Navy Experimental Diving Unit
321 Bullfinch Rd.
Panama City, FL 32407-7015

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THREE-HOUR DIVES WITH EXERCISE WHILE BREATHING OXYGEN PARTIAL PRESSURE OF 1.3 ATM

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Author: B. Shykoff, Ph.D.

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19. ABSTRACT: Four-hour dives including underwater exercise at Po_2 = 1.3 atm showed an accumulation of pulmonary effects despite 20-hour surface intervals between dives. Similar three-hour dives, with 21-hour intervals, were tested for accumulation of pulmonary oxygen toxicity. We measured pulmonary function (flow-volume loops and diffusing capacity for carbon monoxide, D_LCO) and asked about symptoms before and after underwater exercise dives with1.3 atmospheres (atm) of oxygen. While underwater for three hours at a time in a 15-foot deep pool, U.S. Navy divers breathed surface-supplied, humidified 100% oxygen open circuit from full face masks with demand regulators. Divers alternated 30 minutes of rest with 30 minutes of cycle ergometer exercise in a swimming configuration and at heart rates of 105 ± 5 beats/minute. Sixteen divers began, and fifteen finished, a series of five daily dives with 21 hours between dives. The incidences of signs and symptoms of pulmonary oxygen toxicity were no different from those after a single four-hour dive, and regressions of values against dive numbers showed no significant nonzero slopes. We conclude that pulmonary changes do not accumulate with three-hour dives with exercise at Po_2 = 1.3 atm when divers have 21 hours between dives. This diving schedule can be repeated indefinitely.

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INTRODUCTION

The *U.S. Navy Diving Manual* authorizes divers to breathe oxygen for up to 240 minutes per day at depths of 20 feet of seawater (fsw) or less but does not address the possible accumulation of effects over multiple days.[1] When we conducted experimental four-hour dives with oxygen partial pressure (Po_2) of approximately 1.4 atmospheres (atm)[2,3] with divers at rest, we concluded that the limit of 240 minutes in 24 hours is acceptable for multiple days. However, when divers exercised for 120 minutes of their underwater time, mild pulmonary effects accumulated.[4] The question addressed in this component of the NAVSEA-funded task, *Pulmonary Oxygen Toxicity While Swimming: How Exercising Underwater or Using a Rebreather Underwater Breathing Apparatus Affects Pulmonary Function After 1.35 Atm Oxygen Exposures,*[5] was whether pulmonary effects accumulated over five days of three-hour dives when half of the dive time was spent exercising.

We measured changes in pulmonary function and assessed symptoms immediately and for several days after diving exposures. The pulmonary function variables determined from forced flow-volume loops were forced vital capacity (FVC), forced expired volume in one second (FEV_1), peak expired flow or maximum forced expired flow (FEF_{max}), and average forced expiratory flow from 25% to 75% of expired volume (FEF_{25-75}). Diffusing capacity of the lung for carbon monoxide (D_LCO) was determined from single breath tests. The lower limits of normal for pulmonary function variables were defined as the lower 95% confidence bands for each variable — that is, as decreases from baseline of 2.4 times the coefficient of variation (cv) found for the Navy Experimental Diving Unit (NEDU) population: namely, 7.7% for FVC, 8.4% for FEV_1, 16.8% for FEF_{max}, 17.0% for FEF_{25-75}, and 14.2% for D_LCO.[6] Because we had seen hyperoxic myopia after a series of five six-hour dives,[7] we also measured visual refraction when we tested pulmonary function.

METHODS

GENERAL

The dives were identical to those for the four-hour exercise dives[4] for all but dive duration. Each subject dove on five consecutive days for three hours each day and beginning at the same time of day, for a 21-hour surface interval. During the dives in NEDU's fifteen-foot-deep test pool, subjects in comfortably warm water (84 ± 5 °F; 29 ± 3 °C) breathed humidified 100% oxygen open circuit from the MK 20 underwater breathing apparatus (UBA). The divers alternated 30 minutes of underwater cycle ergometer exercise with 30 minutes of rest. The ergometers were mounted to mimic a swimming configuration, with the centers of the shoulder supports 12 ± 2 inches (30 ± 5 cm) above the axis of the pedals and 3.5 feet (1.1 m) above the pool bottom. A diver on an ergometer had his regulator under about 11 feet (3.4 m) of water and his chest only slightly deeper, for 1.3 atm Po_2 and little hydrostatic imbalance. Sitting or lying on the bottom, a diver at rest was under about 14 feet (4.3 m) of water, for 1.4 atm Po_2. To eat or drink, divers surfaced and breathed room air for five minutes at the beginning of each rest period.

