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Decompression induced nitrogen elimination

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Dick APK, Vann RD, Mebane GY, Feezor MD. Decompression induced nitrogen elimination. Undersea Biomed Res 1984; 11(4):369–380.—A method for measuring nitrogen elimination after air diving has been developed in which a subject breathes air instead of oxygen or helium-oxygen. Accuracy is improved with this method because only nitrogen absorbed during the dive is eliminated. Nitrogen stored in the lungs and tissues at sea level is unaffected. Measurements were made with a closed-circuit breathing apparatus using a spirometer as a counterlung. The oxygen partial pressure in the apparatus was controlled at 0.209 ± 0.003 atm. The spirometer volume was recorded periodically with the subject holding his breath at functional residual capacity. Increases in spirometer volume were used to define a nitrogen elimination curve. Elimination measurements were made after resting and exercising dives to 60, 100, and 130 fsw (2.8, 4.0, and 4.9 atm) at the U.S. Navy no-decompression exposure limits. Exercise during a dive increased the volume of nitrogen eliminated after the dive, but results for both resting and exercising divers were variable. Possible causes of this variability include bubble formation and changes in blood flow.

nitrogen washout	decompression sickness
inert gas elimination	exercise
decompression	no-decompression dives

A diver breathing compressed air absorbs nitrogen while at pressure and eliminates it during and after decompression. The rates of absorption and elimination are affected by factors such as exercise, temperature, body position, pressure change, and breathing gas (1–11). The influence of these factors on inert gas exchange can be investigated by measuring respiratory nitrogen elimination. This information is important to understanding the mechanisms of decompression.

A frequently used method for measuring nitrogen elimination is to have a subject rebreathe a large volume of oxygen or helium-oxygen while serial volume and trace nitrogen concentration measurements are made (1–11). These measurements are used to calculate the eliminated nitrogen volume. Nitrogen stored in the subject's lungs and tissues at sea level, however, is eliminated as well as nitrogen absorbed during a dive. This problem may be avoided by using air instead of oxygen or helium-oxygen. A method developed for this purpose is described below. The method was used to study nitrogen elimination after resting and exercising no-decompression dives.

METHODS

Elimination measurements were made with a low-volume, closed circuit breathing apparatus whose gas composition was controlled closely to that of air. The nitrogen volume in the apparatus was calculated from its temperature, oxygen partial pressure (Po_2), and total volume. A nitrogen elimination curve for a subject breathing from the apparatus was defined by the progressive increase in the calculated nitrogen volume.

The apparatus had a dead space of 6 liter and used a 13 liter Collins spirometer as a counterlung (Fig. 1). The spirometer volume was measured with a potentiometer and the temperature and humidity were measured with dry and wet thermistors. Carbon dioxide was removed by an absorbent canister placed immediately downstream of the subject. The distal end of the canister contained a heat exchanger which was flushed with cold water to regulate the gas temperature to ambient at a relative humidity of 96%. The average Po_2 was determined from three galvanic oxygen sensors (Rexnard Safety Products, Malvern, PA.) placed at different locations in the breathing loop.

All measurements were made and recorded on magnetic disk by a Digital Equipment Corporation 11/34 computer. The computer operated a solenoid valve which added oxygen to the

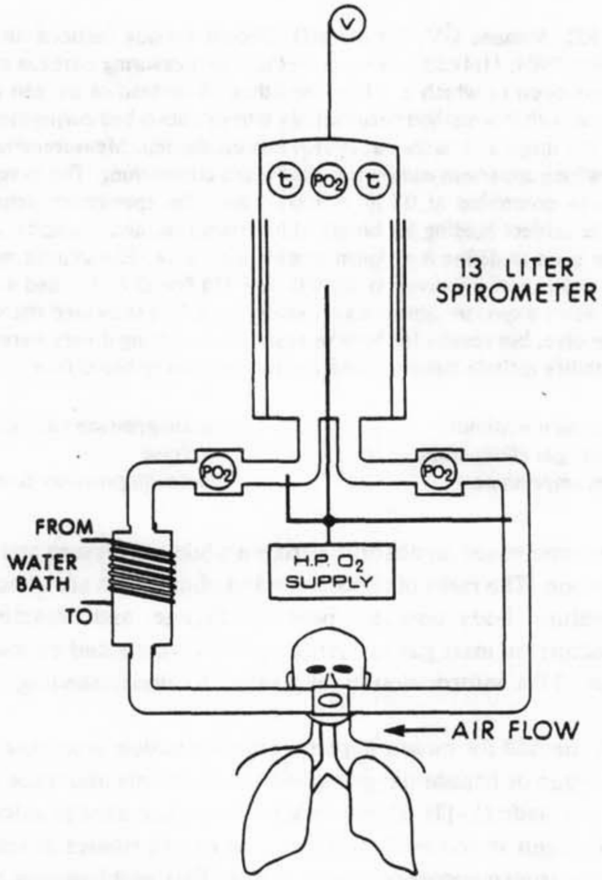

Fig. 1. Experimental apparatus. V is a potentiometer that measures spirometer volume. The t's are thermistors for measuring wet and dry bulb temperatures. Po_2's are sensors for measuring oxygen partial pressures.

