Pulmonary effects of submerged oxygen breathing in resting divers: repeated exposures to 140 kPa.

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Shykoff BE. Pulmonary effects of submerged oxygen breathing in resting divers: repeated exposures to 140 kPa. Undersea Hyperb Med 2008; 35(2):131-143.To detect cumulative effects of and check required recovery times between underwater exposures to 130–140 kPa oxygen, we assessed pulmonary oxygen toxicity after resting dives for four and six hours on two, five, and six or ten days, and three hours twice on each of two days. Despite a slight downward trend in diffusing capacity, four-hour resting dives could be repeated for at least ten days if intervals between them were 20 hours: 17% of divers had mild symptoms; 5%, mild changes in flow-volume parameters. In contrast, six-hour resting dives caused symptoms in 33% of divers. When dives were repeated daily (after 18 hours), but not with one day off (after 42 hours), changes in diffusing capacity accumulated, and hyperoxic myopia occurred after five dives. Divers complained of fatigue more with daily than with alternate day dives. When daily exposure was split into two three-hour dives, the incidences of symptoms and changes in pulmonary function depended on the surface intervals: on the second day, with two and 16 hours between dives, two three-hour dives were similar to a six-hour dive; with four and 14 hours, to a four-hour dive; with six and 12 hours, to a six-hour dive.

INTRODUCTION

Divers who use mixed-gas rebreather underwater breathing apparatus (UBA), divers using the mixed-gas nitrogen-oxygen (nitrox) diving tables (1), and divers who use well-purged 100% oxygen rebreather UBAs at depths of 3.7 to 4 meters (12 to 13 feet) all are exposed to oxygen partial pressures (PO_2) between 130 and 140 kPa (1.3 and 1.4 atm). Although the risk of central nervous system toxicity is very low at that PO_2, long or repeated dives may cause pulmonary oxygen toxicity. We conducted a series of experiments at Navy Experimental Diving Unit (NEDU) to define "long" in this context and to check for possible cumulative effects. The divers in these series rested underwater; the results should be of direct interest to divers who breathe this PO_2 at depth while using motorized propulsion and for divers during decompression. The effects of exercise will be considered separately.

We previously concluded that eight hours underwater was too long for exposure to PO_2 of 140 kPa: significantly more divers experienced respiratory symptoms than after either eight hours underwater with PO_2 of 30 kPa (breathing air) or six hours with PO_2 of 140 kPa (2). We also found that effects did not differ between single four-hour underwater resting exposures to PO_2 of 140 kPa or PO_2 of 30 kPa (2). We recognized, though, that effects undetectable after one dive might accumulate over several days.

To test for cumulative effects with divers at rest, we conducted separate dive series: we tested two four-hour dives with surface intervals of either 44 hours or 20 hours, five four-hour dives with surface intervals of 20 hours, and two working weeks of five four-hour dives with surface intervals of 20 hours. We also tested two six-hour dives with an 18-hour surface interval, five six-hour dives with 18-hour surface intervals, and six six-hour dives with 42-hour surface intervals. We further tested six-hour daily exposures with the exposures split into two three-hour dives.

The primary goals of these studies were to assess cumulative pulmonary effects of multiple four- or six-hour dives with PO_2 of 140 kPa and to begin to determine recovery requirements between dives. Secondary goals were to assess nonrespiratory symptoms, which included hyperoxic myopia.

METHODS

All protocols were approved by the NEDU Institutional Review Board, and subjects gave written informed consent. For at least four days before the studies, subjects had not dived, and, except for the experimental dives, they did not dive again until their final pulmonary function measurements were complete, three to four days after their last experimental dives. Dive and subject characteristics are listed by dive series in Tables 1-3.

Table 1. Dive and Subject Characteristics, 4-hour Resting Dives

# dives per person	SI *hours*	# divers End (Start)	Age Median (Range) *years*	Height Median (Range) *cm*	Weight Median (Range) *kg*	# smokers Current (Former)
2	44	18	39 (31–47)	183 (168–188)	88 (70–110)	0 (3)
2	20	17	35 (26–45)	175 (173–188)	86 (70–100)	1 (0)
5	20	15 (16)	41 (31–48)	180 (168–183)	89 (68–102)	0 (7)
5 + 5	20	9 (16)	36 (28–49)	177 (168–188)	86 (68–120)	2 (5)

SI is surface interval

Table 2. Dive and Subject Characteristics, 6-hour Resting Dives

# dives per person	SI *hours*	# divers End (Start)	Age Median (Range) *years*	Height Median (Range) *cm*	Weight Median (Range) *kg*	# smokers Current (Former)
2	18	13	39 (28–48)	175 (168–188)	85 (72–100)	0 (6)
5	18	16 (17)	36 (30–43)	175 (173–188)	86 (72–105)	0 (7)
6	42	14	36 (30–43)	175 (173–188)	86 (72–105)	0 (7)

SI is surface interval

Table 3. Dive and Subject Characteristics, Split 6-hour Resting Exposure with Short Surface Intervals, Four Dives per Subject.