For one week before the study, subjects had not been exposed to P_{O_2} greater than 1.2 atm, and for four days they had not performed any dive. Except for the experimental dives, they refrained from diving throughout the testing period. Each subject's smoking behavior and history of respiratory allergies were noted, and subjects' general health and use of medications also were recorded during the studies. All subjects were in good health.

Table 1.
Subject characteristics

n = 16	Median	(range)
Age (Yr)	37	(26–47)
Height (in)	71.5	(68–72)
Weight (lb)	195	(165–285)
Smokers (#)	*never,* 12; *former,* 3; *current,*1	
Respiratory allergies, pollen or other (#)	6 (2 in allergy season)	
Medication use (#)		
Anti-inflammatory, 4; Decongestant, 1; Antihistamine, 1		

To measure pulmonary function, at each session we acquired three flow-volume loops performed and repeatable according to American Thoracic Society standards.[8] FVC, FEV_1, FEF_{max}, and other variables were read from the flow-volume loops. The sessions also included three single-breath D_LCO measurements made with a 10-second breath hold. 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,[9] and the samples were chosen to ensure that the analyzer signal was stable when measurements were recorded.[10]

Baseline pulmonary function tests (PFTs) were done within the week before the test dives and, for flow-volume tests, also immediately before diving. The averages of three technically correct diffusing capacity tests and of three properly performed flow-volume loops from both sessions were used for comparisons with later values. For repeated dives, measurements of flow-volume loops were made in the morning before each dive; any diver with FVC or FEV_1 less than twice the 95% confidence interval below baseline was to discontinue diving in the series. Both flow-volume curves and diffusing capacities were measured within an hour of surfacing and for one or two days after the only or the final dive. If FVC, FEV_1, FEF_{max}, or D_LCO was below the lower limit of normal variability around baseline, the measurement was repeated until pulmonary function was within those limits.

Visual refraction was measured at each session measuring pulmonary function. Divers were not permitted to continue in the series if their refractions in the morning had decreased from baseline by 0.75 diopters (D) or more.

Divers were questioned about specific symptoms (Table 2) each hour during the dive and at each session measuring pulmonary function.

Table 2.
Symptoms list

During the dives:	After the dives:
Vision changes	Visual complaints
Ringing or roaring in ears	Ear problems
Nausea	
Tingling or twitching	Unreasonable fatigue
Light-headedness or dizziness	Reduced exercise tolerance
Chest tightness	Chest pain or tightness
Shortness of breath	Shortness of breath
Rapid shallow breathing	
Inspiratory burning	Inspiratory burning
Cough	Cough

EXPERIMENTAL DESIGN AND ANALYSIS

Pulmonary function variables were considered to be different from baseline if they were outside the 95% confidence bands based on normal variability.[6] Confidence in estimates of the incidence of changes in pulmonary function or of symptoms with $\alpha = 0.1$ (90% confidence in the proportion) was obtained from the binomial distribution. Fisher's Exact Test was used to compute the probabilities that pairs of proportions represented samples from the same population. Linear regression was used to assess trends of changes from baseline with time, with dive number as the independent variable.

EQUIPMENT AND INSTRUMENTATION

The Collins CPL and Collins GS Modular Pulmonary Function Testing System instruments (Ferraris Respiratory; Louisville, CO) were used to measure pulmonary function. The test gas used to measure D_LCO contained 0.3% CO and 0.3% methane. A CO oximeter (Instrumentation Laboratory; Lexington, MA) determined the pretest carboxyhemoglobin and hemoglobin concentrations from a venous blood sample. An autorefractor (Humphrey model 599, Carl Zeiss Meditec; Dublin, CA) was used to measure visual refraction.

Humidifiers (bubblers) built at NEDU for the purpose were connected in the gas circuits at the test pool. Electrically braked cycle ergometers (Collins Medical; Louisville, CO), modified for use underwater, provided the exercise load. While in the pool, divers monitored their heart rates by using Polar heart rate chest straps and watches (Polar USA; Lake Success, NY).

