

The effect of hyperoxic environment on lung function and myopisation in an extended closed-circuit rebreather diving expedition

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Abstract

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Introduction: Repetitive closed-circuit rebreather (CCR) dives subject the human body to a hyperoxic environment. Prolonged oxygen exposure can lead to lung abnormalities and myopic shift. The aim of this study was to analyse the effects of a 31-day period of repeated CCR dives on divers' lung function and visual acuity.

Methods: The CCR divers recruited for the study were participating in a research project in Chuuk Lagoon, Micronesia. Weekly measurements included lung function using spirometry and visual acuity with a Snellen chart. Oxygen exposure was calculated using multiple models. The impact on spirometry was tested by comparing the values before and after the expedition and by running regression analysis against accumulated oxygen exposure.

Results: The divers ($n = 12$) performed a total of 173 CCR dives with mean (SD) maximum depth of 38 (13.9) msw and dive time 101 (38.8) min. The daily oxygen exposure limits for unit pulmonary toxic dose and central nervous system toxicity were respected. One diver had a decrease in multiple lung function parameters. Another developed spirometric evidence of mild obstruction by the end of the expedition. However, there were no statistically significant changes in spirometry results. Visual acuity showed fluctuations throughout the expedition, but no overall trend.

Conclusions: Diving expeditions can be executed safely when respecting the guidelines for oxygen exposure. Reasonable oxygen exposure does not seem to significantly affect lung function or visual acuity.

Introduction

Scuba diving can be used as a tool to collect scientific data underwater, especially in the fields of marine biology and archaeology. Scientific diving is a form of occupational diving requiring specific data collection techniques underwater. It is often practised during expeditions with limited time, where the goal is to maximise data collection through consecutive and intensive diving sessions. Closed-circuit rebreathers (CCRs) have become increasingly popular in scientific diving as they allow for longer and deeper dives.

Consecutive CCR diving regularly exposes the human body to hyperbaric and hyperoxic environments. Oxygen toxicity primarily affects three target organs: the central nervous system (CNS), the lungs, and the eyes. Hyperoxic exposure can also have systemic effects, such as the decrease of haemoglobin concentration and increased ferritin.¹ More than 35 years ago, the National Oceanic and Atmospheric Administration (NOAA) established oxygen exposure standards that remain widely used today.² These guidelines

were designed to prevent the onset of acute CNS oxygen toxicity symptoms. While the unit pulmonary toxic dose (UPTD) was initially developed over half a century ago to quantify the pulmonary risk related to repetitive exposure,³ it is still widely used by divers, with few alterations to the formula over the years.⁴ However, the old UPTD model has been replaced by models that consider physiological recovery, such as the Arieli K index.⁵ This has been further improved into equivalent surface oxygen time (ESOT), which is simpler to use when planning diving operations.⁶ Additionally, the residual oxygen time (ROT) model can be used when the partial pressure of oxygen (PO_2) is near 130kPa.⁷

A constant high PO_2 , as often used in CCR diving, can have toxic effects on the lungs. In the early stages of pulmonary toxicity, alveolar exudate forms due to endothelial dysfunction, followed by low-grade airway inflammation. If the exposure continues, small-airway fibrosis will develop. The clinical symptoms of pulmonary oxygen toxicity include dry cough, tracheal irritation, shortness of breath and chest

discomfort.⁸ Spirometry is a commonly used method to measure lung function when investigating pulmonary oxygen toxicity. Although the evidence remains contradictory, it is believed that oxygen toxicity can cause a decrease in vital capacity (VC) and possibly other parameters, such as forced expiratory flows (FEF).⁹

Prolonged exposure to a hyperoxic environment can cause changes in vision, more commonly the development of myopia. An accumulation of high PO₂ damages the structure of the lens increasing its refractive power.¹⁰ However, this is typically reversible after the exposure ends.¹¹ This phenomenon is more common in hyperbaric oxygen treatment (HBOT) patients, and the evidence in divers is scarce.¹² As CCR diving maintains a consistently high PO₂, divers are at a higher risk of developing myopia during periods of intensive diving.^{13,14}

Anecdotally, divers report having an 'end of expedition cough' or 'blurry vision' after prolonged diving expeditions. However, to our knowledge, there is little real-life data to show such changes. Thus, the aim of this study was to analyse the effects of a 31-day period of repeated CCR dives on divers' lung function and visual acuity, the two principal targets of long-term oxygen toxicity.

