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

TA 06-15
NEDU TR 06-13
SEPT 2006

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

NAVSEA
NAVAL SEA SYSTEMS COMMAND
Navy Experimental Diving Unit

Author: B. Shykoff, Ph.D.

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING AUTHORITY	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEDU Technical Report No. 06-13	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit 6b. OFFICE SYMBOL (If Applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015	7b. ADDRESS (City, State, and Zip Code)
8a. NAME OF FUNDING SPONSORING ORGANIZATION NAVSEA N873 8b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) CNO N873, Deep Submergence, Chief of Naval Operations, Submarine Warfare Division, 2000 Navy Pentagon, PT-4000, Washington, DC 20350	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. 01A / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) Four-Hour Dives with Exercise While Breathing Oxygen Partial Pressure of 1.3 Atm

12. PERSONAL AUTHOR(S)
B. Shykoff, Ph.D.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT	15. PAGE COUNT
Technical Report	From Oct 2005 to May 2006	September 2006	21

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Oxygen diving, pulmonary oxygen toxicity, FVC, D_LCO, FEV_1, diffusing capacity, 1.3 atm, pulmonary function, 4-hour dives, underwater exercise

19. ABSTRACT: Underwater exercise, which increases the load on the cardiorespiratory system, may provoke pulmonary changes or exacerbate effects of oxygen. To compare dives with exercise to four-hour resting dives where divers breathed oxygen underwater, 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 four 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 either 110 ± 5 or 105 ± 5 beats/minute. At the higher heart rates, 40 divers performed single dives; at the lower heart rates, 16 began a series of five daily dives with 20 hours between dives, and 32 began a series of two dives with 15 hours between them. Two divers could not complete the five dives — one because of inspiratory burning and dyspnea, and the other because of a ruptured eardrum — and four divers could not complete the two dives because ergometers flooded. Within 20 hours after single dives, of 56 divers who exercised and of 75 who rested, 17% reported symptoms, and no more than 5% had changes in pulmonary function. With 20-hour intervals between exercise dives, however, after the second consecutive dive the incidence of symptoms increased to 38% among 16 divers; during the third dive one subject developed symptoms so severe that he could not continue. After the fourth dive the incidence of symptoms was 43%, and of flow-volume changes 21%, among 14 divers. Although pulmonary function for most subjects remained within the bands of normal variability around baseline, linear regression revealed significant downward trends in D_LCO and in some flow-volume indices across five days of diving. With 15-hour intervals between dives, the incidence of symptoms was not different from that after one dive, but some flow-volume decreases from baseline were evident on the first day after the dives. After all experiments, divers had recovered to within normal limits of baseline by the fourth day after diving. We conclude that pulmonary changes accumulate during dives that include exercise, but pulmonary effects of two dives remain mild even with a 15-hour surface interval. After two dives, a recovery day is recommended to reduce the risk of mission-limiting symptoms. After nine dives with 20-hour intervals between pairs of dives, a longer break should be taken for recovery of pulmonary function.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
[ ] UNCLASSIFIED/UNLIMITED [X] SAME AS RPT. [ ] DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
NEDU Librarian	850-230-3100	03

PAGE INTENTIONALLY LEFT BLANK

CONTENTS

Page No.

LISTS OF TABLES AND FIGURES

TABLES

FIGURES

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] We have conducted experimental four-hour dives with oxygen partial pressure (P_{O_2}) of approximately 1.4 atmospheres (atm)[2,3] and have concluded that the limit of 240 minutes in 24 hours appears to be acceptable for multiple days if divers are at rest. Still, because the increased ventilatory demands and blood flow to the lungs during underwater exercise may cause pulmonary injury or may increase oxygen-induced injury over those ventilatory demands and blood flows experienced at rest, we tested divers after they had exercised underwater while being exposed to 1.3 atm oxygen for four hours. Although we cannot differentiate oxygen effects from exercise effects with this study, we can examine the combined effects. Testing was conducted as part 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.*[4]

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.[5] Because we had seen hyperoxic myopia after a series of five six-hour dives,[6] we also measured visual refraction when we tested pulmonary function.

METHODS

GENERAL

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 P_{O_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 P_{O_2}. To eat or drink, divers surfaced and breathed room air for five minutes at the beginning of each rest period.

We conducted three separate dive series: one with single exercise dives, one with exercise dives on five consecutive days with twenty hours between dives, and one with exercise dives on two consecutive days but with fifteen hours between dives. Only the last series exceeds the oxygen exposure limits in the *U.S. Navy Dive Manual.* We recruited 40 divers for the first set of dives, 16 for the second set, and 32 for the third set.

For one week before the study, subjects had not been exposed to Po_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

Single Dives	
n = 40	**Median (range)**
Age (Yr)	37 (26–48)
Height (in)	71 (66–75)
Weight (lb)	190 (137–260)
Smokers: (#)	*never*, 28; *former*, 8; *current*, 4
Respiratory allergies, pollen or other (#)	10 (1 in allergy season)
Medication use (#)	Anti-inflammatory, 1; Decongestant, 2; Antihistamine, 2

Five Dives with 20-hour Surface Interval	
n = 16	**Median (range)**
Age (Yr)	36 (25–44)
Height (in)	71 (68–74)
Weight (lb)	197 (170–265)
Smokers: (#)	*never*, 8; *former*, 5; *current*, 3
Respiratory allergies, pollen or other (#)	3 (0 in allergy season)
Medication use (#)	none reported

Two Dives with 15-hour Surface Interval	
n = 32	**Median (range)**
Age (Yr)	37 (25–50)
Height (in)	71 (66–75)
Weight (lb)	195 (160–270)
Smoking: (#)	*never*, 19; *former*, 8; *current*, 5
Respiratory allergies, pollen or other (#)	12 (3 in allergy season)
Medication use (#)	Anti-inflammatory, 6; Antihistamine, 1

To measure pulmonary function, at each session we acquired three flow-volume loops performed and repeatable according to American Thoracic Society standards.[7] 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,[8] and the samples were chosen to ensure that the analyzer signal was stable when measurements were recorded.[9]

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 refraction 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	Lowered 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.[5] 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. Divers reported to the laboratory at the appointed time for predive measurements. They donned equipment and entered the water, under direction of the dive supervisor, in groups of four, with a 15-minute interval between water entry for the groups. The four-hour period for each group started when they 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 50 Watts. Every five minutes, exercising divers were asked their heart rates. If their heart rates were less than 100 beats per minute (bpm), the ergometer load was increased, and if their heart 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, for testing of pulmonary function and visual refraction, and for recording of symptoms. On the days after diving, the measurements were repeated.

