Optimal Use of Nitrogen to Suppress the High Pressure Nervous Syndrome

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Five subjects were compressed to 1000 ft (31 ATA) for 2 h breathing 3.2 ATA nitrogen, 0.5 ATA oxygen, and the remainder helium. The compression took 33 min with a 10-s stage at 50 ft (2.5 ATA), 1 min at 320 ft (10.7 ATA), and 2 min at 700 ft (22 ATA). Hypothetically, this 1:10 ratio for nitrogen-helium partial pressures should induce neither nitrogen narcosis nor the High Pressure Nervous Syndrome (HPNS). Tests, therefore, were made during the experiment of postural tremor, spontaneous electroencephalogram, psychomotor and intellectual activities, and subjective sensations. One diver worked underwater for 40 min on a simulated engineering assembly while breathing with a closed-circuit breathing apparatus and wearing a battery-heated suit in water at 56°F. Decompression was in 4 d using 0.8 ATA oxygen and helium. The performance tests indicated no narcosis and little or no signs of HPNS. No tremor or EEG changes were seen. The "wet" diver reported sensations of mild euphoria but the other four reported no difficulties. No nausea or dizziness of HPNS was reported. It is concluded that use of a ratio of 1:10::N_2:He is effective in the control of narcosis and HPNS during rapid compression to 1000 ft (31 ATA).

ON COMPRESSION with oxygen-helium to depths greater than 500 ft (16 ATA), signs and symptoms of the High Pressure Nervous Syndrome appear (1,12), including nausea, dizziness, tremors of the hands and arms, increased slow wave activity in the electroencephalogram, especially in the theta band (4-7 Hz) with depression of alpha (8-13 Hz) and beta (20 Hz and higher). In man, lapses of consciousness may occur at depths greater than 1000 ft (31 ATA) and, in animals, convulsions may occur. The HPNS becomes more severe with increasing depth and with fast rates of compression.

Earlier studies in animals and, to a limited extent, in man (9,10,11,14,19,20), have indicated that the HPNS may be controlled by addition of a mild narcotic, such as by use of an increased nitrogen partial pressure.

More recently, Bennett, Blenkarn, Roby, and Youngblood (6,7) examined the effects of exposing four men to depths of 720 ft and 1000 ft (23 ATA and 31 ATA) breathing oxygen-helium to which had been added 5.6 ATA nitrogen to give 25% nitrogen at 720 ft (23 ATA) and 18% at 1000 ft (31 ATA).

This nitrogen percentage was derived from the ability of inert gases to be absorbed by an egg phospholipid monolayer (8). The latter work indicated that surface tension rose for increased pressures of helium but fell for increased pressures of nitrogen. Coupled with the "critical volume" hypothesis for the mechanism of anesthesia (15) and the relationship of regular solution theory to anesthesia (5), it is inferred that anesthesia or narcosis as produced by the nitrogen component of compressed air (2) occurs when the volume of a hydrophobic region is caused to expand beyond the critical volume which hydrostatic pressure (or helium pressure, since the hydrostatic pressure effects are greater than its narcotic ability to increase the volume of the region) reverses to reduce anesthesia.

However, although the addition of 18% and 25% nitrogen to oxygen-helium was most effective in controlling the tremors and nausea of the HPNS, the nitrogen partial pressure was too great and signs and symptoms of nitrogen narcosis occurred.

Recent application of regular solution theory to anesthesia mechanisms (13) have concluded that the cohesive energy (δa) of the anesthetic "site" is equal to 4.3 $(cal/cm^3)^{1/2}$ and is in keeping with the Meyer-Overton hypothesis that the site of action of anesthesia is similar to olive oil.

Therefore, a model was developed (16) based on the Gibbs adsorption equation which would permit the prediction of the correct proportion of helium and nitrogen to be used for exposure of men to high pressures without either HPNS or narcosis.

The model required the following assumptions.

1. Anesthetic molecules act at nonspecific sites in a membrane with the same oil-water partition coefficients as olive oil.
2. The gases obey Henry's Law at all pressures.
3. Helium compresses membranes whereas nitrogen and oxygen expand it.
4. The condition for elimination of HPNS and narcosis is that the membrane volume should remain constant at the pressure desired.