Methods

This study was conducted according to the Declaration of Helsinki 2024. The ethical review of the study (authorisation number 37/17) and research permission were granted by the University of Milan, Milan, Italy.

STUDY SUBJECTS AND DIVING

The technical divers ($n = 12$) recruited for the study were participating in a nautical archaeological research project in Chuuk Lagoon, the Federated States of Micronesia. All divers gave their written informed consent to participate in this study. The divers used back-mount CCR for research dives and open circuit scuba (OC) for safety dives. They completed 1–2 dives per day with regular days off during the 31-day expedition. For CCR diving, PO₂ setpoints were 70 kPa at surface and during descent, and 130 kPa for the remainder of the dive. Dive time was restricted to a maximum of 180 minutes for a single dive. The divers used their own gear and dive computer for dive planning and decompression. Liberty ($n = 5$), JJ-CCR ($n = 5$), XCCR ($n = 1$) and AP Inspiration ($n = 1$) electronic rebreathers were used. Buhlmann ZHL-16C decompression software with gradient factors of 50/70 were used for decompression planning. The investigators did not have access to the divers' gear. Hence, the dive profiles were collected from additional dive computers in the gauge-only mode (iX3M 2 Tech+, Ratio Computers, Valpiana, Italy). Dive logs were analysed in the application Dana Health (DAN Europe, Roseto, Italy). The retrieved data included maximum depth, dive time, decompression profile and gradient factors.

OXYGEN TOXICITY

Oxygen exposure was calculated separately for CNS%, pulmonary oxygen toxicity (POT) and accumulated exposure. The CNS% was calculated as a percentage of the duration of the maximum single exposure at a constant PO₂ of 130 kPa according to NOAA, which is equal to 180 minutes.² POT was estimated using UPTD,¹⁵ ESOT⁶ and ROT.⁷ The ESOT value, and its recovery formula, were considered to reset after 12 hours, if the ESOT load was less than 500.¹⁶ Additionally, the probability of toxicity was derived from ROT.⁷ A constant partial pressure of 130 kPa was assumed for the whole duration of the dive. The accumulated exposure throughout the expedition was calculated as hours at 101 kPa breathing 100% O₂.¹²

LUNG FUNCTION

To evaluate lung function, spirometry was performed before the first dive, and thereafter weekly until the end of the expedition. The measurements were performed by a single operator at least three hours after the previous dive by a Medikro Pro Spirometer (Kuopio, Finland). The device fulfilled the ISO 26782 and ATS/ERS criteria for diagnostic use and calibration was performed by the manufacturer. Spirometry was performed, according to the European Respiratory Society's guidelines in sitting position at least three times with less than 5% difference, and the highest values were recorded.¹⁷ The following parameters were analysed as predicted percentages for the reference group: forced vital capacity (FVC), forced expiratory volume in one second (FEV₁), FEV₁/FVC ratio, forced expiratory flow 75 (FEF₇₅), and forced expiratory flow 25–75 (FEF_{25–75}). GLI 2017 reference equations for Caucasians were used as reference values.

VISUAL ACUITY

Visual acuity was measured using a Snellen chart. The baseline measurement was taken before any diving activities. If a diver wore glasses, measurements were done both with and without them. Throughout the expedition visual acuity was measured once a week and the last measurement was performed after the last dive. Subjects were standing 6 m from the chart on a covered terrace. Measurements were taken during daylight; however, the exact time could not be standardised due to logistic issues. Both eyes were measured first separately and then together.

STATISTICAL ANALYSIS

The Shapiro-Wilk test was used to test for normality of the spirometry data. To check if the expedition affected spirometry results, paired Student *t*-tests were used on the first and last measurement of five parameters (predicted FVC, FEV₁, FEV₁/FVC, FEF₇₅ and FEF_{25–75}). To evaluate the effect of accumulated physiological load on spirometry results, linear mixed-effects regression models were used.

The analysis was performed using the lme4 R package,¹⁸ with random intercepts for the divers. As fixed effects, we included the number of CCR dives, accumulated UPTD, or ROT probability of toxicity from the previous dive, to form three models. The normality and homoscedasticity of regression residuals were checked using the Shapiro-Wilk test and visual inspection. A two-sided significance level of 0.05 was used for all statistical tests to account for possible training effect, recovery, or adaptation. To account for multiple testing, Bonferroni correction was applied separately to t-tests and to regression models. All analyses were performed using R version 4.5.3. Visualisation was done using base R graphics¹⁹ or ggplot.²⁰ The data are presented as means (standard deviation). Additionally, for oxygen exposure, maximum values are also reported.