PROCEDURES

Eight divers began each set of dives, one group in the morning and one in the afternoon. Divers reported to the laboratory at the appointed time for predive measurements. Under direction of the dive supervisor, they donned equipment and entered the water in groups of four, with a 15-minute interval between water entry for the groups. The four-hour period for each group started when those divers began to breathe oxygen. The first four divers began with ergometer exercise and the second group with rest. Target pedal cadence was 60 rotations per minute (rpm). Initially the ergometers were set for 35 Watts. Every five minutes, exercising divers were asked their heart rates. If their rates were less than 100 beats per minute (bpm), the ergometer load was increased, and if their rates were more than 110 bpm, the load was decreased.

After the first divers had exercised for 30 minutes, they were instructed to stop work. The second group then moved to the ergometers to begin their first 30-minute exercise session. The first group surfaced for a 5-minute air break, during which they could eat and drink. The groups continued to alternate on and off the ergometers until four hours had elapsed since the start of oxygen breathing. Divers then were instructed to surface.

After diving, the subjects were escorted to the laboratory for blood draws, testing of pulmonary function and visual refraction, and recording of symptoms. On the days after diving, the measurements were repeated.

RESULTS

One subject without signs or symptoms of pulmonary oxygen toxicity withdrew on the third day because of a scheduling conflict. Two subjects switched morning for afternoon groups with each other on the fourth day of diving, also to accommodate outside scheduling. Neither diver had signs or symptoms of pulmonary oxygen toxicity after their adjusted surface intervals.

PULMONARY FUNCTION AND RESPIRATORY SYMPTOMS

Five Dives, 21-hour Interval

Incidences of symptoms and signs

Four subjects of the 15 who completed five dives reported respiratory symptoms at some time during or after the series of five dives (Table 3).

On no day do the incidences of reported symptoms or measured pulmonary function changes after a three-hour exercise dive differ statistically from those after one or more 4-hour resting dives.

Two subjects showed changes in at least one flow-volume measure, and two in diffusing capacity, at some time during or after the series of five dives (Table 3).

Table 3.
Respiratory symptoms and decreases in pulmonary function after five daily 3-hour dives with exercise at Po_2 = 1.3 atm

Diver	**During or after dive #**					
	1	**2**	**3**	**4**	**5**	**post**
1	c,d	d,t	c,t,d	c,t,d	d,t D_LCO −19%	-
2	**(c)**	c	-	c	-	-
3	-	-	-	c,i	c	c
4	t	i				
5	-	D_LCO −14%	D_LCO −16%	-	-	-
6	-	FEF_{mid} −18%	-	FEF_{mid} −22%% FEV_1 −9.7%	-	FEV_1 −8.5%
7	-	-	FEV_1 −8.7%	FEV_1 −8.7%	-	FVC −7.8% FEV_1 −8.9%
8–16	-	-	-	-	-	-

Values indicate the most severe occurrence for the time interval where, for example, "3" means from the start of Dive 3 until the start of Dive 4.
Diver numbers are not linked to those in other reports.
Abbreviations: "c" is cough, "d" is dyspnea (shortness of breath), "i" is inspiratory burning, and "t" is chest pain or tightness. "FEF_{mid}" is FEF_{25-75}.
All symptoms listed were mild.
Because subject 2 in this table reported cough before Dive 1, the moderate cough reported after Dive 1 (bold in parentheses) was assumed to be unrelated to the dive.

Progression of changes over time

Pulmonary function showed no trend with increasing dive number (Figures 1 and 2). Slopes were FVC: 0.1%/day, Standard Error (SE) 0.2%/day; FEV_1: 0.03%/day, SE 0.18%/day; FEF_{max}: 0.1%/day, SE 0.3%/day; FEF_{25-75}: −0.2%/day, SE 0.3%/day, and DLCO: 0.2%/day, SE 0.3%/day.