apparatus when the average Po_2 fell below that of air. With this control system, the Po_2 was held at 0.209 ± 0.003 atm. Oxygen was added through a constant mass-flow orifice (12) when the solenoid value opened. The computer calculated the subject's oxygen consumption every few minutes. Oxygen was added at three points in the apparatus to promote even mixing. The volume of nitrogen in the apparatus was calculated using equation

$$V_{N_2} = (V_t \times (1 - Po_2/P_B) - V_{O_2} \times F_{N_2}) \times 273 \times P_B/(273 + T) \times 760$$

where V_{N_2} = nitrogen volume (STP); V_t = total apparatus volume (spirometer plus dead space); Po_2 = oxygen partial pressure in atm; P_B = barometric pressure in ATA; V_{O_2} = oxygen volume added to maintain a constant Po_2; F_{N_2} = nitrogen fraction in V_{O_2} (usually about 0.1%); T = temperature in °C; and all volumes are in milliliters.

Although the nitrogen volume in the apparatus could be calculated to an accuracy of ± 15 ml, the volume in the subjects' lungs changed during respiration and could not be measured easily. To overcome this problem, the subjects assumed a relaxed chest position (functional residual capacity) for 10 s while measurements were taken. The relaxed position gave a more reproducible reference lung volume and was less fatiguing than forced expiration (residual volume) which also has been used (11).

Nitrogen elimination was studied after no-decompression dives to the U.S. Navy exposure limits of 60 min at 60 fsw (2.8 atm), 25 min at 100 fsw (4.0 atm), and 10 min at 130 fsw (4.9 atm). The dives took place in a dry pressure chamber with compression and decompression rates of approximately 60 fsw/min (1.8 atm/min). On reaching the surface, the subjects walked from the chamber to the apparatus in about 30 s where they began a 60 or 90 min nitrogen elimination period. The subjects were at rest during this period with a mean oxygen consumption of 0.4 liters/min (range 0.3 to 0.5 liters/min).

Both resting and exercising dives were tested. The subjects rested during one dive and exercised on a bicycle ergometer during part of the next. They exercised only during the initial part of the dive so that they were completely at rest on return to the surface. The exercise periods were 20, 10, and 5 min for the 60, 25, and 10 min dives. Exercise periods were shorter for the shorter dives to allow heart rate to return to normal before decompression. The exercise loads were 360 KPM/min (60 W), 720 KPM/min (120 W), and 1080 KPM/min (180 W) for the 60, 25, and 10 min dives. These exercise rates approximate the degree of exertion commonly experienced by sport divers in dives to these depths. The 10 and 20 min exercise periods were followed by 2 min of sit-ups.

The subjects were three young, slim males with normal pulmonary functions (Table 1). Subject A was a recreational jogger in moderate physical condition; Subject B was a competitive runner in excellent condition; and Subject C exercised only occasionally. Subject A was

TABLE 1
VITAL STATISTICS FOR SUBJECTS

Subject	Age	Height, cm	Weight, kg	Body Fat, %	Vital Capacity, liters
A	26	196	77.1	10	6.4
B	21	178	73.5	8	4.9
C	24	170	63.6	12	4.7

exposed to all three depths, Subject B only to 130 fsw (4.9 atm), and Subject C only to 100 fsw (4.0 atm).

RESULTS

Control experiments

The accuracy of the apparatus was tested in surface control experiments. Subjects with no recent pressure exposure breathed from the apparatus for 60 or 90 min. Under these conditions, no net nitrogen exchange should occur, and an elimination curve should be a horizontal line. Figure 2 shows the results of a surface control experiment. The point-to-point scatter of data for a well-trained subject was usually less than 50 ml and was primarily the result of errors in reproducing functional residual capacity.