Results

POPULATION AND DIVING

The demographics of the divers participating in the study are shown in Table 1. Pre-existing medical conditions included hypothyroidism treated with thyroxine ($n = 1$), medication treated hypertension ($n = 1$), previous decompression sickness (DCS) ($n = 2$), patent foramen ovale (PFO) closure ($n = 1$), back surgery ($n = 1$), and previous cataract surgery ($n = 1$). The latter was excluded from the myopisation part of the study. The rest of the divers ($n = 7$) had no medical conditions or medications.

The divers ($n = 12$) performed a total of 173 CCR dives during a 31-day period, with no diving occurring on three of those days. The divers took additional days off for gear maintenance, administrative tasks, illness, or rest. However, none of these were due to symptoms of pulmonary or visual oxygen toxicity or decompression sickness. The divers participated in the project for two to four weeks resulting in 5–26 dives per diver. Additionally, six divers performed a total of 26 OC safety dives. One research dive was performed using OC due to CCR malfunction. The OC dives were excluded from the analysis. The summary of the descriptive statistics for each diver is shown in Table 2. The mean maximum diving depth was 38 (13.9) msw and mean dive time was 101 (38.8) min. Diver E had a high number of OC dives (nine) compared to the number of CCR dives (nine). Thus, the diver was excluded from spirometry analysis due to OC diving being a remarkable confounding factor.

OXYGEN TOXICITY

Oxygen exposure was estimated using the dive time and constant PO_2 of 130 kPa, as there was no access to the divers' own computers. The daily exposure for diving days was summarised in Table 3. It contains the mean and maximum CNS%, UPTD, ESOT, ROT and ROT probability of toxicity along with established daily limits. Two divers were contacted retrospectively and the real CNS% and UPTD were received for 35 dives to compare and assess the

Table 1

Diver demographic data presented as mean (standard deviation); BMI – body mass index CCR – closed-circuit rebreather; msw – metres of seawater

Parameter ($n = 12$)	Mean (SD)
Age	41.6 (10.6)
BMI ($kg \cdot m^{-2}$)	28.9 (4.2)
Years of diving	20.7 (10.6)
Number of dives	2,846 (1,757)
Years of CCR	10.2 (6.1)
Hours of CCR	1,072.0 (969.6)
Max. depth (msw)	106.8 (33.0)

extent of approximation error. For a single dive, the median (IQR) percentage error of CNS% was -1.2 (-4.2–2.7) % and for UPTD 2.3 (0.17–4.2) %. The cumulative error was estimated using the bootstrap method. Depending on the number of dives (5–26) that a diver completed, the mean and 95% confidence interval for the percentage error was between -1.04 (-6.51–6.55)% and -1.09 (-3.49–1.75)% for cumulative CNS% and between 3.20 (0.32–9.62)% and 3.04 (1.44–5.34)% for cumulative UPTD. This means the cumulative UPTD from CCR dives is likely to be overestimated for most divers. Some identified sources of error included descent at PO_2 of 70 kPa, a manual increase of PO_2 at safety or decompression stops and alternating the PO_2 manually on shallow dives. Unfortunately, the oxygen exposure was not recorded for all the safety dives. Out of the 26 OC dives, the data were available for 11. Their mean (SD) CNS% was 3.71 (2.38) and UPTD 5.39 (4.94). The mean accumulated oxygen exposure was 32.0 (20.5) hours at 101 kPa breathing 100% O_2 . The OC dives were excluded from the analysis of accumulated oxygen exposure.

LUNG FUNCTION

Lung function was measured by weekly spirometry during the expedition. The result of the paired *t*-test is shown in Table 4. There was no significant difference between the first and last measurements. For the regression models, spirometry data from all weeks was used, however, we decided to exclude six measurements from the ROT predicted toxicity model as the spirometry was performed more than one day after diving. The final dataset for the linear mixed-effects models is visualised in Figure 1, with detailed model results shown in Table 5. These models showed no significant association of FVC Pred% with accumulated UPTD, number of CCR dives or ROT probability of toxicity.