As a result of these calculations, the correct ratio of nitrogen to helium would seem to be 1:10 (Fig. 1).

Therefore, to test this finding, men were exposed to 1000 ft (31 ATA) as previously reported (6,7), with the 18% nitrogen reduced in the present dive to some 10%.

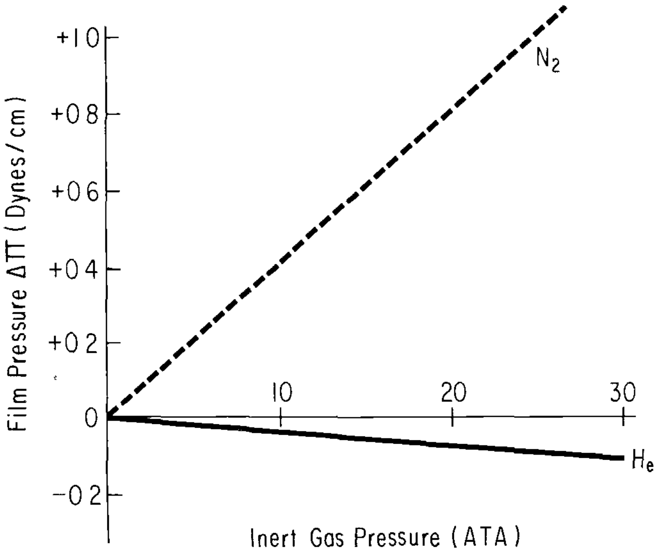

Fig. 1. Prediction of the penetration of nitrogen and helium into a monolayer of olive oil based on the Gibbs adsorption equation (16).

MATERIALS AND METHODS

Five young men took part in the investigation. Four of them were commercial divers and had just completed training, while the fifth was a medical practitioner and Research Fellow on the Duke Medical Center Staff, who was responsible for the health and safety of the divers while at pressure.

Dive Profile: The compression time of 33 min was the same as the previous study but the rates of compression were modified to provide increasingly slower compression with depth (Table I). Stages of 50 ft (2.5 ATA), 320 ft (10.7 ATA), and 700 ft (22 ATA) were inserted to allow decisions to be made on the condition of the subjects and whether or not to proceed with the rapid compression.

Compression started upon the chamber air by addition of 75% He/25% N_2 until 320 ft (10.7 ATA) and helium from 320 ft to 1000 ft. Oxygen was made up as required to give 0.5 ATA at 1000 ft (31 ATA).

During the decompression, which required 97 h using the modified Buhlmann table described previously (6), the oxygen partial pressure was increased from 850 ft (26.7 ATA) to 0.8 ATA until 60 ft when the subjects breathed air.

This gave at depth a nitrogen partial pressure of 3.2 ATA against a pressure of 31 ATA for the 1000 ft exposure.

The duration of exposure at 1000 ft (31 ATA) was 2 h.

Tests: A test battery was administered to three of the five subjects, while the fourth organized the tests and the fifth made a 40-min working dive in the wet chamber. The performance tests consisted of:

1. Arithmetic. Sheets of 40 multiplication sums (eg. 76 × 8 =) are presented for 1 min and the subjects required to answer as many as possible (3). The test quantifies short-term memory and intellectual performance.

2. Ball Bearing Test. In 1 min the subject has to pick up ball bearings one at a time with tweezers and place them in a tube of almost the same diameter. The score is the number of ball bearings in the tube (3) and is a test of sensitive psychomotor and visual coordination.

3. Purdue Peg Board. Pegs and washers must be assembled correctly on a board. Four parts to each unit must be assembled consisting of one peg, a flat washer, a thick washer (¼-in), and a further flat washer. Time for the test is 1 min and the score is the number of pieces assembled. It is a test of psychomotor performance.

4. Test Questionnaire. A check-list questionnaire (18) asks questions as to signs and symptoms of HPNS or narcosis and the occurrence of arthralgias as designated on a "stickman."

5. Tremor. Postural tremor is measured over 1 min with a Grass SPA transducer attached to the middle finger of a subject with a rubber band and the output

TABLE I. 1000 FT (31 ATA) PROFILE.