The subjects completed 16 control experiments of 60 min duration. These were distributed throughout the experimental dives to ensure the apparatus was functioning properly. In 14 control experiments, the calculated nitrogen volume at the end of the test was within 25 ml of the initial volume. In the other two experiments, the final volume was within 50 ml of the initial volume. Four control experiments were continued to 90 min with a volume error of less than 25 ml.

Diving experiments

Figure 3 shows the results of a typical diving experiment. A nitrogen elimination curve has been fitted by hand to data points taken at 1 min intervals. This curve represents nitrogen

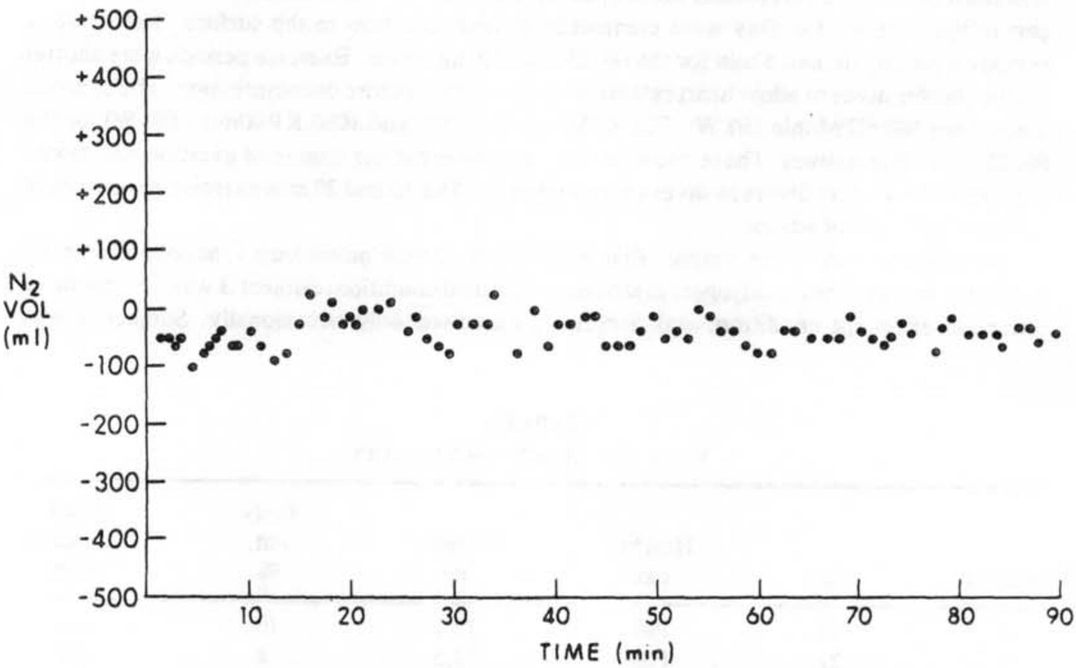

Fig. 2. Results of an isobaric control experiment. Subject had no recent pressure exposure and no net nitrogen elimination occurred.

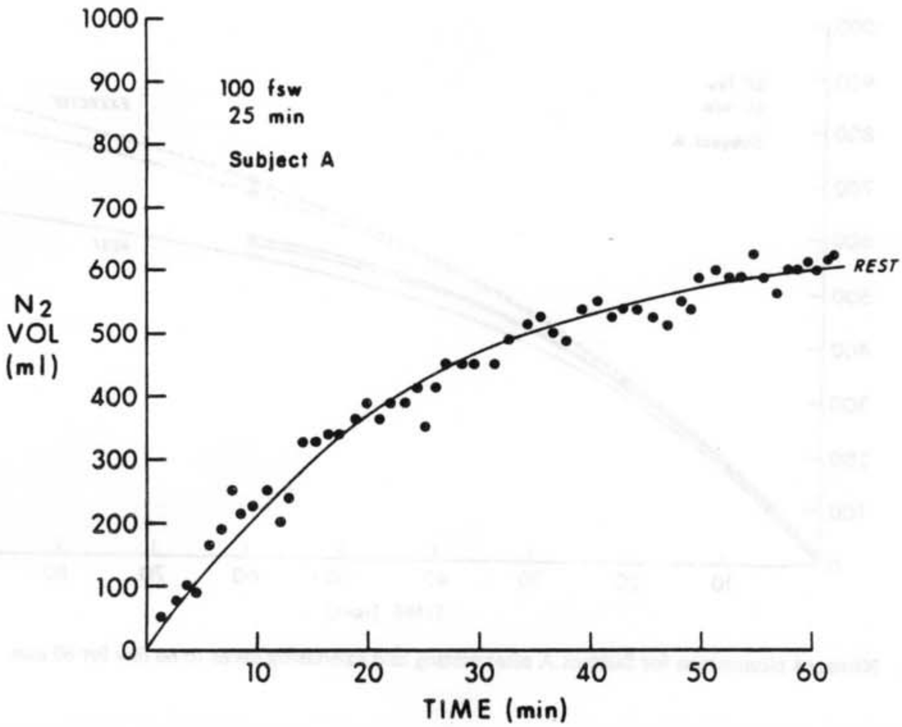

Fig. 3. Nitrogen elimination for Subject A after a resting dive to 100 fsw for 25 min. Curve through data points was fitted by hand.