SIs day/night *hours*	# divers	Age Median (Range) *years*	Height Median (Range) *cm*	Weight Median (Range) *kg*	# smokers Current (Former)
2/16	12	42 (27–46)	175 (170–188)	89 (69–98)	0 (7)
4/14	24	35 (24–46)	175 (170–190)	89 (69–107)	0 (11)
6/12	12	38 (33–42)	180 (173–185)	88 (69–119)	1 (6)

SI is surface interval

Dives were conducted in the NEDU test pool in 4.6 m (15 ft) of fresh water. Water temperature was 32 ºC ± 3 ºC (90 ºF ± 5 ºF). Subjects relaxed in lounge chairs on the bottom of the test pool or on the bottom itself, where they watched movies.

Divers breathed surface-supplied, humidified oxygen open circuit from full face masks fitted with one-way valves and demand regulators (AGA Divator mask, Interspiro; Cliffwood Beach, NJ). The demand regulators were submerged under 3.4 to 4.0 m (11 to 13 ft) of fresh water, depending on diver activity and posture, providing PO_2s between 130 and 140 kPa. The pressure at the very bottom of the test pool was 146 kPa. Divers were permitted to surface, breathe room air, and eat or drink for no more than five minutes per hour.

Pulmonary function was assessed from flow-volume curves and single-breath diffusing capacity maneuvers. Normal variation was defined as a decrease from baseline not more than the 95% confidence interval (CI) that we had defined — namely, 7.7% in forced vital capacity (FVC), 8.4% in forced expired volume in one second (FEV_1), 16.8% in maximum forced expired flow (FEF_{max}), 17% in forced expired flow between 25% and 75% of volume expired ($FEF_{25–75}$), and 14.2% in diffusing capacity of the lung for carbon monoxide (D_LCO) (2).

Measurements were made within the week before the dives (baseline), after diving was finished for the day, and for several days following the last dive. Pulmonary function was scheduled to be measured for one to three days following the last dive, but it was measured on additional days if the last scheduled measurement was less than the lower limit of normal variation. On days with two dives, flow-volume measurements also were made during the short surface interval and, for all dive series, before each dive. If a subject showed a value decreased from baseline by more than twice the defined lower limit of normal, he was not permitted to enter the water.

For all tests, each pulmonary function measurement session resulted in three repetitions that met the American Thoracic Society standards (3). Averages of those values were compared to the baseline averages where the "baseline" for flow-volume parameters included the first predive values. We used the Collins CPL and Collins GS Modular Pulmonary Function Testing System instruments (Ferraris Medical; Louisville, CO). The specific values studied included FVC, FEV_1, FEF_{max}, $FEF_{25–75}$, and D_LCO. The test gas for D_LCO single-breath measurement contained 0.3% carbon monoxide and 0.3% methane, and the results were adjusted for hemoglobin and carboxyhemoglobin concentrations (4) determined (CO-Oximeter, Instrumentation Laboratory; Lexington, MA) from a venous blood sample taken just before testing. The sample time and volume for single-breath diffusing capacity maneuvers were adjusted to avoid analyzer transients (5). Subjects were asked about symptoms once per hour while they were underwater and at each session for measuring pulmonary function.

The first dive series conducted was that with two four-hour dives, followed by two six-hour dives and five six-hour dives. Following the incidence of myopia in those dives (see "**RESULTS**,**Vision, Fatigue** <u>Six-hour Resting Dives, 18-hour Surface Interval</u>, *Vision*," below), we introduced measurements of visual refraction and included a termination criterion based on refraction change in the subsequent series. Before and after the series of five or ten daily four-hour dives and the series of six six-hour dives every other day, divers received complete eye examinations, including cycloplegic refraction and fundoscopy, at the Tyndall Air Force Base Optometry Clinic. For all series, we measured visual refraction with an automatic refractometer (Model 530, Allergan Humphrey; San Leandro, CA) before and after each dive, after the dive series when we measured pulmonary function, and again one week after the last dive. Divers with a decrease of at least 0.5 diopters (D) from baseline refraction before a scheduled dive were excluded from further diving. As we became more familiar with variability in refraction measurements, we relaxed the termination criterion to –0.75 D or more for the split exposures dives.

RESULTS

Respiratory system

<u>Four-hour Resting Dives</u>

44- or 20-hour Surface Intervals (SIs)

Overall, single four-hour resting dives at PO_2 of 140 kPa were completed 75 times, and pairs of dives with 20 hours between them were completed 49 times. Five four-hour dives with 20 hours between them were completed by 28 divers, and two weeks of five four-hour dives were completed by nine divers. Several divers began but did not complete the five-day or double five-day dive series (Table 1): in the series of five dives, one subject showed an asymptomatic depression of flow-volume parameters before he was to begin his fifth dive. In the series of two weeks with five dives each week, no withdrawal was related to pulmonary oxygen toxicity. One subject contracted a viral illness during the week. Three subjects withdrew because of corneal irritation: one after a sports accident, one from warped contact lenses, and one from a torn contact lens. Three subjects demonstrated temporary refraction changes of –0.5 D in the morning before diving but had no changes later.

The incidence of symptoms after the second dive was less than or equal to the incidence after the first dive, whether the surface interval was 44 or 20 hours (Table 4). The incidences of changes in flow-volume parameters and in D_LCO were not different with the different surface intervals (Table 4).

Table 4. Incidence of Symptoms and Signs after Two Four-hour Dives.