When looking at individual results, there was one diver with substantially reduced absolute values for lung function parameters at four weeks compared to baseline as follows: FVC -7.0%, FEV_1 -16.1%, FEV_1/FVC -9.7%, PEF -9.6%, FEF_{25-75} -44.8%. However, the diver did not have any clinical symptoms of pulmonary oxygen toxicity, such as

Table 2

Summary of the dives for each diver; total days off refers to the number of days the diver was not diving, diving period describes the length of the expedition in days, and longest consecutive refers to the longest streak of consecutive diving days. *Diver E was excluded from further analysis due to a high number of OC dives. CC – closed-circuit; OC – open-circuit; EAN – enriched air nitrox

Diver	Total CC	Total off	Diving period (days)	Longest consecutive (days)	Max depth (msw)	Dive time (min)	Total OC dives	OC max depth (msw)	OC dive time (min)	OC gas O ₂ (EAN)
A	5	7	11	4	38 (3.1)	98 (19.2)	0	0 (0)	0 (0)	0 (0)
B	6	7	11	4	34 (5.9)	90 (8.6)	0	0 (0)	0 (0)	0 (0)
C	8	13	21	4	27 (9.9)	93 (12.8)	0	0 (0)	0 (0)	0 (0)
D	9	0	13	10	34 (12.1)	110 (31.2)	4	22 (15.4)	28 (13.1)	30 (0.1)
E*	9	1	13	10	25 (9.7)	88 (27.2)	9	20 (10.2)	35 (16.8)	30.1 (0.3)
F	12	6	20	4	28 (5.7)	73 (15.7)	5	14 (6.5)	20 (19.8)	30.9 (1.3)
G	14	1	12	10	34 (8.8)	66 (22.2)	5	15 (6.0)	23 (12.3)	30.1 (0.1)
H	17	7	24	6	35 (12.9)	100 (36.6)	0	0 (0)	0 (0)	0 (0)
I	19	3	9	6	50 (13.7)	130 (25.1)	1	23 (0)	35 (0)	30 (0)
J	23	6	30	9	35 (11.8)	99 (32.2)	3	20 (2.9)	54 (14.2)	30 (0)
K	25	4	27	9	49 (11.7)	130 (34.6)	0	0 (0)	0 (0)	0 (0)
L	26	5	28	9	43 (11.6)	100 (44.7)	0	0 (0)	0 (0)	0 (0)

chest discomfort or dry cough. One diver developed mild obstruction (FEV₁/FVC z-score declined from -1.16 to -1.93) by the end of the expedition. Another diver was already mildly obstructive at the beginning of the expedition. All parameters were still within the normal range, and both were asymptomatic.

VISUAL ACUITY

Thirty-six measurements of visual acuity were performed during the expedition. The number of measurements per diver varied between two and five depending on the length of their expedition. One diver was excluded from the analysis due to previous cataract operation. None of the included divers ($n = 11$) had any previous eye surgeries, trauma or infections within two months prior to the expedition. The measurements were conducted approximately weekly; however, for two divers they were performed less frequently due to logistical constraints. Two divers had no changes in their eyesight. The remaining nine divers had fluctuations throughout the expedition, mostly a one-line improvement or worsening in one eye. When the baseline measurements were compared to the last measurement, two divers had an improvement of one line with both eyes, whereas the rest had no changes. Thus, there was no change of visual acuity throughout the expedition.

Discussion

In this extended, 31-day field study, research divers participated in marine archaeological work consisting of CCR dives. It was found that some divers may develop mild, asymptomatic pulmonary obstruction during extended oxygen exposure. There were no significant changes in visual acuity observed. Thus, most divers completed the expedition safely without any major adverse effects.

OXYGEN EXPOSURE AND TOXICITY

Conservative dive planning and a limited number of dives per diver kept the oxygen exposure within an acceptable range. A new guideline suggests that the acceptable exposure time limit to manage risk of cerebral oxygen toxicity when diving at a constant PO₂ of 130 kPa is four hours of working dive and four hours of rest.²¹ As the older and more conservative NOAA guidelines of CNS% were respected during this expedition,² it is not surprising that there were no major adverse effects related to oxygen toxicity. Both UPTD and ESOT had mean and maximum values below accepted limits. The current recommendations only consider up to seven days of consecutive diving due to limited evidence. In this dataset, the longest consecutive diving period was 10 days and there were no pulmonary adverse effects. ROT showed that by diving mostly once per day, divers did not accumulate oxygen exposure, as there was enough time for recovery. This can also be seen in the low probability of toxicity. In a recently published review, the total oxygen exposure in divers leading to myopic changes was higher (68 or 110