eliminated after a resting dive to 100 fsw (4.0 atm) for 25 min. The net expired volume of nitrogen after 60 min was 600 ml.

Figure 4 shows the results for Subject A after five dives to 60 fsw (2.8 atm) for 60 min. Three resting dives produced similar nitrogen elimination curves. The amount of nitrogen eliminated in 60 min varied from 540 to 580 ml with a mean of 565 ml. When the subject did moderate exercise for the first 25 min at depth in two dives, a mean of 680 ml of nitrogen was eliminated in 60 min.

Figure 5 shows elimination curves for Subject A after dives to 100 fsw (4.0 atm) for 25 min. After six resting dives, the volume of nitrogen eliminated in 60 min varied from 425 to 630 ml with a mean of 520 ml. Moderate exercise for the first 20 min of six dives resulted in increased elimination at 60 min of 750 to 900 ml with a mean of 830 ml.

Figure 6 shows nitrogen elimination curves for Subject A following dives to 130 fsw (4.9 atm) for 10 min. After three resting dives, the volume of nitrogen eliminated in 60 min varied from 420 to 485 ml with a mean of 440 ml. After four dives with exercise for 5 min followed by rest for 5 min, nitrogen elimination at 60 min increased and ranged from 600 to 925 ml with a mean of 720 ml.

Figure 7 shows the nitrogen elimination for Subject B following dives to 130 fsw (4.9 atm) for 10 min. Elimination at 60 min after five resting dives varied from 375 to 560 ml with a mean of 450 ml. After four exercising dives, Subject B eliminated 570 to 710 ml of nitrogen at 60 min with a mean of 670 ml. One experiment stopped at 50 min after 970 ml of nitrogen were eliminated.

Figure 8 shows nitrogen elimination curves for Subject C following dives to 100 fsw (4.0 atm) for 25 min. The measurement period was 90 min, and the elimination curves after resting

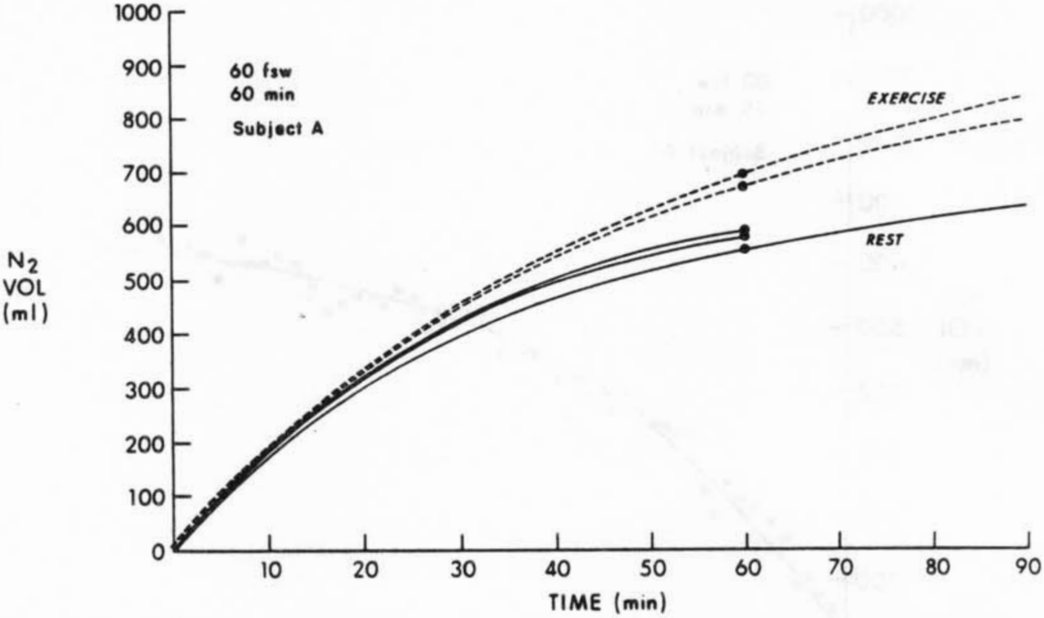

Fig. 4. Nitrogen elimination for Subject A after resting and exercising dives to 60 fsw for 60 min.

