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CO_2 retention during hyperbaric exercise while breathing 40/60 nitrox

D. KEREM, Y. I. DASKALOVIC, R. ARIELI, and A. SHUPAK

Israeli Naval Medical Institute, P.O. Box 8040, Haifa 31080, Israel

Kerem D, Daskalovic YI, Arieli R, Shupak A. CO_2 retention during hyperbaric exercise while breaching 40/60 nitrox. Undersea Hyperbaric Med 1995; 22(4):339–346.—We evaluated CO_2 retention in 24 Navy construction divers breathing air at 1 atm abs (101.3 kPa) and 40% O_2 (40/60) nitrox at 4 atm abs (PO_2 of 162.1 kPa) inside a pressure chamber. The divers sat immersed to the sternal notch and exercised against pneumatically loaded pedals at a $\dot{V}O_2$ of approximately 1.3 liter/min. The mean end-tidal CO_2 tension (PET_{CO_2}) at 1 atm abs (45.7 ± 5.0 SD torr) was significantly higher than that of non-divers and diving trainees (40 ± 5.0) but did not increase significantly at depth (47.1 ± 6.3). The ranking of CO_2 retention was not maintained at depth. Unpredictable upward and downward shifts of up to 10 torr occurred in some divers. The PET_{CO_2} of six of the divers at pressure was greater than 50 torr, which based on animal studies markedly increases the risk of central nervous system oxygen toxicity. We translated their values into individual depth limits with 40/60 nitrox: three with $50 < PET_{CO_2} < 55$ torr were forbidden to dive beyond 25 m and three with values > 55 torr were restricted to 20 m. We propose that whenever possible, PET_{CO_2} during exercise at pressure be measured in potential nitrox users and that the above PO_2 limits be enforced on moderate and extreme CO_2 retainers, respectively.

oxygen toxicity risk, hypercapnia, oxygen enriched mixtures, diver screening

Divers with hypoventilatory hypercapnia may be at risk of suffering central nervous system oxygen toxicity while diving on oxygen-enriched mixtures. It is well documented in animal studies that CNS O_2 toxicity is hastened by external CO_2 (1–3), and although no systematic studies show this to be true for hypoventilation-induced hypercapnia, the inference is highly probable. The high density and PO_2 of nitrox and the prevalence among professional divers of an inherent or acquired tendency to hypoventilate during underwater exercise can all contribute to hypercapnia during a working dive (4).

The Israeli Naval Medical Institute (INMI) was alerted to this issue by an undersea construction job requiring rather heavy exertion at depths of 20–30 m. This job prompted a request by the divers to approve the use of 40/60 nitrox with open-circuit scuba rather than with the more cumbersome semi-closed breathing apparatus.

This paper presents the results of our ensuing measurements of ventilation and end-tidal CO_2 tension (PET_{CO_2}) on a group of divers exercising on air at 1 atm abs and on 40/60 nitrox at 4 atm abs.

METHODS

Subjects: Subjects were 24 healthy male construction divers, selected according to intended use of open system nitrox, who volunteered to participate in the study after hearing an explanatory lecture and signing an informed consent. The experimental protocol was approved by the Human Experimentation Committee of the IDF Medical Corps. All divers had at least basic hard-hat and mixed-gas training, both with nitrox and heliox mixtures. Physical characteristics of the subjects and a summary of their diving experience are presented in Table 1. Seven of the divers were smokers (mean of 2 yr at seven cigarettes/day).

Trials were done at varying times in the day from 0900 to 1500 h. Divers performed their regular daily activity during the study period and were not restricted with respect to diet and physical training. They did not engage in additional diving on the day of the test.

Apparatus: Tests were performed in a 2-m-long Morin–Lanphier-type wet compartment of a 1.5-m-diameter pressure chamber. Water temperature ranged from 25° to 30°C. Exercise was performed on a piston pedal ergometer with the load regulated pneumatically. Figure 1 is a diagram of the experimental system.

The breathing circuit consisted of a mouthpiece and 4-cm-diameter breathing hoses. The inspiratory hose was attached to a 3-way stopcock which could be directed either to chamber atmosphere or via a Conshelf-14 regulator to a built-in breathing system with air and 40/60 nitrox outlets. The expiratory hose could similarly be switched either directly to chamber atmosphere or to a turbine-type flowmeter (K.L. Engineering–Pneumoscan), mixing box, and a sodalime canister. Gas sampling and calibration (Airspec QP9000 mass spectrometer) were routed through an eight-ported, minimal-dead-space mini-valve (Omnifit).