Table 3

Summary of daily oxygen exposure (based on a constant inspired PO_2 of 130 kPa) for different models presented as mean (standard deviation) and maximum; the daily limit recommendation is displayed if there is one. CNS (%) – percentage of the maximum allowed exposure for central nervous system toxicity; ESOT – equivalent surface oxygen time; ROT – residual oxygen time; UPTD – unit pulmonary toxic dose

Exposure model	Mean (SD)	Maximum	Daily limit	Ref no.
CNS (%)	58.2 (19.5)	97.8	100	2
UPTD	156.9 (52.7)	272.2	300	15
ESOT	190.9 (63.7)	320.6	450	6
ROT	1.8 (0.6)	3.1	–	7
ROT Probability of toxicity (%)	6.5 (1.9)	11.3	–	7

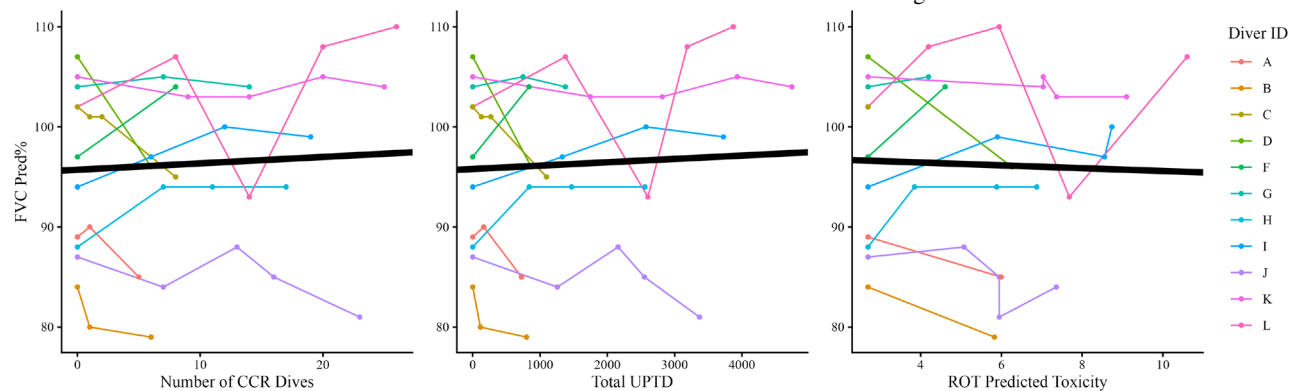
Table 4

Paired *t*-test results for the change in predicted spirometry values between the start and end of the diving periods of 11 divers. The *P*-value was adjusted using Bonferroni correction. CI – confidence interval, $\text{FEF}_{75}\%$ – forced expiratory flow of 75% of lung volume; $\text{FEF}_{25-75}\%$ – forced expiratory flow of 25–75% of lung volume; FVC – forced vital capacity; FEV_1 – forced expiratory volume during the first second, FEV_1/FVC – ratio of FEV_1/FVC

Variable	Estimate (95% CI)	<i>P</i> -value	Adjusted <i>P</i> -value
FVC Pred%	-0.72 (-5.06–3.61)	0.71	1
FEV_1 Pred%	-2.46 (-7.07–2.16)	0.26	1
FEV_1/FVC Pred%	-2.09 (-5.29–1.11)	0.18	0.88
FEF_{75} Pred%	-11.73 (-34.8–11.3)	0.28	1
$\text{FEF}_{25-75}\%$ Pred%	-7.55 (-20.0–4.89)	0.21	1

Figure 1

Predicted forced vital capacity (FVC Pred%) measurements plotted against three measures of accumulated oxygen exposure: number of closed-circuit rebreather (CCR) dives, total unit pulmonary toxic dose (UPTD) and residual oxygen time (ROT) predicted toxicity. The thick line shows the linear mixed model trendline for an average diver



hours of 100% O_2 at 101 kPa) compared to the mean of this group (32.0 [SD 20.5] hours of 100% O_2 at 101 kPa).¹²