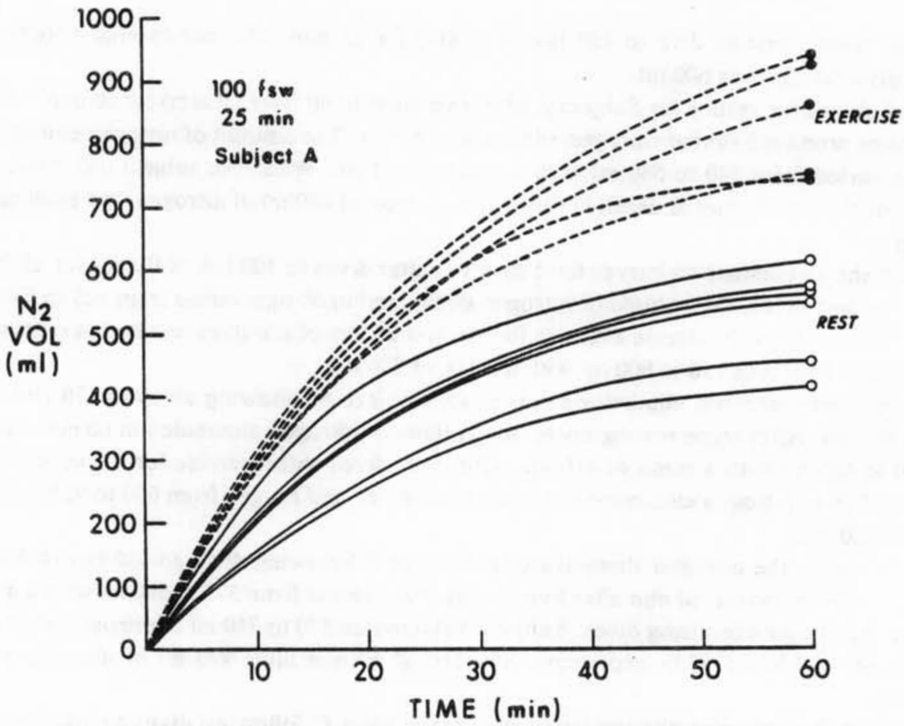

Fig. 5. Nitrogen elimination for Subject A after resting and exercising dives to 100 fsw for 25 min.

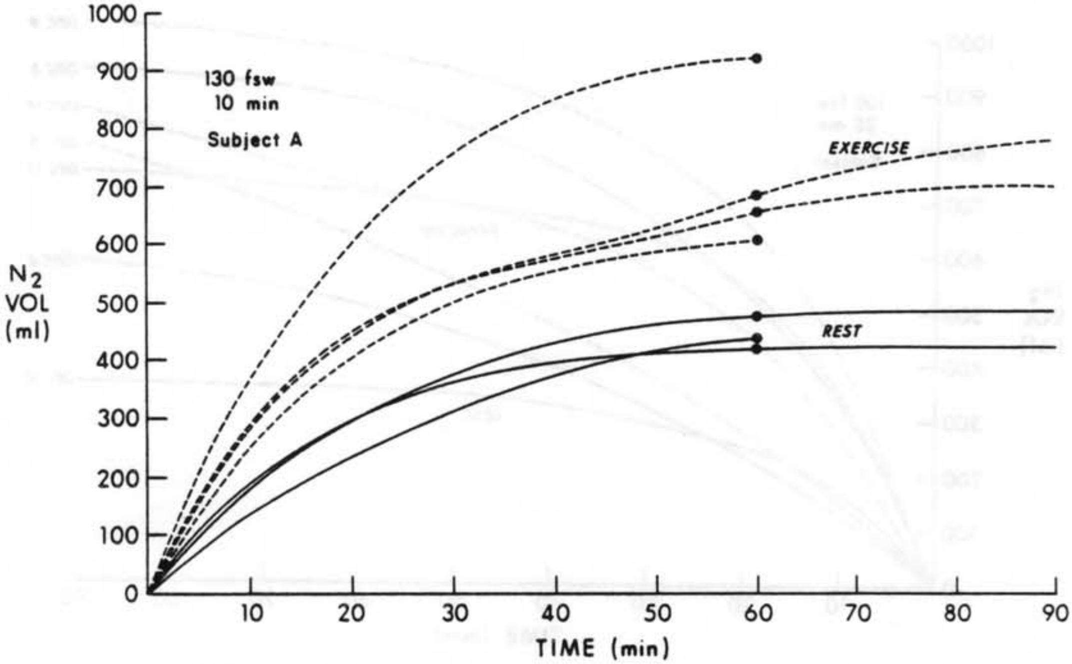

Fig. 6. Nitrogen elimination for Subject A after resting and exercising dives to 130 fsw for 10 min.