	44-hour SI (n = 18; 1 person = 5.6%)		**20-hour SI** (n = 17; 1 person = 5.9%)	
	Dive 1	Dive 2	Dive 1	Dive 2
Symptoms	28%	28%	53%	41%
Flow-Volume	6%	22%	6%	29%
D_LCO	0	11%	0	12%

Multiple Four-hour Dives with 20-hour Surface Interval

Results were pooled for all four-hour resting dives with 20-hour surface intervals. The first dives from the 44-hour surface interval series are included, and the incidences after a single dive include those reported previously (2). Changes in parameters from baseline are presented as functions of day from the start of diving in Figure 1. Each point represents the differences from baseline of the averages of three measurements for an individual subject. Predive (morning) measurements are shown as half days from the start, and postdive (afternoon) measurements as whole days in Fig. 1a. Numbers of data decrease as numbers of dives increase. Measurements after the last dive were completed have been grouped as recovery ("R") data; "R1" represents Day 15 after the ten dive series, Day 8 after the five dive series, and Day 3 after the two dive series.

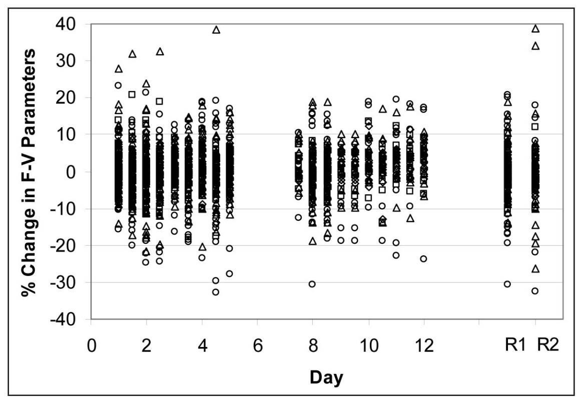

Fig. 1a. Changes in FVC (◊), FEV_1 (□), FEF_{max} (Δ), and $FEF_{25–75}$ (○) with increasing number of four-hour resting dives (20-hour surface interval). Each point represents the value for a diver. "R" means recovery. Regression slopes are not different from zero.

The changes in flow-volume parameters are independent of the numbers of dives (Figure 1a). However, D_LCO, despite the wide scatter, shows a statistically significant downward slope with an increasing number of dives (Figure 1b); the first-order linear regression line is superimposed on the graph.

Symptoms and pulmonary function deficits present in the morning before a dive often resolved while the diver was underwater breathing oxygen. The largest measurable changes and most noticeable symptoms were not necessarily associated with large numbers of dives; scatter in changes in pulmonary function was large on all days (Figures 1a and 1b), and moderate symptoms were reported by one subject after only one dive and by another after seven to ten dives.

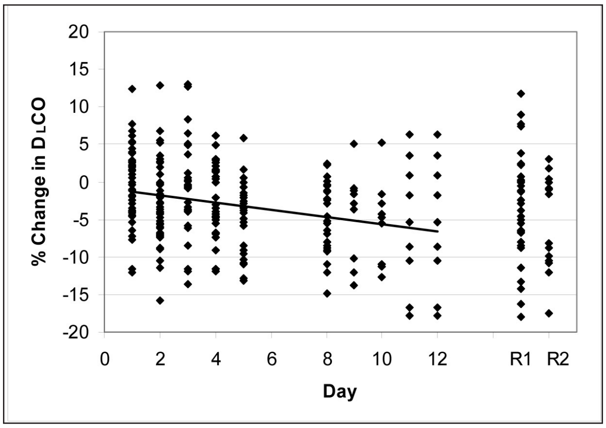

Fig. 1b. Changes in D_LCO with increasing number of four-hour resting dives (20-hour surface interval). Each point represents the value for a diver. "R" means recovery. Regression slope, –0.5%/day, is significant (p<0.01).

Table 5 lists incidences of symptoms and measurable pulmonary function deficits after increasing numbers of dives. After two dives, the incidence of deficits in flow-volume parameters is higher by Fisher's Exact Test than after one dive, but the binomial 95% CI on the incidences overlaps. Similarly, the incidence of changes in D_LCO is greater after nine dives than after two, but the binomial 95% CI overlaps. Thus, these differences must be considered inconclusive.

<u>Six-hour Resting Dives, 18-hour Surface Interval</u>

Overall, single six-hour resting dives at PO_2 of 140 kPa were completed 52 times, and pairs of dives with 18 hours between them were completed 29 times, while five six-hour dives with 18 hours between them were completed by 16 divers. Mild to moderate respiratory symptoms or changes in pulmonary function occurred throughout the time periods (Table 6).

Table 5. Incidences of Respiratory Symptoms and Changes in Pulmonary Function as a Function of the Number of Four-hour Dives with 20 Hours between Them.

# dives, n_d	# divers to complete at least n_d dives	Incidence, Symptoms	Incidence, flow-volume changes	Incidence, D_LCO change
1	77	16.9% (9–27%)	5.2% (1–13%)	0
2	51	13.7% (6–26%)	17.6% (8–31%)	3.9% (0.5–13%)
3	30	20.0% (8–38%)	3.3% (0.1–17%)	0
4	29	20.7% (8–40%)	13.8% (4–32%)	0
5	28	17.9% (6–37%)	3.6% (0.1–18%)	0
(Weekend – no diving)				
6	10	10.0% (0.2–45%)	0	10.0% (0.2–45%)
7	10	10.0% (0.2–45%)	0	0
8	10	10.0% (0.2–45%)	10.0% (0.2–45%)	0
9	9	11.1% (0.3–48%)	0	33.3% (7–70%)
10	9	22.2% (3–60%)	0	22.2% (3–60%)

Values in parentheses are binomial 95% CI.