LUNG FUNCTION

In this study, most of the divers did not have changes in their lung function, although one diver had a 7–44.8% decrease in multiple parameters. In addition, one diver developed mild obstruction, though it was clinically insignificant. It could

be argued whether using general reference z-score -1.64 for the lung impairment is correct in this population. Wingelaar et al. demonstrated that, in annual fit-to-dive evaluations for military divers, applying a lower normal limit of 2.5% (z-score -1.96) was sufficient without compromising diver health. More extensive lung function testing did not identify any additional contraindications to diving when combined with detailed medical history taking.²²

Table 5

Results of linear mixed-effects models with random intercepts for the divers and fixed effects specified in the 'Independent variable' column; the *P*-values were estimated using the Kenward-Roger method. CCR – closed-circuit rebreather; FVC Pred% – percentage of predicted forced vital capacity; ROT – residual oxygen time; UPTD – unit pulmonary toxic dose

Dependent variable	Independent variable	Estimate (95% CI)	<i>P</i> -value	Adjusted <i>P</i> -value	Marginal R^2 / Conditional R^2	<i>n</i> observations (<i>n</i> divers)
FVC Pred %	CCR <i>n</i> dives	0.064 (-0.12–0.25)	0.50	1	0.003 / 0.81	40 (11)
	Total UPTD	0.00034 (-0.00077–0.0015)	0.56	1	0.003 / 0.81	40 (11)
	ROT toxicity	-0.14 (-0.85–0.58)	0.67	1	0.001 / 0.80	34 (11)

The comparison of the first and last spirometry measurements of each diver using paired *t*-tests did not show any statistically significant changes. However, the confidence intervals were quite wide, especially for FEF₇₅ Pred% and FEF_{25–75} Pred%. Therefore, more evidence is needed to draw reliable conclusions. There were also no significant associations found between accumulated oxygen exposure and spirometry changes tested using regression models. This is not unexpected, as the pulmonary oxygen exposure was kept within safe limits, minimising the likelihood of large spirometry changes. Simultaneously, spirometry variation introduced by the long observation time, combined with a modest sample size, limits the statistical power for finding small changes in spirometry. Nevertheless, the regression model results and associated confidence intervals imply that similar diving expeditions are unlikely to result in clinically significant FVC Pred% changes in an average diver. This is most evident in the regression on the number of CCR dives where the estimated change in FVC Pred% was only 0.064 (95% CI -0.117–0.250) per dive.

Table 6 summarises studies using spirometry in evaluating lung function in divers.^{14,23–29} The results shown were contradictory. It is argued that spirometry is not the most sensitive test to detect early signs of pulmonary toxicity.³⁰ Some studies measured diffusion capacity for carbon monoxide (D_LCO), which seems to be a more sensitive measurement for pulmonary oxygen toxicity.^{28,30} Studies involved either a single bounce dive or 4–14 consecutive days of diving. Diver's subjective symptoms like coughing or chest discomfort, did not correlate with abnormal spirometry results.^{14,28} Conversely, some individual divers showed deteriorated lung function - as was the case for one diver in our study - but no subjective symptoms.

The question of how to recognise divers that are at risk of developing lung dysfunction after extended diving expeditions remains. Increasing the surface time between long hyperoxic exposures was shown to decrease both subjective symptoms and the diffusion capacity for the carbon monoxide (D_LCO) regression slope.²⁸ Although these experiments were done in a pool with resting divers, the findings can be applied to working divers who are more prone to hyperoxic injury.^{21,28} In working oxygen CCR divers, smaller airways (maximal expiratory flow at 25% [MEF₂₅] and maximal expiratory flow at 50% [MEF₅₀]) seemed more affected, suggesting long-term hyperoxic pulmonary injury.³¹ Recent revised guidelines strongly recommend that if pulmonary oxygen toxicity symptoms develop, the diver should wait until fully recovered before resuming diving activity.²¹

VISUAL ACUITY

There were no significant changes in the visual acuity of divers during this expedition. Some fluctuation in the measurements was observed. However, this was most likely due to the natural fluctuation of eyesight. On some

Table 6

Summary of spirometry results after single or several days of diving; *the study had 14 divers providing 20 data sets collected in several expeditions in 2007–2010 and pooled together. CCR – closed-circuit rebreather; FEF_{25–75}% – forced expiratory flow at 25–75% of lung volume; FEV₁ – forced expiratory volume in one second; FVC – forced vital capacity; MEF₂₅ – maximum expiratory flow when 25% of lung volume is left; O₂-CCR – oxygen rebreather; OC – open-circuit; n.a. – not available; ssOC – surface supply OC; Unpub – unpublished data previously recorded by the authorship team