Depth (ft)	Rate of Travel ft/min	Travel Time min:s	Stop Time min:s	Compression Time min:s	Decompression Time h:min	Elapsed Time h:min	%O_2	Gas
0- 50	60	0:50		0:50			Make	He 75/25 N_2
50			:10	0:10			up	He 75/25 N_2
50- 320	60	4:30		5:30			O_2 as	He 75/25 N_2
320			1:00	6:30			reqd	He 75/25 N_2
320- 700	40	9:30		16:00			2.6-2.0	He
700			2:00	18:00			2.0	He
700-1000	20	15:		33:00			2.0-1.6	He
1000			120:00			2:30	1.6	He
1000- 975	2.5	10:			:10	2:40	2.5-2.6	He, O_2, N_2
975- 950	2.5	10:			:20	2:50	2.6-2.7	He, O_2, N_2
950- 925	2.5	10:			:30	3:00	2.7-2.8	He, O_2, N_2
925- 900	2.5	10:			:40	3:10	2.8-2.8	He, O_2, N_2
900- 875	2.5	10:			:50	3:20	2.8-2.9	He, O_2, N_2
875- 850	2.5	10:			1:00	3:30	2.9-3.0	He, O_2, N_2
850	60		15:00		1:15	3:45	3.0	He, O_2

displayed on a Grass electroencephalograph. The recordings are made with the subject sitting and the hand outstretched with the elbow resting on the raised knee.

6. Electroencephalogram. Electrodes are attached to the head at the vertex and left occipital areas with a ground behind the ear. The measurements are made on a Brush six-channel polygraph with on-line frequency analysis using a Nihon Kohden EEG Frequency Analyzer MAF 5 in the activity bands delta (2-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta 1 (13-20 Hz), and beta 2 (20-30 Hz). Measurements are made for 1 min with eyes open and 1 min with eyes shut (4).

The test battery was administered on the surface prior to compression and immediately on arrival at 1000 ft, after 1 h 40 mins prior to decompression, and again on the change from trimix to oxygen-helium at 850 ft (26.7 ATA). The subjects were well practised with the tests prior to the experiment.

Dive in the Water: While at 1000 ft (31 ATA), a diver entered the "wet" chamber wearing Spirotechnique electric underwear and dry suit with an Oceaneering International Inc Rathat helmet and Biomarine CCR-1000 breathing apparatus. Then 44 min were spent underwater working on the task of bolting two 8-in blind flanges to a short spool with 16 1¼-in studs, which required nuts on each end.

The water temperature was 56°F and the battery-supplied electric underwear was operated at 24 v.

RESULTS

Subjectively, on arrival at 1000 ft (31 ATA), the subjects felt very good with checks in the categories "good," "satisfied," and "happy." Three of the five indicated a feeling of "slight inefficiency" but there were no tremors noted nor nausea or dizziness. One of the five, the individual who made the dive underwater, reported sensations of mild euphoria although the feelings were in some way different from those experienced in compressed air narcosis. Much of the comment related to "visual disturbances" with the chamber lights appearing to shimmer and scintillate. Compression-induced arthralgia was mild. During the tests just prior to decompression, 1 h 40 min later, these effects had disappeared and the remarks "good," "satisfied," "happy," and "no difficulty" were predominant. During the decompression, on transfer to helium-oxygen at 850 ft (26.7 ATA), no undue signs or symptoms were noted.

The 0.8 ATA oxygen during the decompression resulted in early symptoms of oxygen toxicity as described in similar decompressions (6), including throat irritation, tightness, and mild sub-sternal soreness and numbness of fingers and toes. These improved steadily on the change to air at 60 ft (2.8 ATA), although full recovery did not occur until some time after return to the surface.

The performance tests indicated little or no deterioration (Fig. 2) during the time at 1000 ft (31 ATA) and the tremor transducer showed no increase in tremor (Fig. 3) as a result of the compression and exposure. The "wet" diver was able to perform his task effectively.

The electroencephalogram remained within normal limits throughout with no sign of the increased theta activity as a result of HPNS, or reduction in EEG activity in general, reported in other dives with helium-oxygen alone (4).