Table 6. Incidences of Respiratory Symptoms and Changes in Pulmonary Function as a Function of the Number of Six-hour Dives with 18 Hours between Them.

# dives n_d	# divers to finish at least n_d dives	Incidence, symptoms		Incidence, flow-volume changes	Incidence, D_LCO changes
		mild	moderate		
1	52	33% (20%–46%)	4% (0.5%–13%)	6% (1–16%)	0
2	29	34% (18%–54%)	10% (2%–27%)	3% (0.1–18%)	0
3	16	44%	0	25%	0
4	16	50%	0	6%	6%
5	16	31%	6%	6%	13%

Values in parentheses are binomial 95% CI, listed only for n>20.

As was the case after the four-hour dives, subjects who had symptoms commonly did not show changes in pulmonary function, and those with measurable changes were often without symptoms. Symptoms or signs sometimes resolved before the next dive, sometimes persisted until the next dive and, then sometimes resolved during the next dive.

Changes in parameters from baseline after six-hour resting dives are presented as functions of day from the start of diving in Figures 2a, b, where predive flow-volume measurements are 0.8 days from the previous dive and postdive measurements one day after. Measurements after the last dives were completed have been grouped as recovery ("R") data; "R1" represents Day 8 after the five dive series and Day 3 after the two dive series.

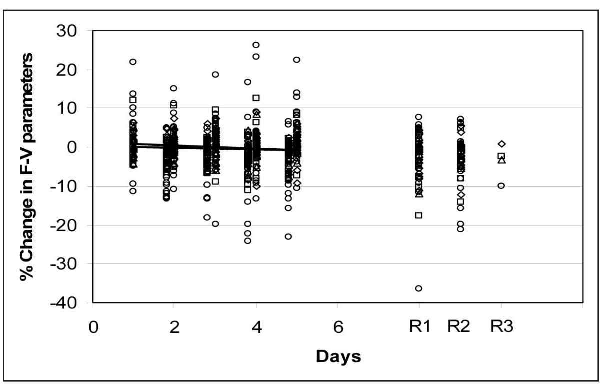

Fig. 2a. Changes in FVC (◊), FEV_1 (□), FEF_{max} (Δ), and $FEF_{25–75}$ (○) with increasing number of six-hour resting dives (18-hour surface interval) and during recovery. Predive measurements are shown 0.8 days from the previous postdive measurement. Each point represents the value for a diver. "R" means recovery. Regression line for FVC has slope –0.4%/day, (p<0.08).

The scatter in the magnitude and in the direction of changes in pulmonary function are large. Decreases were found in D_LCO (–1.7%/day, standard error SE 0.5%/day, p<0.01) during the dive week. The changes in FVC (–0.4%/day, SE 0.2%/day, p<0.08), FEV_1 (–0.2%/day, SE 0.3%/day), FEF_{max} (0.3%/day, SE 0.3%/day) and $FEF_{25–75}$ (–0.4%/day, SE 0.3%/day) were not significant with successive dives.

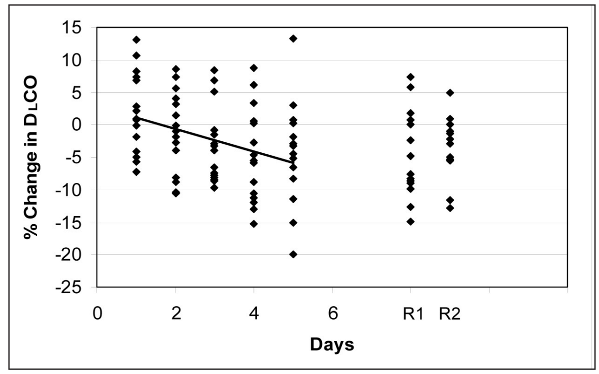

Fig. 2b. Changes in D_LCO with increasing number of six-hour resting dives (18-hour surface interval). Each point represents the value for a diver. "R" means recovery. Regression slope (–1.7%/day) is significant (p<0.01).

Six-hour Resting Dives, 42-hour Surface Interval

Once again, mild to moderate symptoms and mild changes in pulmonary function were seen after any number of dives, and scatter in changes was large (Table 7, Figures 3a and 3b). With the 42-hour break between dives, daily measurement of pulmonary function, and predive measurement of flow-volume parameters, no downward trends were seen in any flow-volume parameter or in diffusing capacity.

Table 7. Incidences of Respiratory Symptoms and Changes in Pulmonary Function as a Function of the Number of Six-hour Dives with 42 Hours between Them.

n_d	# divers to finish ≥ n_d dives	Incidences: symptoms, mild	Incidences: symptoms, moderate	Flow-volume changes	D_LCO changes
1	52	33% (20%–46%)	4% (0.5%–13%)	6% (1–16%)	0
2	14	14%	0	36%	7%
3	14	29%	0	21%	7%
4	14	50%	14%	36%	0
5	14	28%	7%	15%	0
6	14	28%	0%	15%	7%

Values in parentheses are binomial 95% CI.