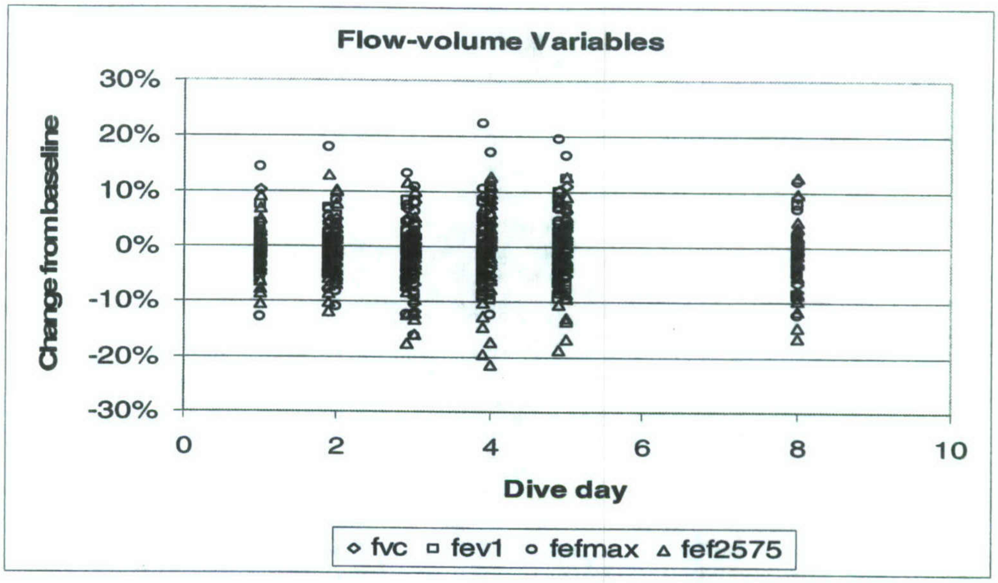

Figure 1. Flow-volume variables, % changes from baseline, 3-hour exercise dives, 21-hour surface intervals. The slopes of the regression lines (not shown) are not significantly different from zero. Each point represents the mean of three measurements for a subject. Sixteen divers are represented until Day 3, and fifteen thereafter.

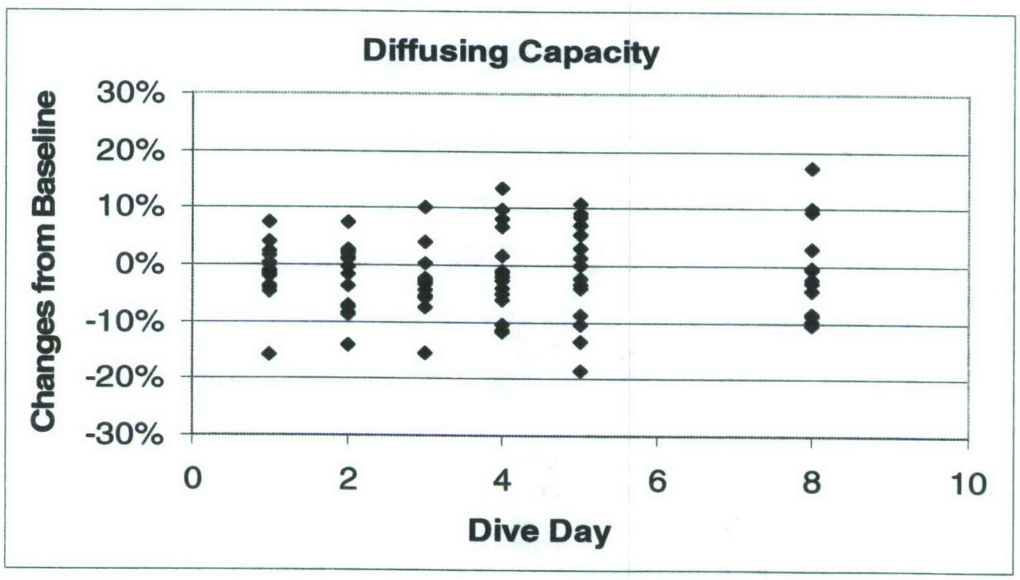

Figure 2. D_LCO changes from baseline, 3-hour exercise dives, 21-hour surface intervals. Slope of the regression line (not shown) is not different from zero. Each point represents the mean of three valid measurements (adjusted for hemoglobin concentration) for a subject. Sixteen divers are represented until Day 3, and fifteen thereafter.

OTHER SYMPTOMS AND SIGNS

No divers had significant changes in visual refraction. Only one diver showed postdive dehydration sufficient to increase hemoglobin concentration by 10% or more, and only after his fifth dive. Eight of sixteen divers complained of ear discomfort with fullness and difficulty clearing, generally throughout the dive series. One diver developed an external ear infection after the dive series. Four subjects reported unreasonable fatigue at some time during the series.

DISCUSSION AND CONCLUSIONS

When the interval between dives is 21 hours, pulmonary effects do not accumulate after three-hour dives at P_{O_2} of 1.3 atm — even when the dives include one and one-half hours of exercise. This result is similar to that with 20 hours between four-hour dives when divers rest,[3] but not to that when divers exercise for two of the four hours. Three-hour dives conducted once a day at the same starting time with P_{O_2} = 1.3 atm can be repeated indefinitely, even when divers exercise.

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