin concentrations[11] and adjusted the time and sample volume to avoid the time of instrument overshoot. However, by following the usual NEDU technique for performing D_LCO measurements, one of the methods recommended by the instrument manual,[11] we potentially increased the gas transfer surface area. Our subjects held their breaths at maximum lung volume using muscular effort with open airways. The continued, strong inspiratory effort generated by this maneuver draws blood into the lungs during the breath-hold. To minimize the perturbation, subjects should have inhaled slightly submaximal volumes, then held their breaths while they relaxed their respiratory muscles against a valve or a closed glottis. However, decreases caused by postdive thickening of the alveolocapillary membrane would still have been evident.

DIVING

This study was designed to look for an average response, although the pulmonary effects of diving show much difference among individuals. Thus, statistics based on the average response fail to report instances of possible significant pulmonary injury.

Seven of eight divers reported symptoms after the 8-hour exposure to oxygen at 1.4 ATA, 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 without symptoms showed changes in pulmonary function.

When symptoms and pulmonary function deficits coexist, vital capacity could be limited by pain. However, the lack of correlation between signs and symptoms suggests that pain is not the primary cause of reduced vital capacity in this or other[4] studies. Further, the highly motivated diver-subjects appeared to be exerting maximal effort during the pulmonary function tests.

Symptoms are likely to occur without pulmonary function deficits because symptoms are 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[13] and thereby to increase the permeability of the pulmonary capillary membranes.[14] 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. Even severe interstitial edema makes little difference to VC; the maximum possible increase in interstitial membrane thickness is 15% to 20%,[14] corresponding to a decrease in VC of less than 50 mL. D_LCO could decrease by as much as 13% to 17% with severe interstitial edema if the membrane thickened without a change in blood distribution. However, pulmonary vascular resistance tends to increase when capillaries become leaky, and increased resistance increases inflow pressure, which recruits more capillaries. As only about 33% of the pulmonary capillaries are normally open in a person at rest, the potential for the gas transfer surface area to increase to minimize the gas transfer (and D_LCO) deficit, is considerable. A subject with interstitial edema might have normal VC and D_LCO but marked cough.

Once liquid begins to accumulate in the interstitial spaces of the alveolocapillary membrane, it drains rapidly into the more compliant spaces around blood vessels and airways.[14] Accumulation of fluid around the airways may increase airway resistance by forming liquid-filled cuffs around them; in small airways with laminar flow, a 2% decrease in the radii changes peak flow about 8% if the driving pressure does not change. The regions where liquid can accumulate outside the blood vessels connect to lymph ducts, and lymphatic drainage can increase ten- to fifteenfold in the face of increased membrane permeability.[14] Only if the lymphatic drainage is overwhelmed will fluid enter the alveoli, when measurable changes in vital capacity and D_LCO can be expected. Thus, relatively severe PO_2T with edema becomes evident with a reduction in VC, intermediate levels of injury appear as D_LCO or peak flow decrement, and even mild injury may be manifest as cough.

The presence of measurable pulmonary function deficits without symptoms is surprising, but also has been reported by other investigators.[4] Subjects may sometimes fail to report symptoms that they considered "normal after diving". However, some changes in lung function may be truly asymptomatic. For example, because of higher P_IO_2, local pulmonary vascular tone may relax to allow greater pulmonary blood volume in some subjects. This is the presumed mechanism by which oxygen breathing reduces vital capacity in subjects at altitude.[15] In subjects breathing room air, local alveolar oxygen partial pressures in the most dependent regions of the lungs can be at or below 90 Torr, the partial pressure below which, in order to optimize gas exchange, pulmonary vascular resistance increases markedly.[14] However, with elevated P_IO_2, even relatively over-perfused regions of the lung can maintain alveolar oxygen partial pressures above 90 Torr, and reflex pulmonary vasoconstriction might not reduce blood pooling in the lung bases. Although we have no data to address this question, a short-lasting,

asymptomatic reduction in vital capacity, if caused only by blood volume shifts, arguably would not be a manifestation of toxicity.