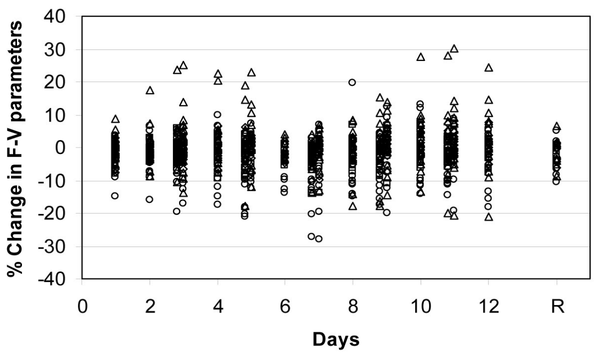

Fig. 3a. Changes in FVC (◊), FEV_1 (□), FEF_{max} (Δ), and $FEF_{25–75}$ (○) with six-hour resting dives every other day (42-hour surface interval), tests postdive, predive and between dives. ”R” means recovery, Day 13. Predive measurements are shown 0.8 days from the measurement on the previous nondiving day. Each point represents the value for a diver. Regression slopes do not differ from zero.

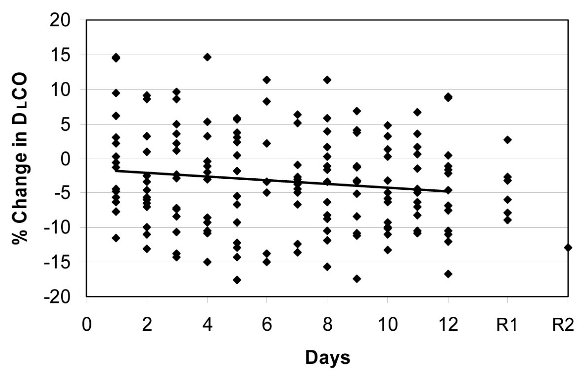

Fig. 3b. Changes in D_LCO with increasing number of six-hour resting dives every other day (42-hour surface interval), tests daily. Each point represents the value for a diver. ”R” means recovery, “R1” =Day 13. Regression slope is not significant (–0.3%/day, p>0.07).

Split 6-hour Dives Daily, Short Surface Intervals

Mild to moderate symptoms were reported, and mild changes in pulmonary function were seen after any number of three-hour dives. One subject reported moderately severe symptoms a day after the series of dives with two-hour surface intervals each day, and one subject did so immediately following the fourth dive in the four-hour surface interval series. The incidences of decreased pulmonary function and reported symptoms are given in Table 8.

Table 8. Incidence of Symptoms and Flow-volume Changes after Short Surface Interval (SI) Dive Days.

SIs day/night *hours*	n	Day 1 (2nd dive) incidences		Day 2 (2nd dive) incidences	
		Symptoms	Flow-Volume changes	Symptoms	Flow-Volume changes
2/16	12	42%* (8%>mild)	17%*#	50%** (8%>mild)	8%
4/14	24	17% (4%>mild)	4%	13% (4%>mild)	17%
6/12	12	25%	25%*#	42%**	17%

For Day 1, *indicates a value greater than the upper 95% CI for a single 4-hour dive # indicates a value greater than the upper 95% CI for a single 6-hour dive.
For Day 2, ** indicates a value greater than the upper 95% CI for two 4-hour dives with 20 hours.

With a two-hour surface interval and sixteen hours overnight, the incidence of symptoms was significantly greater after the second day of diving than it was after two four-hour dives (Fisher’s Exact p = 0.003). With a four-hour surface interval and fourteen hours overnight, significantly fewer divers reported symptoms than did those after diving for six hours with eighteen hours overnight; the incidences of symptoms did not differ from those for two four-hour dives. With a six-hour surface interval and twelve hours overnight, the incidence of respiratory symptoms on the first day did not differ from that after a single four-hour dive (Fisher’s Exact p = 0.45) but it was significantly greater on the second day (Fisher’s Exact p = 0.04), when it did not differ from that for two six-hour dives.

No downward trend was evident in flow-volume parameters for any of the short surface interval series (Figure 4). Between the last day of and the first day after diving, D_LCO decreased on the average for all three series, by –3.5%, SE 0.8%, p<0.01, for the two-hour and 16-hour surface intervals; by –1.9%, SE 0.7%, p<0.02, for the four-hour and 14-hour surface intervals; and by –3.1%, SE 1.2%, p<0.02, for the six-hour and 12-hour surface intervals.