RESULTS

All subjects who began the single dives completed the tests. Two who began five-day series were forced to withdraw on the third day, one because of severe respiratory symptoms and one because he had ruptured his eardrum. Four divers were forced to stop during the two-day, 15-hour surface interval dives because an ergometer box had flooded.

PULMONARY FUNCTION AND RESPIRATORY SYMPTOMS

Single Dives

Incidences of symptoms and signs

The subjects who reported symptoms in conjunction with these dives did not demonstrate changes in pulmonary function variables, and those who had changes did not report symptoms. The types of symptoms and severity of changes are shown by subject in Table 3.

Nine of 40 subjects (23%; binomial confidence interval 12–36% at $\alpha = 0.1$) reported mild respiratory symptoms at some time during or after the dives, as shown in Table 3. This is not statistically different from the 13 of 75 divers (17%) who reported symptoms during or after previous single four-hour resting dives.[2,3]

Two subjects (5%; binomial confidence interval 0.9–15% at $\alpha = 0.1$) showed changes in one or more flow-volume parameters, an incidence not different from 5 of 75 subjects (6%) after single resting dives.[2,3] Although one subject showed large decrements in flow-volume parameters, he was free from symptoms and had difficulty producing three consistent flow-volume maneuvers at any session. The decrements, probably artifacts of subject performance, have been included in the incidence calculations but not in the assessments of severity.

Two subjects (5%; binomial confidence interval 0.9–15% at $\alpha = 0.1$) showed decreased D_LCO associated with these dives. While none of the 75 subjects had shown changes after similar resting dives,[2,3] the lower end of the confidence interval indicates that an incidence of one subject in 111 would still not differ from two subjects in 40; although we have too few measurements to see a difference between rest and exercise because of low incidence in both cases, the difference between "very low" and "extremely low" incidence is unimportant in practice.

Table 3.
Respiratory symptoms and decreases in pulmonary function after single dives with exercise

Diver	Immediately after dive	Day +1	Day +2
1	d	-	-
2	-	i,c	c
3	d,t	-	-
4	-	c	-
5	i	-	-
6	i,c	-	-
7	i	-	-
8	i	-	-
9	c	-	-
10	-	-	D_LCO −17.6%
11	D_LCO −16.7%	-	-
12	-	FEF_{25-75} −18.6%	-
13*	-	-	(FEV_1 −21% FEF_{max} −20% FEF_{25-75} −51%)*
14–40	-	-	-

Abbreviations: "c" is cough, "d" is dyspnea (shortness of breath), "i" is inspiratory burning, and "t" is chest pain or tightness. All symptoms were mild.
* Severity is probably an artifact of subject difficulty in performing PFT maneuvers — see page 5.

Five Dives, 20-hour Interval

Incidences of symptoms and signs

Nine subjects of 15 — including the one who aborted the series because of severe symptoms — reported respiratory symptoms at some time during or after the series of five dives (Table 4).

The incidences from the series with only one exercise dive (Table 3) were combined with those from the first dive of this series for comparison. After single exercise dives, 10 of 58 subjects reported symptoms, an incidence not different from that after single resting dives. On a day-by-day basis, the incidence of reported symptoms after more than one exercise dive is greater than after one similar dive after two and after four dives (Table 5), and the severity of symptoms is increased after three dives. However, although proportionally more divers reported symptoms after exercise dives than after resting dives (Table 5), small sample sizes prevented the day-by-day incidences from differing statistically, rest to exercise, except for those after two dives.

Four subjects showed changes in at least one flow-volume measure at some time during or after the series of five dives (Table 4). The day-to-day incidences (Table 5) show an increase after four dives as compared to one dive, but the other comparisons are not significantly different; very few changes were found.

One subject showed depressed diffusing capacity during the series of five dives (Table 4), as did one diver immediately after and another still later after single exercise dives (Table 3). None of the incidences was statistically different from those after either one exercise dive (Table 5) or one resting dive.[2] The lower end of the 90% binomial confidence interval (CI) for two episodes in 56 subjects (Dive 1) is one in 156, and for one in 14 subjects (Dives 4 and 5) it is one of 270, while we had only 75 measurements at rest.

Table 4.
Respiratory symptoms and decreases in pulmonary function after five daily dives with exercise

Diver	**During or after dive #**					
	1	**2**	**3**	**4**	**5**	**post**
1	c,t	c,i	c,i	c,I FEF_{mid} – 18%	c,t	-
2	-	c	-	c	-	-
3	-	-	c,i	c,i	c,i	-
4	-	i	***i***,c,**d**,t FEV_1 –9.8% FEF_{max} –23% FEF_{mid} –20%	Aborted because of symptoms		**d**
5	-	-	c	c FEF_{mid} –23%	-	c
6	-	c	-	-	-	-
7	-	t	-	t	t	-
8	-	c	-	-	-	-
9	-	-	d	d,t	d,i,t	-
10	-	-	-	D_LCO –16%	D_LCO –18%	-
1	-	-	FEF_{mid} –17%	FEV_1 –9.0%	-	-
12	-	-	-	Ruptured ear drum		-
13–16	-	-	-	-	-	-

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 tables.
Abbreviations: "c" is cough, "d" is dyspnea (shortness of breath), "i" is inspiratory burning, and "t" is chest pain or tightness. "FEF_{mid}" is $FEF_{25–75}$.
Bold italic characters represent severe, **bold** characters represent moderate, and regular roman characters represent mild symptoms.
Grayed boxes indicate that the subjects aborted the dive series.