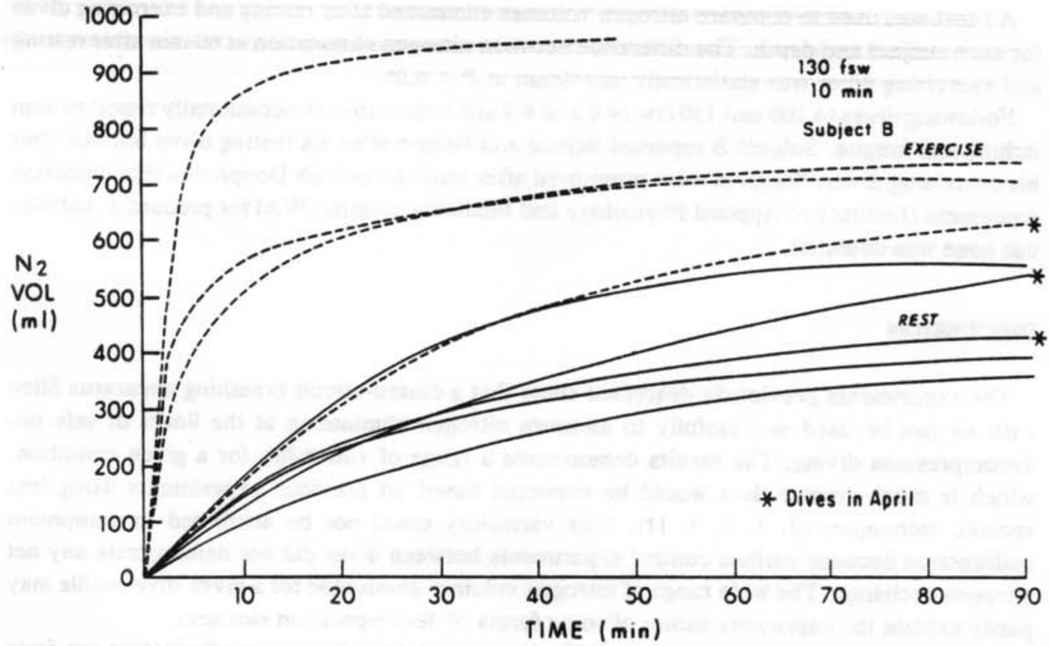

Fig. 7. Nitrogen elimination for Subject B after resting and exercising dives to 130 fsw for 10 min.

and exercising dives overlapped. After three resting dives, nitrogen elimination varied from 355 to 925 ml with a mean of 610 ml. After four dives with moderate exercise for the first 15 min, 740 to 1025 ml of nitrogen were eliminated with a mean of 850 ml.