Many previous studies have measured pulmonary function only immediately after the end of the oxygen exposure. Had we 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. Although the underreporting would have been less after the 6-hour and 4-hour oxygen exposures, we would have missed all pulmonary function changes and two of the six reports of symptoms after air exposures.

Tissue damage from oxygen toxicity, like that from sunburn, is not complete when the exposure is over. Symptoms and pulmonary function at the end of the exposure represent the accumulated injury. Subsequently, damaged tissues trigger an inflammatory response.[16] Injured cells either die or are repaired, and cells proliferate during healing. Even if no signs or symptoms appear immediately after the oxygen exposure, symptoms or changes in pulmonary function during the days following oxygen exposure indicate that the tissue damage has been sufficient to trigger an inflammatory response. Thus, symptoms or decreases in pulmonary function for three or four days after an oxygen exposure indicate that damage has occurred during the exposure.

The dives for 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 ATA, below the 0.5 ATA previously used as the threshold for pulmonary toxicity to occur.[4] Because of the small increase in P_IO_2 from atmospheric partial pressure, the symptoms and decrements in pulmonary function more likely resulted from 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.

After the 8-hour oxygen exposure, pulmonary function decreased in 50% of the subjects, and 87.5% reported symptoms. The incidence of pulmonary function deficit would be 37.5% if we had not deemed one diver's small D_LCO deficit significant because we had six weeks of baseline data on the subject. In a comparable experiment when divers breathed oxygen from the LAR V at 20 fsw, changes in pulmonary function were reported in 73% of them.[2] 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. Although the number of our subjects who showed decreased pulmonary function after eight hours of oxygen exposure was not statistically different from that after similar air exposure, the number of days when subjects reported symptoms was significantly greater after the 8-hour oxygen exposure than after the 8-hour air exposure. Five of the eight subjects reported symptoms during or immediately after the dive, and another two

subjects reported symptoms on the next day. In the LAR V study, 45% of the divers reported symptoms.[2]

Depending on how many surface breaks were taken, the unit pulmonary toxic dose[3] (UPTD) calculated for the 8-hour oxygen dives ranges from 842 to 908. For the 6-hour oxygen dives, the range is 634 to 681, and for the 4-hour exposures, from 426 to 454. UPTD cannot be calculated for P_IO_2 less than 0.5 ATA. The Harabin minimized model for dry exposures with these UPTDs predicts median changes in VC of –4.4% for the 8-hour exposure, –3.3% for the 6-hour exposure, and –2.2% for the 4-hour exposure.[3] However, the median change seen in FVC was +1.9% for the 8-hour exposure, +0.6% for the 6-hour exposure, and +0.4% for the 4-hour exposure (Table 4). The operationally necessary surface intervals when subjects breathed atmospheric air may have helped protect them from PO_2T. It seems unlikely, though, that a 5:55 ratio of air to higher P_IO_2 exposure could totally eliminate the decrement in VC. It is more likely that the Harabin model, which was developed from data for long exposures in dry chambers, fails for shorter exposures or in the water.

CONCLUSIONS AND RECOMMENDATIONS

No threshold of exposure duration was apparent for symptoms or changes in pulmonary function, but the incidence of symptoms increased with dive duration. We conclude that a 4-hour underwater exposure to P_IO_2 = 1.4 ATA is no worse than one to P_IO_2 = 0.3 ATA, but that air breathing under water is associated with some pulmonary injury. A 6-hour exposure warrants further investigation: because one subject out of eight had a moderately severe and prolonged reduction in peak flow after a 6-hour oxygen exposure, we cannot conclude that six hours at P_IO_2 = 1.4 ATA is safe for the lung. In a majority of subjects, an 8-hour underwater oxygen exposure causes mild to moderate pulmonary insult that does not resolve for a few days.

The small number of studies included in this test make conclusions for the two shorter exposures somewhat preliminary. More study of underwater exposures for 4- to 6-hour durations will help refine the conclusions.

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