Fig. 4

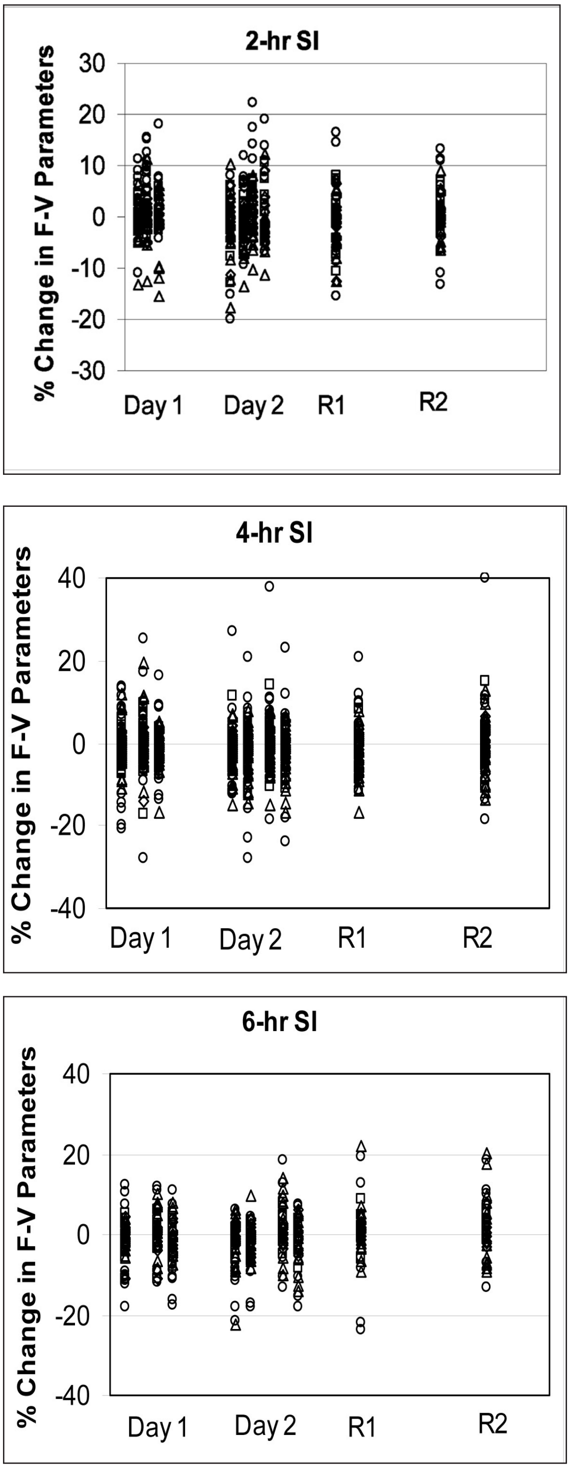

Fig. 4. Changes from baseline in FVC (◊), FEV_1 (□), FEF_{max} (Δ), and $FEF_{25–75}$ (○) with time, split 6-hour exposures. From left to right, columns are Postdive 1, Predive 2, Postdive 2 (Day 1); Predive 3, Postdive 3, Predive 4, Postdive 4 (Day 2); Recovery Day 1, Recovery Day 2.

Vision, Fatigue

Four-hour Resting Dives

Vision

No significant changes in vision were seen during any of the four-hour dive series. One presbyopic subject reported a transient improvement in near vision over the weekend following the five-day series.

Fatigue

Two of the 15 divers completing five four-hour dives, but none of the additional nine divers during the ten-dive series, reported unusual fatigue.

Six-hour Resting Dives, 18-hour Surface Interval

Vision

Significant changes in visual acuity occurred after the series of five daily six-hour dives. Unfortunately, we did not yet have a way to measure refraction. One change was dramatic and unequivocal: a change in acuity for both eyes from 20/16 at baseline to 20/40 on the fifth day after his last dive, a change lasting for approximately twelve days. Other changes were more subtle and occurred earlier: one subject showed a change from 20/25 and 20/30 to 20/30 and 20/40 on the day of his fifth dive, a change that resolved very slowly; another subject showed a change in only one eye from 20/16 at baseline to 20/25 three days after the last dive— a change returning to 20/16 by 10 days after the last dive. One subject reported deterioration in one eye from 20/16 to 20/25 after the fifth dive, with complete resolution three days later. Another subject had a shift in acuity from 20/16 in both eyes to 20/20 in one and blurred vision in the other immediately after the five dives, with restoration four days after diving. Still another changed from 20/20 in both eyes to 20/25 in both, with restoration four days after the last dive; and one other subject reported acuity changed in both eyes from

20/25 at baseline to 20/40 after the fifth day of diving, a change that had probably resolved the next day and certainly by three days after the fifth dive. Two subjects also reported short-term improvements in distance vision, with or without loss of apparent accommodative power: one diver reported acuity changes from 20/20 at baseline to 20/16 after five dives and to 20/10 in one eye at three days after the fifth dive, and another subject showed changes from 20/20 to 20/10 with deterioration in near vision. For all divers, acuity and near vision returned to baseline, but the durations of the changes ranged from a few days to several months.

Fatigue

After diving for six hours on two successive days, four of the 13 subjects (31%; 95% CI: 9% to 61%) reported unreasonable fatigue. After diving for five successive days, nine of 16 divers (56%; 95% CI: 30% to 80%) reported unusual fatigue or exercise intolerance. One diver withdrew after two of five planned dives because his sleep was disturbed by profoundly distressing dreams. One diver was light-headed after the fifth dive in the series.

<u>Six-hour Resting Dives, 42-hour Surface Interval</u>

Vision

The longer interval reduced greatly but did not completely eliminate effects on vision. Six days after the last dive, one subject had a shift of –0.5 D in both eyes and an acuity change from 20/25 and 20/30 at baseline to 20/30 and 20/40 although we had measured no change on the fourth day after the dives. His refraction was restored when we measured it two weeks later. Four subjects complained of slightly blurry vision after one or more dives, but none had measurable changes in refraction.