Table 5.
Comparison of incidences of symptoms and signs after dives

Symptoms					
Exercise Dive #	1	2	3	4	5
Percentage incidence	17%	38%	33%	43%	29%
To 1 resting dive (17%)	ns	p<0.08	ns	p<0.05	ns
To 1 exercise dive (17%)		p<0.08	ns	p<0.05	ns
To similar # resting dives		vs. 14% p<0.05	vs. 20% ns	vs. 25% ns	vs. 18% ns
Flow-volume Changes					
Exercise Dive #	1	2	3	4	5
Percentage incidence	2%	0%	13%	21%	0%
To 1 resting dive (5%)	ns	-	ns	p<0.08	-
To 1 exercise dive (2%)		-	ns	p<0.03	-
To similar # resting dives		vs. 18% -	vs. 3% ns	vs. 14% ns	vs. 4% -
Diffusing Capacity Changes					
Exercise Dive #	1	2	3	4	5
Percentage incidence	2%	0%	0%	7%	7%
To 1 exercise dive (2%)		-	-	ns	ns
To similar # resting dives	vs. 0% -	vs. 4% -	vs. 0% -	vs. 0% -	vs. 0% -

"ns" (not significant) indicates p>0.1, and "-" indicates that a comparison could not be made because of zero incidence. Gray boxes indicate a comparison that would be redundant.

Severity of incidents

The diver who experienced severe symptoms was in the moderate range of pulmonary function deficits, both postdive (Table 4) and on the next day; on the day following the aborted dive, his pulmonary function test values were below baseline by FVC, –6.1%; FEV_1, –8.6%; FEF_{max}, –21%; and FEF_{25-75}, –18%. Chest auscultation revealed crackling sounds that took a few days to clear, and he was short of breath upon even mild exertion for about 36 hours after the dive, after which time his pulmonary function tests were within the normal limits.

None of the changes in pulmonary function was much below the lower limits of normal, and for all but the one subject, symptoms also were mild.

Progression of changes over time

FVC and FEF_{max} showed no trend with increasing dive number (Figures 1 and 3, Table 6), but other variables demonstrated a significant negative trend (Figures 2, 4, and 5, Table 6).

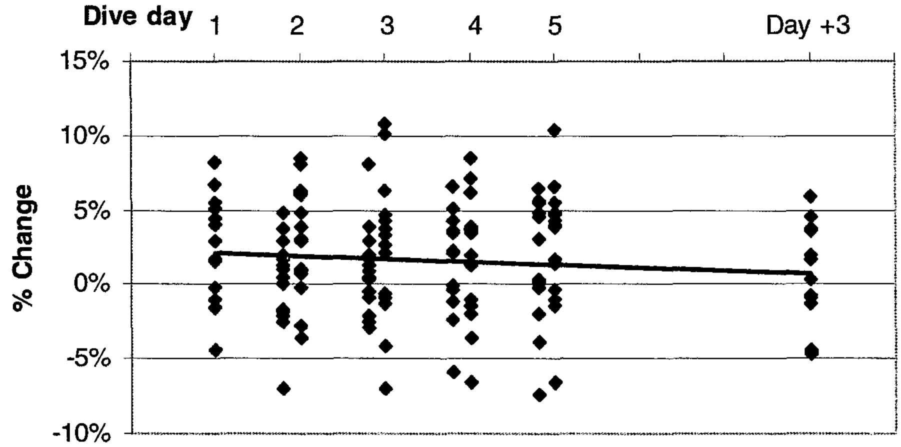

Figure 1. FVC changes from baseline, exercise dives, 20-hour surface interval. The slope of the trend line is not significantly different from zero. Each point represents the mean of three measurements for a subject. Sixteen divers are represented.

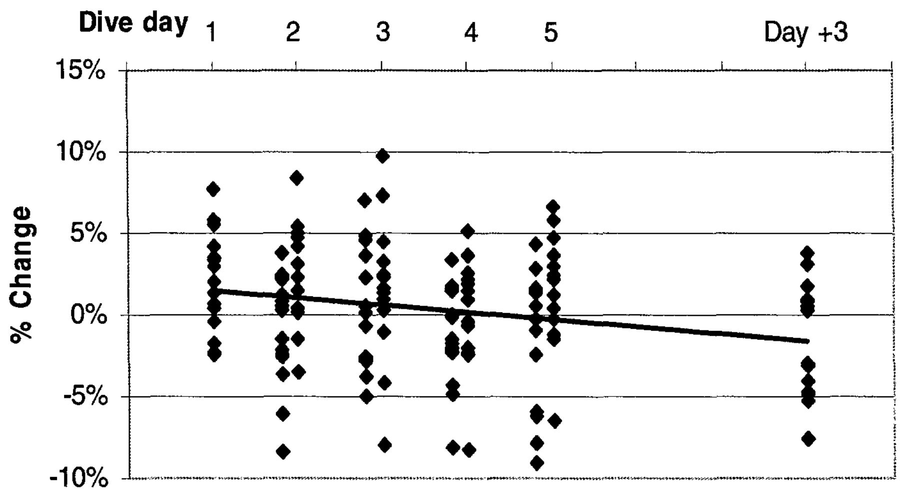

Figure 2. FEV_1 changes from baseline, exercise dives, 20-hour surface interval. Details of the trend lines, slope –0.4%/day, are listed in Table 6. The trend line for only the dive days is superimposed on the other line. Each point represents the mean of three valid measurements for a subject. Sixteen divers are represented.

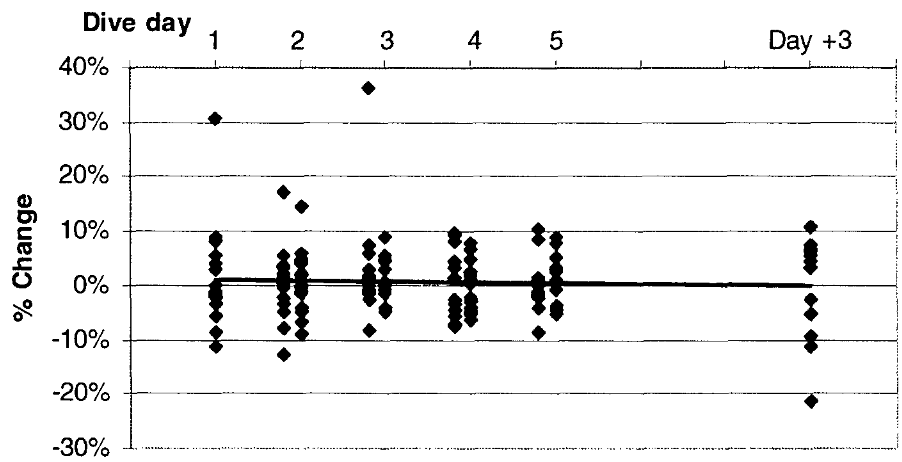

Figure 3. FEF_{max} changes from baseline, exercise dives, 20-hour surface interval. The slope of the trend line does not differ significantly from zero. Each point represents the mean of three measurements for a subject. Sixteen divers are represented.