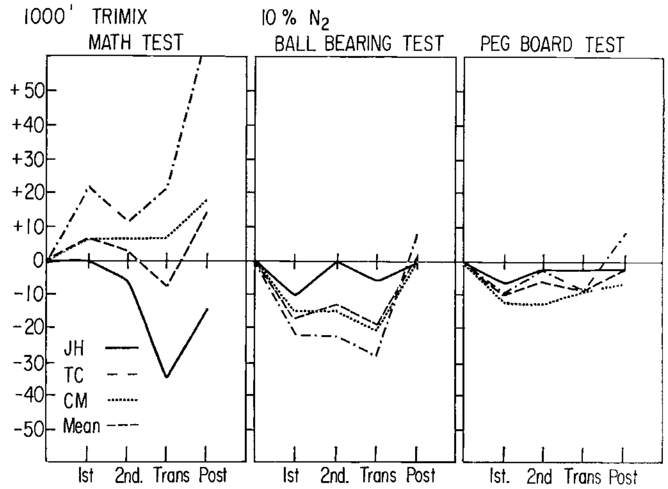

Fig. 2. Performance test results showing the percentage change from surface controls in the three subjects—JH, TC, and CM—in intellectual (math) and psychomotor (ball bearing and peg board) tests. The first test period is on arrival at 1000 ft and the second after 1 hr 40 min at 1000 ft. "Trans" refers to the results after transfer from the trimix to helium-oxygen at 850 ft.

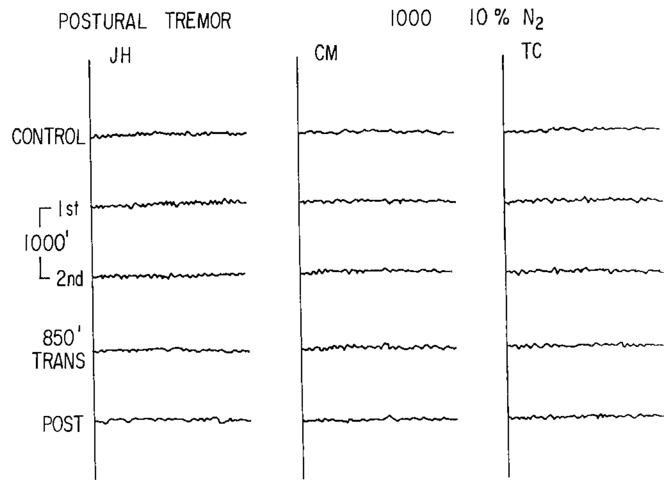

Fig. 3. Postural tremor results of the finger accelerometer during exposure to 1000 ft while breathing trimix with nitrogen at 10%.

DISCUSSION

Compression to 1000 ft in 33 min with the trimix breathing gas containing 10% nitrogen was effective in preventing the majority of HPNS signs and symptoms, except for mild lightheadiness reported by some of the divers on arrival, without incurring the moderate nitrogen narcosis reported in the previous experiments (6,7) with 5.6 ATA (18%) nitrogen at 1000 ft (31 ATA). For example, in the previous study, the Peg Board Test showed a mean decrement of 20% in the trimix with 18% nitrogen whereas, in the present study, the decrement was 10% or less. Similarly, the Ball Bearing Test showed some improvement from a value of about 25%, to less than 20% with the 10% nitrogen mixture.

The most important improvement, however, is reflected by the math test, which measures intellectual performance and relates to the presence of nitrogen narcosis. In the previous investigation with 18% nitrogen in the trimix, the decrement averaged 30% and was compatable with that expected by the presence of 5.6 ATA nitrogen. In the present study, there was no decrement in performance at the math test.

Thus, the present study shows that the 10% nitrogen is as effective as 18% nitrogen in preventing the signs and symptoms of HPNS, but without causing nitrogen narcosis. Further, it may be concluded that the predicted ratio of 10:1::He:N_2 works in practice. Future studies will be required to ascertain if this ratio, as predicted, also holds for higher pressures and deeper dives.

Again, extrapolation of these findings would predict that 5% nitrogen would not be effective in preventing HPNS and this would be reflected by increased decrements in psychomotor tests and the occurrence of tremor. It would be expected that the math test would be unaffected as there would be no nitrogen narcosis.

The use of nitrogen or other narcotic agents in this manner should allow divers to dive in the future both deeper and faster with increased efficiency and safety.

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