Ref	Divers (n)	Dives/diver (n)	Length (days)	Place and temperature	Depth (m)	Dive Time	Gas	OC/CCR	Spirometry results
14	14/20*	n.a.	13	n.a.	69	112 min	PO ₂ 130–140 kPa	CCR	no change
23	26	1	1	n.a., 23–24°C	80–120	243–516 min	heliox	ssOC	FEV ₁ /FVC, MEF ₂₅ decreased to 89.2–87.1% 30 min after the dive, returned to baseline in 24 h
24	7	1–4	4	Tahiti, 27°C	90, 120	160, 180 min	trimix	CCR	FVC 84% vs. 91%, FEV ₁ /FVC 98% vs. 95%, other no change
25	8	8–9	5	Baltic, 16.5/8.5°C	19.7–64.7	54–99 min	air/trimix	CCR	no change
26	6	1	1	pool, 31–32°C	15	20 min	air/PO ₂ 140 kPa	OC/CCR	no change
27	11	2	2	n.a.	5	180 min	pO ₂ 150 kPa	O ₂ -CCR	no change
28	9	10	14	pool, 29–35°C	4.6	4 h / 20 h break	130–140 kPa	ssOC	resting, no change
28	16	5	5	pool, 29–35°C	4.6	6 h / 18 h break	130–140 kPa	ssOC	resting, regression line for FVC -0.4%/day
29	10	5	5	pool, 29–35°C	4.6	6 h / 18 h break	130 kPa	ssOC	exercising vs. resting incidence of changes in flow-volume parameters 17–30% vs. 10–20%
Present article	12	14 (5–26)	31	Micronesia, 30–31°C	36 (14–68)	95 (27–176) min	PO ₂ 70/130 kPa	CCR	FEV ₁ decreased in two weeks, no other changes in the group, one diver had decline in FEF _{25–75} %
Unpub	9	1	1	Finland, 8/4°C	103	167 min	trimix	CCR	no change

days, the divers might have been more tired, or the lighting differed, as the tests were performed outside in natural light. Baseline measurements were taken after the long journey to Micronesia, when divers were fatigued, which might explain the improvement seen. The development of hyperoxic myopia has previously been documented in technical divers during rigorous diving expeditions.^{13,14} Additionally, there has been a case of a recreational diver developing myopia on a diving vacation.¹²

There are a few possible explanations for no changes in the visual acuity. Firstly, the oxygen load remained low compared to HBOT patients, for whom long treatment protocols may cause transient myopisation. Additionally, breaks in the exposure (i.e., weekends), have been shown to allow partial recovery of vision before the next HBOT session begins.³² As divers on this expedition predominantly dove once a day, there was recovery time between exposures. Furthermore, due to the low sensitivity and subjectivity of the Snellen chart, small changes may have been missed. An autorefractor could have provided more precise measurements but it was not available during the expedition. Thus, confounding factors may explain the fluctuations seen in the results. However, had there been major changes in vision, they would likely have been detected.

STRENGTHS AND LIMITATIONS

This study presents real-life data of working scientific CCR divers, collected over 31 days, in a remote location. There is currently little real-world evidence collected systematically for such a long period of time. However, the real-world setting comes at the expense of data quality.

The primary goal of the expedition was to collect archaeological, not physiological, data. Thus, data collection could not always be optimised: the time for spirometry and visual acuity measurements varied and spirometry could not be collected systematically eight hours post dive. A month of data collection includes a number of confounding factors that further added noise to the data: gear malfunctions, divers getting ill and plans changing. For example, test divers suddenly had to perform as OC safety divers due lack of support divers introducing mixed modality diving that we did not have the resources to account for. Finally, the expedition team was international, making follow-up for the affected divers impossible.

Moving forward, we hope to encourage the scientific community to continue data collection in a real-life setting. This type of evidence is needed to further solidify the oxygen exposure limits and hence, make diving safer.

Conclusions

This study demonstrates that diving expeditions can be executed safely, even in remote locations, when planned carefully and conservatively. Diving once a day and adhering

to consensus guidelines for oxygen exposure led to a reasonable total accumulation of oxygen exposure that does not appear to have a substantial effect on lung function or visual acuity. However, more real-life, long-term evidence is required to confirm these conclusions and to detect more subtle changes.

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