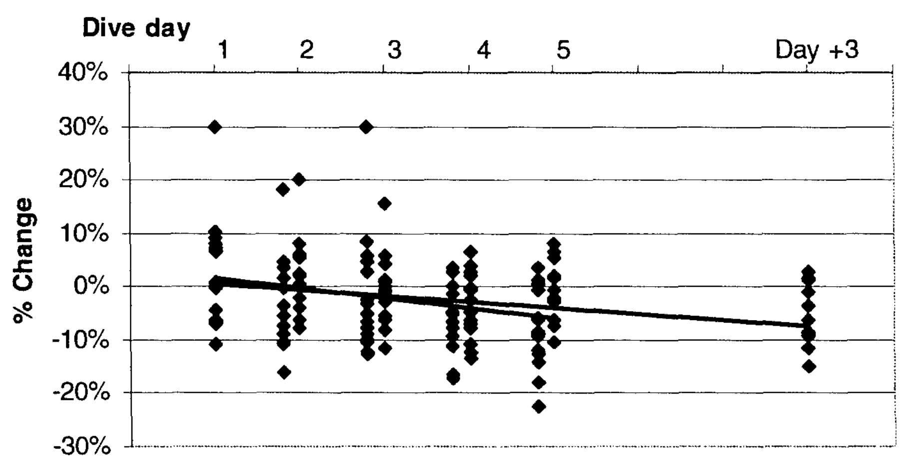

Figure 4. $FEF_{25–75}$ changes from baseline, exercise dives, 20-hour surface interval. Details of the trend lines, slopes –1.1% and –1.8% per day, are given in Table 6. Each point represents the mean of three measurements for a subject. Sixteen divers are represented.

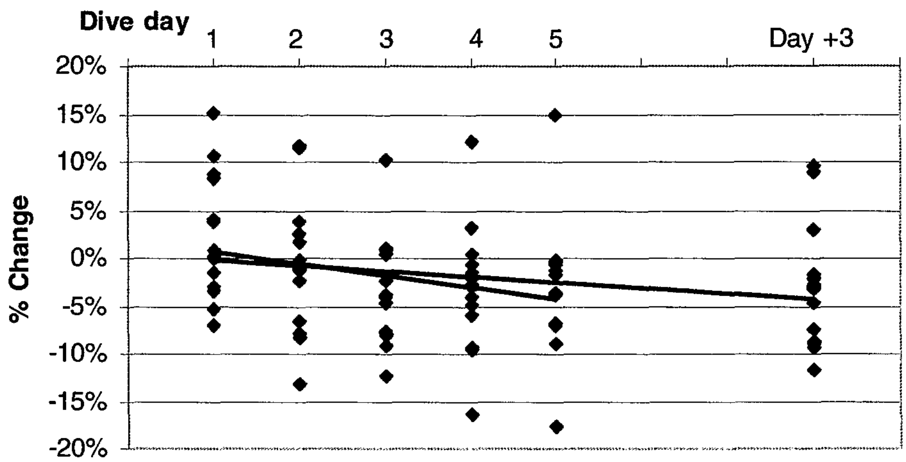

Figure 5. D_LCO changes from baseline, exercise dives, 20-hour surface interval. Details of the trend lines, slopes –0.6% and –1.2% per day, are given in Table 6. Each point represents the mean of three valid measurements (adjusted for hemoglobin concentration) for a subject. Sixteen divers are represented.

Table 6.
Coefficients of linear regressions, % changes from baseline vs. dive day, five daily exercise dives

Test	*s* (%)	r^2	Slope			Intercept		
			(% /day)	SE	Signif.	(%)	SE	Signif.
$FVC^†$	3.8	0.01	–0.2	0.2	ns	2.3	0.7	p<0.01
FVC*	3.8	10^{-5}	–0.1	0.3	ns	1.7	0.8	p<0.04
$FEV_1^†$	3.7	0.05	–0.4	0.2	p<0.01	1.9	0.8	p<0.01
FEV_1*	3.7	0.02	–0.4	0.2	p<0.08	1.8	0.8	p<0.03
FEV_1/ $FVC^†$	2.2	0.04	–0.2	0.1	p<0.02	–0.0	0.1	ns
FEV_1/ FVC*	2.2	0.06	–0.4	0.1	p<0.01	0.1	0.5	ns
$FEF_{max}^†$	6.7	0.002	–0.2	0.3	ns	1.4	1.2	ns
FEF_{max}^*	6.5	0.002	–0.2	0.4	ns	1.4	1.4	ns
$FEF_{25–75}^†$	7.8	0.07	–1.1	0.3	p<0.01	2	1	ns
$FEF_{25–75}$*	8.0	0.08	–1.8	0.5	p<0.01	3	2	p<0.05
$D_LCO^†$	6.4	0.04	–0.6	0.3	p<0.06	0	1	ns
D_LCO*	6.4	0.07	–1.2	0.5	p<0.03	2	2	ns

"ns" (not significant) indicates p>0.1; SE means standard error.
†Diving week and day +3; *Only the diving week without day +3 postdiving value.

The regression slopes represent the trends for the mean values; the scatter evident in the graphs is indicated by the regression coefficients r^2 and the standard deviations s (Table 6).

Two Dives with a 15-hour Interval

Incidences of symptoms and signs

Of the 28 divers who completed the experiment, five subjects (18%; binomial confidence interval 6–34% at $\alpha = 0.1$) reported mild respiratory symptoms at some time after their second dives (Table 7). This incidence does not differ statistically from those after two resting[3] or exercise dives with twenty hours between them (Table 5).

Five subjects (18%; binomial confidence interval 6–34% at $\alpha = 0.1$) showed changes in one or more flow-volume parameters on the first day after the second dive (Day +1) (Table 7), an incidence greater than after one dive ($p<0.02$) but not different from that of the evening and morning after two resting dives with twenty hours between them.[3] Although none of the 16 divers who completed at least two exercise dives with 20-hour intervals showed flow-volume changes (Table 5), the lower end of the confidence interval for the dives with 15-hour intervals corresponds to one of 17 subjects. All values were within normal limits of baseline by the fourth day after diving.