Fatigue

Five of 14 subjects (36%; 95% CI: 16% to 65%) reported unusual fatigue or exercise intolerance after the series of six six-hour dives on alternate days.

<u>Two 3-hour Dives Daily, Short Surface Intervals</u>

Vision

No changes in visual refraction were measured during these dive series.

Fatigue

After the two-hour surface interval dives, no subject reported fatigue. After the four-hour surface interval dives, four of the 24 subjects (17%; 95% CI: 5% to 37%) reported mild fatigue. After the six-hour surface interval dives, three of 12 subjects (25%; 95% CI: 5% to 57%) were unreasonably tired, with two reporting mild fatigue and one reporting moderately severe fatigue.

One diver reported feeling light-headed on both days after his second two-hour surface interval dive and irritable both days after his four-hour surface interval dives.

DISCUSSION

<u>Four-hour Resting Dives</u>

Our data indicate that four-hour resting dives with PO_2 of 130 to 140 kPa once in a 24-hour period can be repeated for at least 10 days; 20 hours is nearly sufficient for complete recovery. The mean of any flow-volume parameter remains unchanged and the decreases in D_LCO are small as the number of diving days increases. On any dive day mild symptoms can be expected in 17% of divers, flow-volume parameter depression in 5% of divers, and decreased D_LCO very rarely (Table 5). Neither fatigue nor visual changes prohibits diving of these resting profiles. These results concur with those of others; the daily oxygen exposure of these dives is just slightly higher than the average daily dose postulated to be tolerable indefinitely for nitrogen-oxygen saturation diving procedures (6).

Mean D_LCO decreases by –0.5%/day while daily four-hour resting dives continue. If we assume that the changes from baseline at any measurement period values are normally distributed around the value given by the regression line, we extrapolate to the dive number at which 25% of divers will have values below the lower limits of normal, as follows:

For a normal variate with mean μ and standard deviation σ, 25% of the distribution is at or below the value

$(\mu - 0.67 \cdot \sigma)$. (Equation 1)

The extrapolated mean value μ after dive number n is given by the regression equation

$\mu = m \cdot n + b$, (Equation 2)

with m = slope and b = intercept of the regression line.

Thus, the dive number at which 25% of subjects will be at or below the lower limit of normal (LLN), $n_{25\%}$, is given by

$n_{25\%} = (\text{LLN} + 0.67 \cdot \sigma - b) / m$ (Equation 3)

$n_{25\%} = (-14.2\% + 0.67 \cdot 5.5\% + 0.80\%) / (-.48\%/\text{day})$.

From the scatter measured (standard error substituted for σ), $n_{25\%}$ for D_LCO with four-hour resting dives is 20 consecutive days of diving; skin and middle ear problems, not decreased D_LCO or other pulmonary function variable, are likely to limit the number of days for which four-hour resting dives can be repeated.

Six-hour Resting Dives

Six-hour resting dives with PO_2 130 to 140 kPa are associated with extreme fatigue and with more frequent symptoms than are similar four-hour dives. After one or more daily dives, 33% of divers can be expected to have mild symptoms and 4% to have moderate symptoms (Table 6). Changes in pulmonary function after up to five daily dives are no more common than those after daily four-hour dives. However, mean D_LCO decreases slowly but significantly as diving continues: one quarter of divers would be expected to show changes in D_LCO after 7 dives; the values for Equation 3 are σ = 6.8%, b = 2.9%, and m = –1.7%/day. When dives are conducted every other day, however, the significant downward trend in D_LCO is eliminated.

For pulmonary recovery after a six-hour resting exposure to PO_2 of 130 to 140 kPa, 18 hours is not sufficient, but 42 hours is. Still, pulmonary factors are not the major limitations to daily six-hour dives at these PO_2s. Skin and ear problems are frequent. Five daily dives can significantly change visual acuity. Even two successive dives produced reports of unreasonable fatigue, and reported fatigue and exercise intolerance lasted for three to four days after five successive dives. Even with the 42-hour recovery period, 36% of the divers reported fatigue, although the fatigue was generally less severe than that with the 18-hour recovery period.

Some or all of the fatigue may result from immersion effects rather than oxygen exposure; increased excretion of water and sodium become significant after about six hours of head-out water immersion (7). Whatever its cause, severe fatigue limits diver capabilities after multiple six-hour dives.

Three-hour Dives Twice Daily

The incidences of respiratory signs and symptoms from the split daily exposures varied with the surface interval (Table 8). Two hours between dives does not appear to be sufficient for recovery from a three-hour dive of this kind: it makes "three hours on, two hours off, three hours on," equivalent to "six hours on." Four hours between dives makes "three hours on, four hours off, three hours on," equivalent to "four hours on." Six hours seems to allow recovery during the day, but some effect appears to accumulate after the shorter overnight break.

These exposures, despite the few sample points and relatively small numbers of subjects, hint that recovery includes a moderately fast component and a slow component. A secondary cause of delayed symptoms may also exist, a cause for which symptoms are evident later only if earlier healing earlier is incomplete.