A continuous recording of the integrated flow signal (tidal volume), mouth pressure (Valydine), ergometer piston pressure, and either mixed expired or mouthpiece O_2 and CO_2 concentration was obtained (Gould 2800S chart recorder). Gas temperature and an electrocardiogram (ECG) from waterproof chest electrodes were displayed separately (Yellow Springs Instrument Co. Inc. and Mennen Medical Co. cardiac monitor, respectively). Volume and gas signals were also tape recorded and fed into a Micro-Vax 4000-200 computer (Digital Corp) programmed to compute and display on-line gas tensions, minute ventilation, $\dot{V}O_2$, and $\dot{V}CO_2$.

Experimental protocol: Before each run, the MS was calibrated with prepared gas mixtures that had been checked against commercial precision mixtures (Scott). In the 1 atm

Table 1: Subjects' Characteristics

Feature	Mean	SD	Range
Age, yr	25	8	19–51
Height, cm	178	8	165–196
Weight, kg	75	12	46–100
VC, liter BTPS	5.2	0.9	3.5–7.6
Years diving	7	8	2–34
Current diving, per month	14	10	1–30

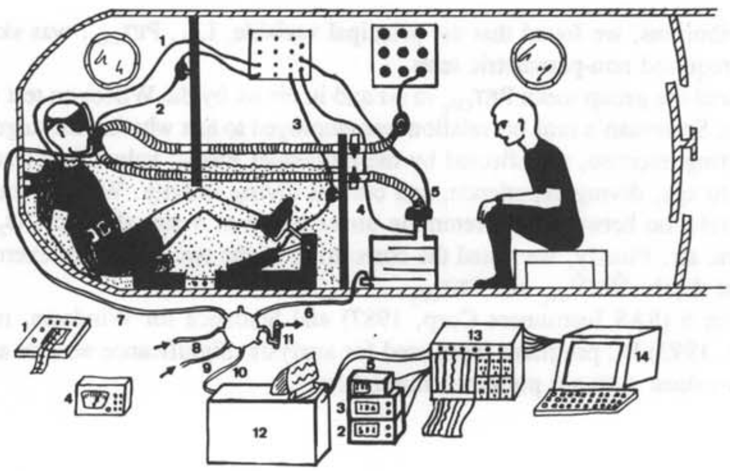

FIG. 1—Scheme of the experimental system. *1*, ECG: *2*, mouthpiece pressure (3 mm i.d. tube); *3*, piston pressure; *4*, expired gas temperature; *5*, expiratory flow/volume; *6*, mixed-expired gas sample from mixing box; *7*, mouthpiece gas sample (0.5 mm i.d. tube); *8*, room pressure calibration source; *9*, 4 atm abs calibration source; *10*, MS probe; *11*, free-flow ambient vent with needle valve and flowmeter; *12*, MS; *13*, chart recorder, *14*, microvax workstation.

abs air-phase calibration setup, the sampling probe of the MS was coupled to the meter-long surface calibrating line and the instrument pumped the gas through the combined length. In the 4 atm abs nitrox-phase setup, theressurized calibration gas was vented at a rate of 0.25 liter/min and the MS sampled from the free-flow stream (5). The flow meter was calibrated with a 3-liter syringe after verifying that such calibration was pres-sure-independent in the 1–4 atm abs range.

Subjects performed spirometry and had their weight and height measured before entering the chamber with an attendant. After verifying a good-quality ECG signal, the subject entered the water, adjusted foot-stroke length, donned a nose clip, and started to breath air from the mouthpiece and demand regulator. An electronic metronome with sound and flashing light set a pedaling rate of 50 strokes/min. The piston pressure was initially set at 1.5–2 atm abs, which put most subjects inside the desired range of 1.2–1.4 liter/min O_2 consumption.

Subjects warmed up for the time needed for mixed-expired gas concentrations to become stable before directing the recorder signals to the tape recorder and the A/D converter. Ventilation and gas exchange were then computed for 5 min and adjustments to the piston pressure were made when necessary. When CO_2 production became stable for at least 2 min, end-tidal CO_2 was recorded and averaged over 2 min to obtain the air value. A second 3-min period of mixed expired gas sampling concluded the 15-min sequence.

Subjects stopped exercising, were switched to breathing nitrox, and the chamber was compressed on air to 4 atm abs at a rate of 1 atm/min. Upon arrival at pressure, the sequence was repeated, this time with a strict time adherence. During the warm-up the piston pressure was raised by 4 atm abs, pressure calibration of the MS was performed, and the CO_2 channel gain was quadrupled.