Two subjects (7%; binomial confidence interval 1–20% at $\alpha = 0.1$) showed depressed diffusing capacities after diving (Table 7), one on the first and one on the third day after the second dive. The incidence is no different from that after two resting dives with 20 hours between them[3] or after one exercise dive (Table 5). Again, although none of the 16 divers who completed two exercise dives with 20 hours between them showed diffusing capacity changes (Table 5), the lower end of the confidence interval is equivalent to one of 78 subjects; we do not have enough measurements to find a difference.

Progression of changes over time

Analyses of variances conducted on individual variables expressed relative to baseline indicate that a statistically significant effect of measurement day ($p<0.01$) was present for FVC, FEV_1, and FEF_{25-75} (Figures 6, 7, and 9) but not for FEF_{max} or D_LCO (Figures 8 and 10).

While FVC did not vary with day during diving, FVC relative to baseline on the first day after the dives (Day +1) was significantly less than the average difference from baseline during the dives (–1.3%, standard error [SE] 0.7% vs. average 2.0%, SE 0.3%; $p<0.01$). Similarly, FVC relative to baseline on the second day after the dives (Day +2) was less than the average during the dives (0%, SE 0.9%; $p<0.02$).

Table 7.
Respiratory symptoms and pulmonary function decreases after two exercise dives with 15 hours between them

Diver	After dive 1	Immediately after Dive 2	Day +1 or +2
1	c	-	-
2	d,t	d	-
3	c	-	c
4	t	-	-
5	-	-	c
6	c	-	c
7	c	-	-
8	-	i	-
9	c	-	-
10	-	-	FEF_{mid} – 17%
11	-	-	FVC –8.1%
12	-	-	FEV_1 –10.8% FEF_{mid} –24%
13	-	-	FEV_1 –8.5% FEF_{mid} –20%
14	-	-	FEV_1 –9.3% FEF_{mid} –22%
15	-	-	D_LCO –14%
16	-	D_LCO –15%	-
17–28	-	-	-

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 were mild.

FEV_1 on Day +1 was statistically below baseline and significantly less than the average FEV_1 during the dives (–2.2%, SE 0.8% vs. average 0.7%, SE 0.4%; $p<0.01$), but FEV_1 was elevated from baseline after the second dive (2.1%, SE 0.7%). FEV_1 on Day +2 (–0.6%, SE 0.9%) was not different from either the average during diving or the baseline.

FEF_{25-75} was significantly below baseline before the second dive (–7%, SE 1%) and again to a lesser degree on Day +1 (–4%, SE 2%). Because of the decrease before the second dive, the relative values on Day +1 and Day +2 did not differ from the average during diving. However, as shown in Table 7, no individual value dropped below the normal limits of variability before the second dive, while four values did on Day +1.

For the values with a significant effect of measurement day, mean values before the second exercise dive and after it with 15-hour intervals were compared to those measured before the second and before the third exercise dives with 20-hour intervals, respectively (Five Dives, 20-hour Interval, Figures 1–5). The morning after a first dive, FEF_{25-75} was lower with the 15-hour surface interval (SI) than with the 20-hour SI

(15-hr SI: –7%, SE 1%; 20-hr SI: –3%, SE 2%; $p_{1\text{-tailed}} < 0.04$). After two dives, FVC was lower with the 15–hour SI than with the 20–hour SI (15-hr SI: –1.3%, SE 0.7%, vs. 20-hr SI: 1.1%, SE 0.7%; $p_{1\text{-tailed}} < 0.03$), but FEV_1 and $FEF_{25\text{-}75}$ after two dives were not statistically different by SI.

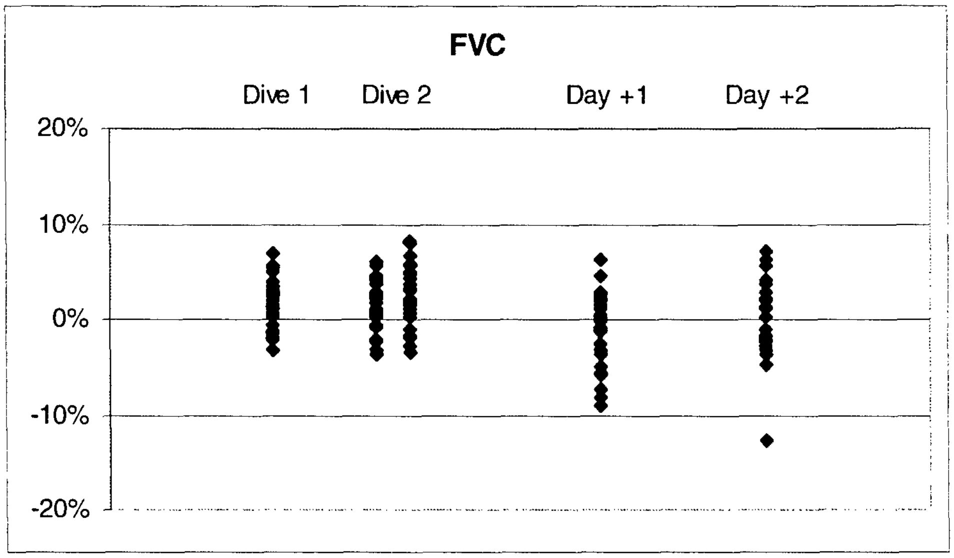

Figure 6. FVC changes from baseline, exercise dives, 15-hour surface interval. Each point represents the mean of three valid measurements for a subject. All 28 divers are represented.