Reports of fatigue and exercise intolerance were not notably different from reports after two six-hour dives, except that the shortest surface interval resulted in no reports. These results are confounded by the work schedule: because subjects began the workday at 0530 for the split exposure dives and were done no sooner than nine, eleven, or thirteen hours later for the two-, four-, or six-hour surface intervals, respectively, greater than normal fatigue was inevitable. The absence of fatigue reports from the shortest days with two three-hour dives and the trend to increased reports with increasing lengths of workday hint that work schedule holds a strong influence. That argument invites further conjecture that dive-related fatigue was reduced by interrupting the dives. However, in the real world, fatigue from any source reduces performance.

Air Breaks

All of our divers took the permissible air breaks of 5 min per hour, for a total of 15 min out of a four-hour dive and 25 min out of a six-hour dive. The ratio of hyperoxic time to normoxic time, 55:5, is considerably greater than 20:5, 25:5, or 30:5 ratios used in U.S. Navy treatment tables (1) is greater than any found to prolong survival in animal trials (8); and is slightly lower than the 15:2 found to have no beneficial effects in pulmonary function in humans during hyperbaric treatments (9). Time-weighted average PO_2 has been suggested as the effective variable if a low ratio of normoxic to hyperoxic periods prevails (8); the range was 121–131 kPa if divers breathed 130–140 kPa on the bottom, a 6–7% reduction in PO_2 from that possible without air breaks. The short surface intervals are unlikely to have affected pulmonary oxygen toxicity.

Vision Changes

The large incidence of changes in visual acuity after five six-hour daily dives must not be discounted, but some of the smaller changes that were reported may be artifact. We did not yet have an autorefractor, and eye chart measurements are always subjective. They also are influenced by eye irritation, room brightness, and squinting. The dives were conducted in several sessions; after the dramatic changes in vision in the one diver became public knowledge, the subjects in later sessions had heightened sensitivity to small changes in their vision, and particularly until that one diver's recovery from an unequivocal case of hyperoxic myopia.

Hyperoxic myopia, reported since the mid 1970s in subjects who have undergone multiple hyperbaric oxygen treatments (10-16), appears to be caused by a change in the refractive index of the lens (12-14,16,17). Until Butler reported the phenomenon in a diver who noticed a visual change after he had completed about eighteen days with an average of four hours per day with Po_2=1.3 atm (18), hyperoxic myopia had not been documented in divers.

Neither the dose of oxygen to provoke hyperoxic myopia nor the way effects accumulate across exposures is known. Absent other information, Table 9 lists published incidences in order of increasing atmosphere hours (atm-hr) of oxygen, with no attempt to consider recovery time between exposures. The series of five four-hour dives reported here had 27 atm-hr O_2 exposure; the five six-hour dives provided 41 atm-hr of exposure; and Butler et al (18) reported on exposure to 94 atm-hr.

Our divers breathed oxygen from full face masks, and the hypothesis has been proposed that corneal exposure to hyperbaric oxygen is necessary for myopic changes. The report by Fledelius et al (14) (Table 9) refutes that hypothesis but does not eliminate the possibility that myopic changes are more pronounced in the presence of corneal exposure than not. Indeed, when myopic changes were compared after treatments delivered with oronasal mask or hood, myopia was more severe in the patients who had used the hood (19).

Table 9. Published incidence of hyperoxic myopia after dry hyperbaric oxygen treatment.

Reference	Eyes in 100%O_2	# Treatmts	O_2 dose (atm-hr)	Incidence, myopia
Roessler et al[10]	n	12	30	0/105 (0%)
Ross et al [11]	y	20	80	2/8 (25%)
Lyne[12]	y	> 20	> 75	18/26 (69%) *
Khan et al[13]	y	30–40	90–120	36/69 (52%)**
Fledelius et al[14]	n	30	120	12/17 (71%)
Anderson[15]	y	40	160	9/10 (90%)
Palmquist et al[16]	y	≥ 50	≥ 100	25/25 (100%)

Visual change appeared permanent: * in 1 subject ** in 5 subjects

However, the diver who first had noted myopic changes from underwater exposure was using a T-bit mouthpiece (personal communication). Furthermore, animal studies have shown similar increases in PO_2 in the aqueous humor whether the eye is in air and the animal is ventilated with 100% O_2 or the eye is in 100% O_2 and the animal is ventilated with air (20), and increases in PO_2 in the vitreous humor of some species when the animal is ventilated with 100% O_2 with the cornea in air (21). The role of corneal oxygen exposure in hyperoxic myopia remains an open question.

CONCLUSIONS

For resting dives with PO_2 of 130 to 140 kPa (e.g., swimmer delivery vehicle operations, decompression), four-hour exposures can be repeated for at least 10 days if the surface interval is 20 hours. However, six-hour resting dives have a larger incidence of symptoms, including fatigue, than do four-hour dives. If six consecutive hours are needed with an 18-hour surface interval at this PO_2, to avoid both pulmonary toxicity and hyperoxic myopia, no more than two consecutive dives should be conducted. If some fatigue can be tolerated, six-hour resting dives can be performed on an every-other-day schedule for at least two weeks (six dives). Six-hour exposures in one day — if split into two three-hour resting dives with four hours between them — have effects similar to those of four-hour dives. At least 14 hours is necessary for full recovery overnight between days with two three-hour dives. In general, six hours of consecutive underwater exposure to PO_2 of 130 to 140 kPa is not recommended as a standard practice. Interrupted exposures that total six hours in 24 hours can be acceptable if both the surface interval between dives and the recovery surface interval after diving are sufficiently long.

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