After ceasing to exercise, subjects joined the attendant in the dry compartment and decompression commenced at a rate of 1 atm/min. A 5-min safety stop at 3 m on O_2 was included for the benefit of the air-breathing attendant.

Data analysis: The group was subdivided into smokers and non-smokers to see whether smoking influenced any of the measured values. Using the Shapiro–Wilk test to verify normal distributions, we found that the principal variable, i.e., PET_{CO_2}, was skewed to a degree that required non-parametric tests.

We compared the group mean PET_{CO_2} in air and in nitrox by the Wilcoxon test for paired observations. Spearman's rank correlation was employed to test whether the degree of CO_2 retention during exercise, as reflected by the individual PET_{CO_2} values in air and nitrox, was related to age, diving experience, and current diving activity. We also looked for a possible correlation between CO_2 retention under nitrox at 4 atm abs and CO_2 retention in normobaric air. Finally, we tested the correlation of the two indices of exercise hypoventilation at depth: $\dot{V}E/\dot{V}_{CO_2}$ and PET_{CO_2}.

SAS version 6 (SAS Instrument Corp, 1987) and Statistica for Windows, release 4.3 (Statsoft Inc, 1993) PC programs were used for analysis. Significance was set at the 0.05 level. Mean values ±SD are presented throughout.

RESULTS

The mean PET_{CO_2} values for the smokers and non-smoker subgroups, at both experimental phases, were within 1 torr of each other. Also, none of the other ventilatory parameters were significantly different in the two subgroups. The subgroups were therefore pooled for further analysis. The group mean CO_2 production rates were 1.15 ± 0.22 liter/min during the air phase and 1.09 ± 0.43 liter/min during the nitrox phase. The difference is not significant.

The principal findings of this study are evident from Fig. 2, which is an XY plot of individual air and nitrox PET_{CO_2} values, respectively. They are as follows:

- The diver group as a whole retained CO_2 under both experimental conditions. We base this contention on a non-diver/novice diver mean PET_{CO_2} value, which from our experience of 20 yr and several hundred subjects exercising on normobaric air was found to be 40 ± 5 torr. In Fig. 2 we have added a grid of the 40-, 50-, and 55-torr lines on the point array. One sees at a glance that the group as a whole is decidedly above (and to the right of) the 40-torr line. We hereafter define individuals with PET_{CO_2} 2 SD or more above this value, CO_2 retainers and those above 3 SD, extreme retainers.
- The importance of the higher density and PO_2 of nitrox in accentuating retention was found to be minor at this simulated depth. Mean group PET_{CO_2} values were 45.7 ± 5.0 torr for normobaric air and 47.1 ± 6.3 for hyperbaric nitrox. This difference did not reach statistical significance.
- The air and nitrox PET_{CO_2} values were positively correlated, yet strict ranking of individuals with regard to this measure was not maintained at pressure. A positive correlation between air and nitrox was established for the group as a whole ($r = 0.60$; $P < 0.005$, Fig, 2). The 95% confidence interval for the 0.85 slope of the regression line contains the slope = 1 identity line in the measured range. Still, as can be seen from Fig. 2, there were unpredictable within-subject nitrox–air differences in PET_{CO_2} (vertical distances of the points from the identity line) ranging from −8 to +10 torr.

Four subjects who according to the above definitions were not retainers on 1 atm abs air became so on 4 atm abs nitrox, one of them attaining the extreme degree. Two subjects demonstrated extreme retention on both mixtures. One retainer subject on air "narrowly escaped" being such on nitrox.

The degree of CO_2 retention on air and on nitrox did not correlate with age, diving experience, or current diving activity. As can be seen in Fig. 3, PET_{CO_2} did show a negative correlation with the independent measurement of $\dot{V}E/\dot{V}CO_2$ ($r = -0.8$; $P < 0.0001$), as would be predicted from the alveolar air equation for CO_2.