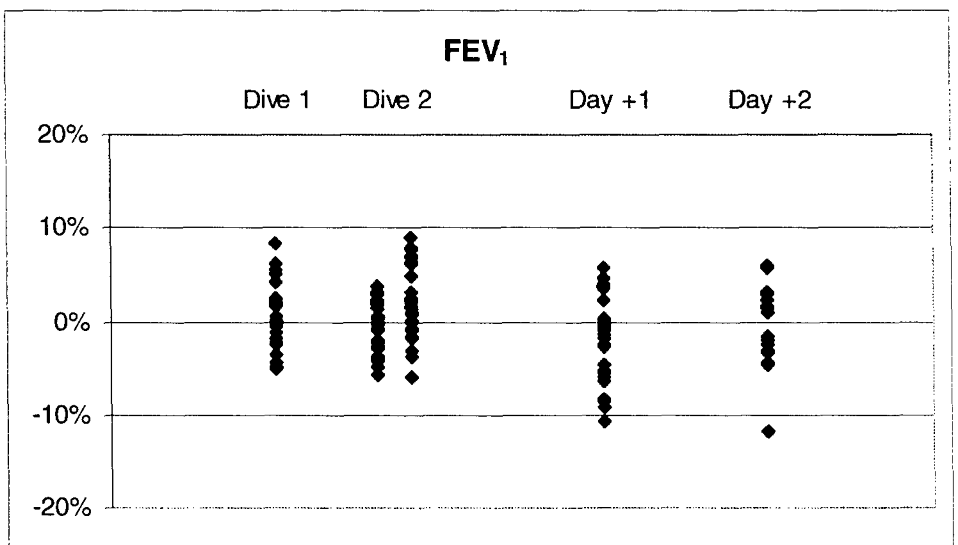

Figure 7. FEV_1 changes from baseline, exercise dives, 15-hour surface interval. Each point represents the mean of three valid measurements for a subject. All 28 divers are represented.

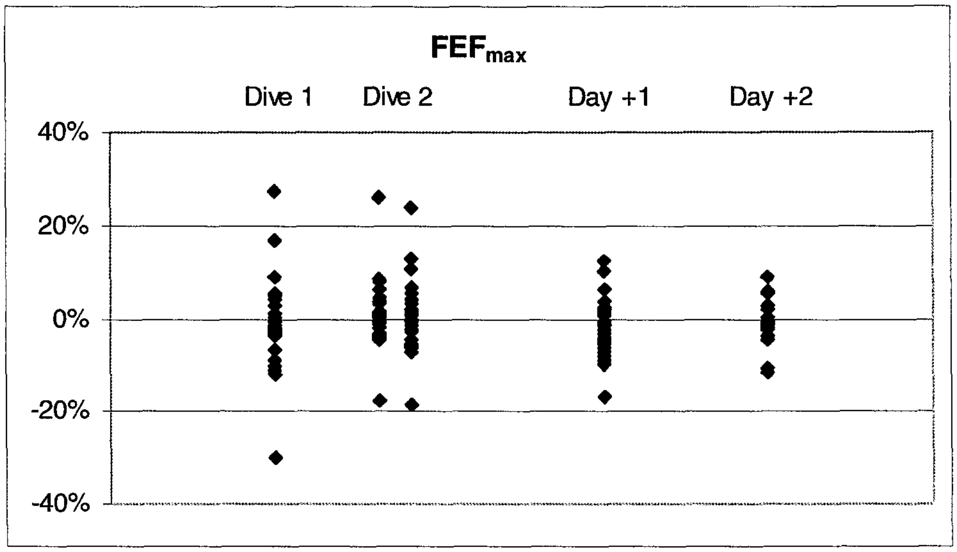

Figure 8. FEF_{max} changes from baseline, exercise dives, 15-hour surface interval. Each point represents the mean of three valid measurements for a subject. All 28 divers are represented.

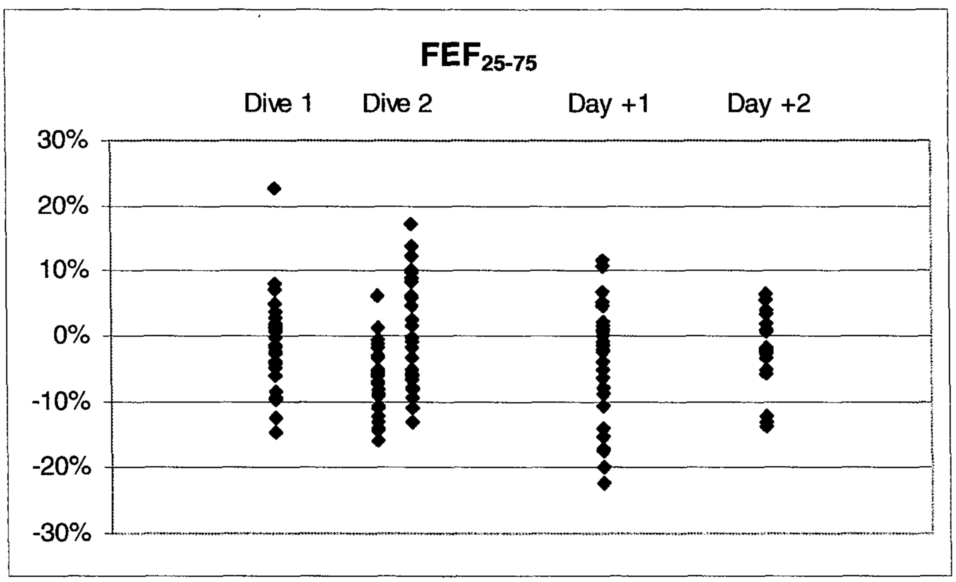

Figure 9. FEF_{25-75} changes from baseline, exercise dives, 15-hour surface interval. Each point represents the mean of three valid measurements for a subject. All 28 divers are represented.