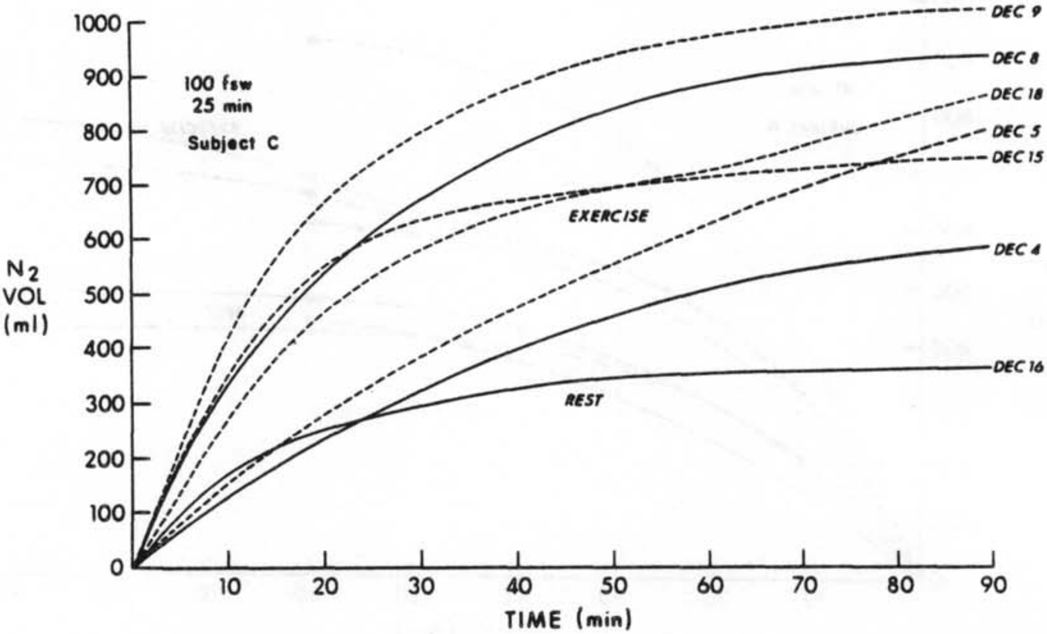

Fig. 8. Nitrogen elimination for Subject C after resting and exercising dives to 100 fsw for 25 min.

A *t*-test was used to compare nitrogen volumes eliminated after resting and exercising dives for each subject and depth. The difference between nitrogen elimination at 60 min after resting and exercising dives was statistically significant at $P < 0.05$.

Following dives to 100 and 130 fsw (4.0 and 4.9 atm), the subjects occasionally reported skin itching and fatigue. Subject B reported itching and fatigue after his resting dives but not after his exercising dives. Subjects were monitored after most dives with Doppler bubble detection equipment (Institute of Applied Physiology and Medicine, Seattle, WA) for precordial bubbles but none was detected.

DISCUSSION

The experiments previously described show that a closed-circuit breathing apparatus filled with air can be used successfully to measure nitrogen elimination at the limits of safe no-decompression diving. The results demonstrate a range of variability for a given condition, which is much greater than would be expected based on previous experiments using less specific techniques (2, 3, 6, 9, 11). This variability could not be attributed to equipment malfunction because surface control experiments between dives did not demonstrate any net nitrogen exchange. The wide range of nitrogen volumes eliminated for a given dive profile may partly explain the capricious nature of some forms of decompression sickness.

The little data in the literature concerning reproducibility of nitrogen elimination are from studies done at sea level with no prior decompression. Behnke and Willmon (3) found that the nitrogen volume eliminated by 30 min of oxygen breathing had a mean error of 3% in six experiments with the same subject. Balldin and Lundgren (6) made two elimination measurements on each of five oxygen-breathing subjects and found differences ranging from about 2% to 10%.

No previous studies have documented multiple nitrogen eliminations on the same subject after decompression. Some studies which have examined the effect of decompression on different subjects have found that the rate of inert gas elimination decreased (13–16) whereas others found that the elimination rate increased (2, 11). Bubble formation has been proposed as the cause of both observations. Extravascular bubbles would decrease inert gas elimination by isolating gas from the circulation and by reducing its tissue tension. Intravascular bubbles, on the other hand, might increase the elimination rate by enhancing the gas-carrying capacity of the blood (11).

Since decompression did occur in the experiments described in this paper, the results could have been influenced by bubble formation. Although no bubbles were detected by precordial Doppler monitoring, the experimental protocol did not allow for optimal use of the Doppler bubble detection equipment. Extravascular bubbles or bubbles too small to be detected may have been present and might have caused some of the observed variability.

Changes in blood flow have also been cited as causes of variable inert gas exchange. Groom et al. (17) found that anesthesia retarded respiratory nitrogen elimination from oxygen-breathing dogs. This resulted from decreased cardiac output and redistributed peripheral circulation. Others have observed transient increases in the rate of respiratory nitrogen elimination lasting from several minutes to several hours (18–21). Vorosmarti et al. (20) interpreted these increases as possible indications of changes in tissue perfusion or in the distribution of pulmonary ventilation. Such changes may have caused the spontaneous increases in nitrogen elimination which occurred between 40 and 50 min in Figs. 6 and 8.

In the experiments following the exercising dives, nitrogen elimination was almost invariably observed to be greater than after the resting dives. Exercise increases muscle perfusion, and increased perfusion has been shown to accelerate the absorption or elimination of many gases in a variety of tissues (22–26). Behnke and Willmon (3) and Jones (4) found that exercise accelerated the elimination of nitrogen and helium during oxygen breathing at sea level. It is likely that the increased nitrogen elimination after the exercising dives was a result of accelerated nitrogen absorption during exercise.