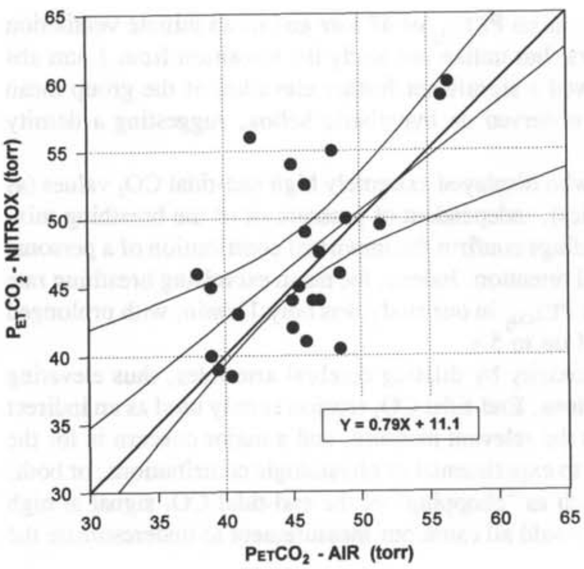

FIG. 2—Individual exercise $P_{ET_{CO_2}}$ values at 4 atm abs 40/60 nitrox vs. the values at 1 atm abs air. Ninety-five percent confidence limits and the slope = 1 identity line are included. *P* value for the null hypothesis of slope = 0 is 0.001, the correlation coefficient is 0.61. Grid lines refer to the definition of CO_2 retention by the upward deviation from the normal mean (*see* text). They mark the 40-torr mean as well as 2 and 3 SD of 5 torr above it, for several hundred non-divers and novice divers exercising on air at 1 atm abs with $\dot{V}O_2$ ranging from 1.0 to 1.6 liter/min.

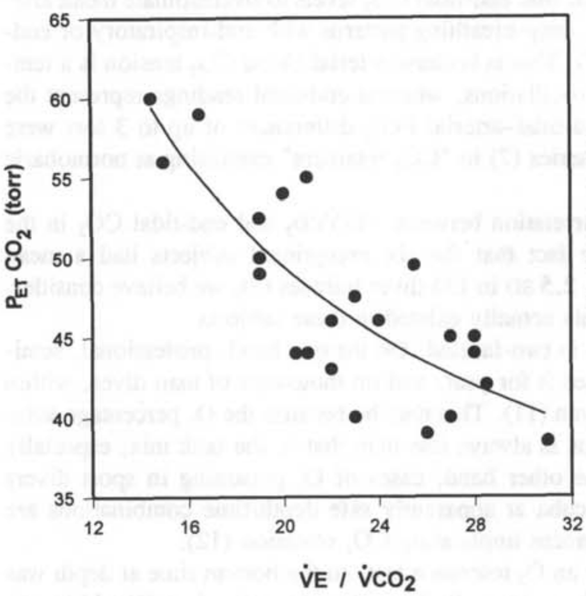

FIG. 3—The relationship of $P_{ET_{CO_2}}$ to the ventilatory equivalent for CO_2 at depth. The line was fitted to the equation: y = a/x + b which approximates the relationship expected from the alveolar equation for CO_2.

DISCUSSION

This study confirmed earlier reports of CO_2 retention during exercise among professional divers (4). It showed that such retention is not expected to be globally aggravated by breathing nitrox down to 30 m, but that individual subjects could be so affected. The main point it brought out is that some individuals, whether by an inherent trait, an effect of hyperbaric nitrox, or both, may sustain end-tidal CO_2 levels above 55 torr while breathing 40/60 nitrox at pressure.

Our study essentially replicates parts of a series of U.S. Navy Experimental Diving Unit (EDU) reports from 1955 to 1958 (6–8) which measured end-tidal CO_2 values in 17 exercising divers (mean $\dot{V}O_2$ of 1.4 liter/min), breathing 1.1 atm abs air, 4 atm abs air, 4 atm abs normoxic nitrox, and 4 atm abs 45% O_2 nitrox and heliox (PO_2 of 1.8 atm abs). The normobaric air results of that series: mean PET_{CO_2} of 47 torr and mean minute ventilation of 28 liter/min are very close to ours, but unlike our study the transition from 1 atm abs air to 4 atm abs air or nitrox involved a significant further elevation of the group mean PET_{CO_2}. Such an elevation was not observed on hyperbaric heliox, suggesting a density effect.

Both studies included individuals who displayed extremely high end-tidal CO_2 values (as high as 70 torr in the American series), independent of pressure or of the breathing mixture composition. The combined findings confirm the important contribution of a personal slow breathing pattern to exceptional retention. Indeed, the mean exercising breathing rate of the three subjects with the highest PET_{CO_2} in our study was only 11/min, with prolonged end-inspiratory/expiratory pauses of up to 5 s.

It is assumed that CO_2 enhances toxicity by dilating cerebral arterioles, thus elevating O_2 flux and mean tissue oxygen tensions. End-tidal CO_2 tension is only used as an indirect estimate of arterial tension which is the relevant measure, and a major concern is for the former to overestimate the latter due to experimental or physiologic contributions, or both. Systematic experimental artifacts such as "chopping" of the end-tidal CO_2 signal at high breathing rates (9), line leaks, etc., would all cause our measurement to underestimate the true end-tidal value.