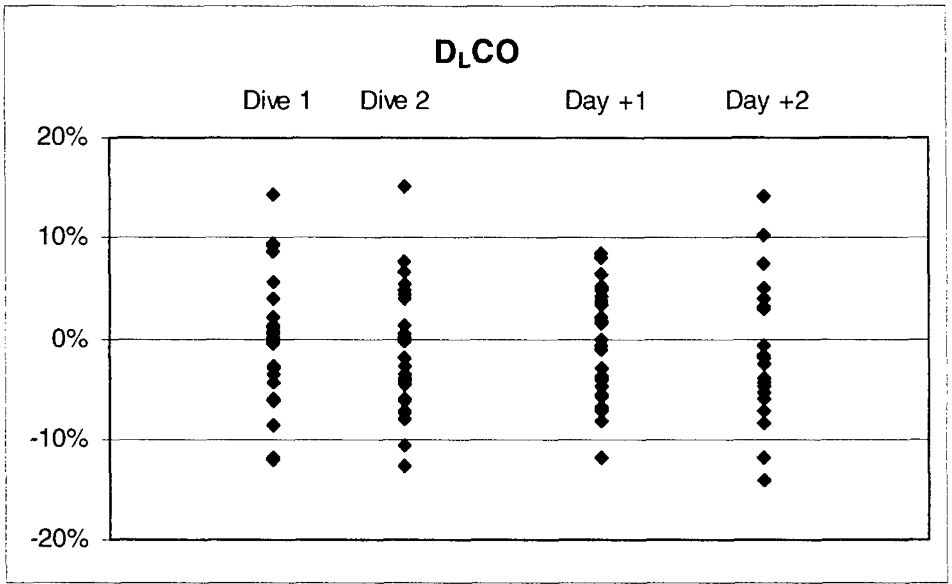

Figure 10. D_LCO changes from baseline, exercise dives, 15-hour surface interval, corrected for hemoglobin concentration. Each point represents the mean of three valid measurements for a subject. All 28 divers are represented.

OTHER SYMPTOMS AND SIGNS

No divers in any of these dive series had significant changes in visual refraction. One diver in the five-day study complained of blurry vision beginning after his third dive and continuing for more than a week, a complaint spanning an unremarkable optometry examination.

After single exercise dives, five of 40 subjects had postdive dehydration sufficient to increase hemoglobin concentration by 10% or more. One of these was the diver with decreased D_LCO immediately after diving; D_LCO not adjusted for hemoglobin concentration decreased 14% rather than 17%. None of the 16 subjects in the five-day dive series, nor the 28 subjects in the two-day, 15-hour surface interval series, had an increase in hemoglobin concentration of 10% or more after any dive.

After the single dives with exercise, 20 of 40 subjects complained of ear discomfort. During the series of five dives, 14 of 16 subjects reported ear discomfort at some time. During the two-day series, 18 of 28 subjects mentioned ear pain or discomfort.

Fatigue was probably underreported. Four of 40 subjects completing a single exercise dive reported unreasonable fatigue lasting for one to three days, but only two during and after the five-day series complained of fatigue or exercise intolerance. Five of 28 subjects had unreasonable fatigue after one or both dives with 15 hours between them.

From the series of single dives one diver reported tingling of his head at the end of the dive, and one reported twitching of one bicep after his second exercise period in the water. From the series of five dives, one diver reported headache during a dive, and one diver had headaches for several days after diving. Two divers in the five-day series noted that they felt irritable, one before his fourth dive and one during his fifth. From the dive series with 15-hour intervals, one subject reported disturbed sleep and bizarre dreams after his second dive, one considered himself to be irritable after the first dive, and one felt irritable during the second half of each dive.

DISCUSSION

Single Dives

Incidences of symptoms and signs

Incidences of respiratory symptoms and signs after single four-hour exercise dives with 1.3 atm Po_2 were not found to differ from those after single resting dives with similar Po_2 and duration. However, the power to find a difference from 17% (symptoms at rest) was greater than 80% only for incidences of 36% or more, and the power to find a difference from 6% (flow volume changes at rest) was greater than 80% only for incidences of more than 20%.[10] Though we cannot be confident that there is no difference, we can be confident that there is no large difference between pulmonary toxicity provoked by single exercise dives and single resting dives.

Five Dives, 20-hour Interval

Incidences and severities of symptoms and signs

Incidences of symptoms were greater with more than one exercise dive than they were with only one dive, and one diver had dive-stopping symptoms during his third dive. Although the incidence of severe symptoms during the third dive was just 6.7% (binomial confidence interval 0.3–28% at $\alpha = 0.1$), the facts that the diver had to leave the water and that he experienced significant symptoms for more than 24 hours makes this an important observation — even if this incidence represented, in fact, the low end of the confidence interval, or 1 of 333 dives.

Progression of changes over time

Unlike resting dives, where each dive preceded by 20 hours or more without diving seems to be independent,[3] dives that include exercise accumulate pulmonary function changes. Because of intersubject variability and large limits of normal variation, few divers had measurable changes after five daily dives. However, by assuming that the changes from baseline of the pulmonary function values are normally distributed, we can extrapolate to the dive number at which 25% of divers will have values below the lower limits of normal.

The lowest 25% of a normal distribution corresponds to $z = -0.67$, where z is the transformed normal variable

$$z = (\text{normal variable} - \mu)/\sigma,$$

with μ = mean value, and σ = standard deviation.

Thus, 25% of the distribution is at or below the value

$$(\mu - 0.67 \cdot \sigma).$$

The extrapolated mean value is given by the regression line

$$y = m \cdot (\text{dive number}) + b,$$

with m = slope and b = intercept, so that the dive number at which 25% of subjects will be at or below the lower limit of normal (LLN), $Dive_{25\%}$, is given by

$$Dive_{25\%} = (LLN + 0.67 \cdot \sigma - b)/m.$$

The results of this calculation are given in Table 8. For convenience, the values used have been transcribed from Table 6, where s is the estimate of σ.

Table 8.
Projected number of dives for 25% of divers to reach LLN

Test	**$Dive_{25\%}$**	**LLN**	***m* (%/day)**	***b* (%)**	***s* (%)**
FVC	>50	−7.7%	−0.01	1.7	3.8
FEV_1	18	−8.4%	−0.4	1.8	3.7
FEF_{max}	>50	−16.8%	−0.2	1.4	6.7
FEF_{25-75}	8	−17.0%	−1.8	3	8.0
D_LCO	10	−14.2%	−1.2	2	6.4

The regression coefficients are those during diving only.

We can estimate that slope for the days after diving from the difference between the regression value for Dive 5 and the average value for Day +3.

Estimated in this way, the changes during the days after diving, m_r, become

FEV_1, $m_r = -0.6$%/day; FEF_{25-75}, $m_r = 0.2$%/day; and D_LCO, $m_r = 0.6$%/day.

Although FEF_{25-75} and D_LCO apparently begin to recover immediately, FEV_1 declines faster immediately after exposure than it does during the exposure.

If we assume that the slope in the days after diving is independent of the number of days of diving that precedes it, we can estimate the effects of rest days on pulmonary function values. In Table 9, the number of days for 25% of the group to be below LLN is presented for two potential schedules for comparison with the values transcribed from Table 8 in the column labeled "Continuous."