Muscle perfusion is about 3 ml·min·100 g at rest and 60 ml·min·100 g during maximal exercise (27). These values correspond to tissue half-times of 23 min and 1 min if nitrogen exchange is perfusion-limited and if the nitrogen solubilities in blood and muscle are equal. With a half-time of 23 min, resting muscle would be 26% saturated with nitrogen after a 10 min dive and 84% saturated after a 60 min dive. Exercising muscles, on the other hand, at a half-maximal perfusion of 30 ml·min·100 g (a half-time of 2.3 min) would be 95% saturated in 10 min and 100% saturated in 60 min. Thus, half-maximal exercise would increase nitrogen absorption by 69% during a 10 min dive but only by 16% during a 60 min dive.

Such effects can be seen in Table 2 where increased nitrogen elimination following exercise was greater after the shorter dives than after the longer dives. This agrees with Behnke and Willmon (3) and with Jones (4) who found that exercise had its greatest effect within about 30 min.

Changes in blood flow might also explain why nitrogen elimination after Subject B's exercising dives was faster in December than in April (Fig. 7). Subject B had fast nitrogen elimination after his exercising dives in December when he was running 4 miles or swimming 1 mile almost daily. The next April, however, he was not physically active, and his nitrogen eliminations were as slow as those of the other subjects. Slow elimination was associated with itching and postdive fatigue in all subjects. These effects were absent when elimination was fast. Perhaps fast elimination prevented itching and fatigue by avoiding bubble formation.

TABLE 2
NITROGEN VOLUMES ELIMINATED UP TO 60 MIN POSTDIVE

		Mean Volume Eliminated				
Dive	Subject	After Resting Dive, ml	No. of Dives	After Exercising Dive, ml	No. of Dives	Increase, %
60 fsw for 60 min	A	565	3	680	2	20
100 fsw for 25 min	C	610	3	850	4	39
	A	520	6	830	5	60
130 fsw for 10 min	B	450	5	670	3	49
	A	440	3	720	4	64

Whether fast elimination was related to a high level of physical fitness is an interesting question for future research.

The cause of the unusually large nitrogen elimination for Subject C on December 8 is unknown (Fig. 8). He was not sick at the time nor was there any obvious change in his physical condition. If his elimination curves are paired, however, as resting and exercising dives on adjacent days (December 4 and 5; December 8 and 9; December 15 and 16), we observed that more nitrogen always was eliminated after the exercising dive. The difference between resting and exercising eliminations was small when the resting elimination was large. Perhaps resting blood flow to his muscles changed during the month and was highest on December 8.

In summary, we have developed a more specific method to measure postdive nitrogen elimination and have found a high degree of variation in the volume of nitrogen eliminated both in experiments using the same subject and also comparing different subjects. Thus, it may not be appropriate to use previously published isobaric respiratory nitrogen absorption and elimination curves to compute no-decompression exposure limits and decompression schedules (28, 29). Exercise during the dive significantly increased nitrogen eliminated post-dive, presumably due to increased uptake during the dive. We also speculate that physical fitness may affect nitrogen elimination in a complex manner but further research is needed to define its effect.

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Dick APK, Vann RD, Mebane GY, Feezor MD. Elimination de l'azote induite par la décompression. Undersea Biomed Res 1984; 11(4):369–380. Une méthode que permet au sujet de respirer de l'air plutôt que de l'oxygéne ou un mélange d'hélium-oxygène a été développée pour mesurer l'élimination de l'azote aprés une plongée à l'air. La précision fut améliorée avec cette technique parce que seulement l'azote absorbée durant la plongée était éliminée. L'azote emmagasinée dans les poumons et les tissus au niveau de la mer n'était pas affectée. Les mesures furent effectuées en circuit fermé avec un appareil respiratoire utilisant un spiromètre comme "contre-poumon." La pression partielle de l'oxygéne dans l'appareil était maintenue à 0.209 ± 0.003 atm. Le volume du spiromètre était enregistré périodiquement pendant que le sujet retenait sa respiration au niveau de la capacité résiduelle fonctionnelle. Les augmentations de volume du spiromètre furent utilisées pour définir la courbe de l'élimination de l'azote. Les measures de l'élimination furent effectuées après des plongées au repos et avec exercice jusqu'à 60, 100, et 130 pieds d'eau salée (2.8, 4.0, et

4.9 atm) aux limites des expositions sans décompression de la Marine américaine. L'exercice durant une plongée augmenta le volume de l'azote éliminé après la plongée, mais les résultats étaient variables pour les deux cas de plongées au repos et avec exercice. Les causes possibles de cette variabilité incluent la formation de bulles et des changements dans le débit sanguin.

lavage de l'azote
élimination de gaz inerte
décompression
maladie de décompression
exercice
plongée sans décompression

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