On the other hand, it is possible for true end-tidal CO_2 levels to overestimate mean arterial levels, especially in very slow, deep-breathing patterns with end-inspiratory or end-expiratory pauses ("skip-breathing"). This is because arterial blood CO_2 tension is a temporal mean of respiratory-induced oscillations, whereas end-tidal readings represent the peaks of such oscillations (10). End-tidal–arterial P_{CO_2} differences of up to 3 torr were actually demonstrated in the EDU series (7) in "CO_2 retainers" exercising at normobaric conditions.

However, based on the strong correlation between $\dot{V}_E/\dot{V}_{CO_2}$ and end-tidal CO_2 in the present study (Fig. 3) and on the fact that the six exceptional subjects had a mean $\dot{V}_E/\dot{V}_{CO_2}$ of 18.3 compared to 25 ± 2.5 SD in 135 diver trainees (7), we believe considerable hypoventilation and hypercapnia actually existed in these subjects.

The safety record of nitrox at sea is two-faceted. On the one hand, professional, semi-closed system divers have safely used it for years and on thousands of man dives, within P_{O_2} limits established for pure oxygen (11). This may be because the O_2 percentage actually inhaled in this type of apparatus is always less than that in the tank mix, especially during heavy exercise (11). On the other hand, cases of O_2 poisoning in sport divers breathing nitrox on open system scuba at apparently safe depth/time combinations are sometimes encountered in circumstances implicating CO_2 retention (12).

This study was not intended to be an O_2 tolerance test, so the bottom time at depth was restricted to what we thought would pose a negligible risk of O_2 poisoning. Would longer times have posed appreciably higher risks on CO_2 retainers? For lack of direct experimentation on O_2 toxicity risk as a function of PET_{CO_2}, and for lack of sufficient human toxicity cases where CO_2 levels were documented, any inference has to be conjectural. Yet guidelines may be drawn from relevant indirect studies.

The addition of 6% CO_2 to the pure O_2 inspired by 122 exercising diving trainees, raised their mean PET_{CO_2} from 40 ± 5 to 53 ± 6 torr (13). The latter value falls in the range of our definition of retainers. Adding 5% CO_2 to the inhaled O_2 of rats exercising at a simulated depth of 10 m shortens the time lag to appearance of paroxysmal electroencephalogram activity from 27 to 16 min (14), a time that falls within the limits that the U.S. Navy allows its O_2 divers (25 min at 10.7 m) (15). Although neither arterial nor end-tidal CO_2 levels were measured in those rats, others (16) have shown arterial CO_2 tensions of resting rats to increase from 35.5 to 45.6 upon breathing 5% CO_2.

Taking all the above into consideration, we believe that divers in both the retainer categories are at a higher risk of incurring CNS toxicity. As the specter of an N_2-loaded nitrox diver convulsing at 30 m is even more ominous than that of a pure-O_2 diver similarly afflicted at a much shallower depth, we recommend that more stringent depth restrictions be applied to CO_2 retainers. The restrictions should be tailored to the individual's degree of CO_2 retention while breathing nitrox at the proposed maximal depth.

To avoid a dive plan complicated by both decompression and O_2 toxicity considerations, a given nitrox mixture at its maximal allowable depth should give a P_{O_2} that still allows a sufficiently long bottom time. At the depth limit of 30 m, 40/60 nitrox has an inhaled P_{O_2} of 1.6 atm abs (162.1 kPa), which by pure O_2 standards could be safely breathed at high exertion levels for up to 4 h (17).

The operational decisions taken by INMI, to be upheld in the future and to be recommended for general use, are as follows:

1. Accept the 1.6 atm abs P_{O_2} ceiling for the normocapnic divers ($PET_{CO_2} < 50$ torr), i.e., allow them a depth limit of 30 msw on 40/60 nitrox.
2. Limit the three CO_2 retainers ($50 > PET_{CO_2} < 55$) torr to a P_{O_2} of 1.4 atm abs or to a depth of 25 msw on 40/60 nitrox.
3. Further limit the three extreme retainers ($PET_{CO_2} > 55$) to a P_{O_2} of 1.2 atm abs or to a depth of 20 meters of seawaer (msw) on 40/60 nitrox.
4. Adopt a 1.4 atm abs P_{O_2} ceiling for all divers on whom no information on PET_{CO_2} during exercise is available.

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