The numbers were obtained as in this example for FEV_1 with 2 days on and 1 day off:

Mean FEV_1 after two dives $= m \cdot (2 \text{ dives}) + b$ (Values in Tables 6 or 8)
$= -0.4\%/\text{day} \cdot (2 \text{ dives}) + 1.8\% = 1.0\%$
Mean $- (0.67 \cdot \sigma) = 1.0\% - (0.67 \cdot 3.7\%)$
$= -1.5\%$ [25% of divers after 2 dives]

Mean FEV_1 after one day off $= m_r \cdot (\# \text{ days}) + \text{starting value}$
$= -0.6\%/\text{day} \cdot (1 \text{ day}) + 1.0\% = 0.4\%$

Mean FEV_1 after next two dives $= m \cdot (2 \text{ dives}) + \text{starting value}$
$= -0.4\%/\text{day} \cdot (2 \text{ dives}) + 0.4\% = -0.4\%$
Mean $- (0.67 \cdot \sigma) = -2.9\%$ [25% of divers after 4 dives]

Mean FEV_1 after one day off $= m_r \cdot (\# \text{ days}) + \text{starting value}$
$= -0.6\%/\text{day} \cdot (1 \text{ day}) - 0.4\% = -1.0\%$

Mean FEV_1 after next two dives $= m \cdot (2 \text{ dives}) + \text{starting value}$
$= -0.4\%/\text{day} \cdot (2 \text{ dives}) - 1.0\% = -1.8\%$
Mean $- (0.67 \cdot \sigma) = -4.3\%$ [25% of divers after 6 dives]

...

Mean FEV_1 after 10 dives $= -6.0\%$
Mean $- (0.67 \cdot \sigma) = -8.5\%$ [25% of divers after 10 dives]
where LLN for $FEV_1 = -8.4\%$

Table 9.
Projected number of dives for 25% of divers to reach LLN with differing numbers of rest days

Test	**$Dive_{25\%}$**		
	Continuous	2 days on, 1 off	2 days on, 2 off
FEV_1	18	10	9
FEF_{25-75}	8	9	9
D_LCO	10	12	17

From these numbers, we estimate that taking a day off after every two dives gains us numbers of possible dives for D_LCO and FEF_{25-75} but loses us days for FEV_1. Table 9 indicates that no more than 8 dives in 8 days or 9 dives in 12 to 17 days can be conducted without expecting 25% of divers to have a measurable decrease in pulmonary function. We must emphasize, however, that these values are obtained by extrapolation from five days of diving followed by two days of rest.

Two Dives with 15-hour Intervals

A 15-hour surface interval corresponds to a dive one afternoon followed by a dive the following morning.

Incidences of symptoms and signs

Overall with two exercise dives at 1.3 atm Po_2, the number of divers reporting symptoms or having a measured pulmonary function variable below the LLN does not differ for 15- or 20-hour surface intervals. The numbers after exercise dives of this type also do not differ from those after resting dives under the same conditions.

Progression of changes over time

Mild progression of injury is apparent after a 15-hour SI, with a decrease in FVC, FEV_1, and to a lesser extent FEF_{25-75} the day after a second dive. D_LCO is not affected by the shorter SI. Furthermore, the average change in FEV_1 the day following the two shorter SI dives is equivalent to that expected after 5.5 days of diving with the longer SI.

CONCLUSIONS

Pulmonary effects accumulate during underwater exercise with1.3 atm Po_2 when the dives are four hours in duration. Because similar measurements have not been made with air as the breathing gas, we cannot partition the effects of exercise and those of oxygen breathing; though many air-breathing exercise dives are done each year, accumulation of pulmonary function changes without impairment would pass unnoticed.

Although two consecutive days of diving while exercising do not cause noticeable increases in symptoms or pulmonary function changes relative to single resting dives even when the SI is decreased from 20 to 15 hours, subtle changes are occurring. Because of symptoms experienced during a third dive by one diver in this series, we recommend at least a one-day break after two consecutive exercise dives. Because of accumulation in pulmonary function changes, we recommend an even longer break after nine exercise dives with 20-hour SIs.

REFERENCES

1. Commander, Naval Sea Systems Command, *U.S. Navy Diving Manual, Revision 5* (Arlington, VA: NAVSEA, 2005), p. 19-16.

2. B. E. Shykoff, *Repeated Four-hour Dives with Po_2 = 1.35 Atm*, NEDU TR 04-29, Navy Experimental Diving Unit, July 2004.

3. B. E. Shykoff, *Two Consecutive Five-Day Weeks of Daily Four-Hour Dives with Oxygen Partial Pressure 1.4 Atm*, NEDU TR 05-21, Navy Experimental Diving Unit, Nov 2005.

4. U.S. Naval Sea Systems Command, *Task Assignment 06-15: Pulmonary Oxygen Toxicity While Swimming: How Exercising Underwater or Using a Rebreather Underwater Breathing Apparatus Affects Pulmonary Function After 1.35 Atm Oxygen Exposures*, 25 Aug 2006, Ser 00C/3094.

5. B. E. Shykoff, *Pulmonary Effects of Submerged Breathing of Air or Oxygen*, NEDU TR 02-14, Navy Experimental Diving Unit, Nov 2002.

6. B. E. Shykoff, *Repeated Six-Hour Dives with 1.35 Atm Oxygen Partial Pressure*, NEDU TR 05-20, Navy Experimental Diving Unit, Oct 2005.

7. American Thoracic Society, "Standardization of Spirometry 1994 Update," *American Journal of Respiratory and Critical Care Medicine*, Vol. 152 (1995), pp. 1107–1136.

8. *Instruction Manual for the Collins Comprehensive Pulmonary Laboratory (CPL)* (Braintree, MA: Collins Medical, 2000), pp. 149; 49.

9. B. E. Shykoff, *Measurement of Diffusing Capacity for Carbon Monoxide (D_LCO)*, NEDU TR 02-04, Navy Experimental Diving Unit, May 2002.

10. J. Cohen, "Differences between Proportions," Chapter 6 in his *Statistical Power Analysis for the Behavioral Sciences*, 2nd edition (Hillsdale, NJ: Erlbaum, 1988).

PAGE INTENTIONALLY LEFT BLANK