Central nervous system reactions during heliox and trimix dives to 51 ATA, DEEP EX 81.

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Værnes R, Hammerborg D, Ellertsen B, Peterson R, Tønjum S. Central nervous system reactions during heliox and trimix dives to 51 ATA, DEEP EX 81. Undersea Biomed Res 1983; 10(3):169–192.—Two groups of divers were compressed to 500 msw with heliox ($n = 3$) and trimix ($n = 3$). They were followed with repeated neuropsychological and neurological tests during compression, at stable intermediate depths, and at 500 msw. For the heliox group there was a marked increase in tremor and EEG slow waves and reduction in handgrip strength. For the trimix group the tremor increase did not occur, but the EEG changes were the same as in the heliox group. On motor tests only the trimix group showed impaired finger dexterity and manual dexterity. The same occurred for fine visuomotor coordination, but both groups had increased intentional tremor. On cognitive tests the same difference occurred. The trimix group was markedly impaired in reasoning and long-term memory, while only a mild impairment was found in the heliox group. Dizziness and other symptoms of high pressure nervous syndrome (HPNS) occurred in both groups. *Conclusion:* There were marked HPNS effects during compression for both groups. Only tremor was inhibited by the nitrogen. In addition, the trimix group was impaired because of nitrogen narcosis. These data indicated that 10% nitrogen did not inhibit HPNS effects during compression to 500 msw, but the considerable differences between subjects shows that susceptibility to compression must be an important area for future research.

trimix	nitrogen narcosis
heliox	EEG
HPNS	performance

Compression in a helium-oxygen atmosphere induces a number of behavioral disturbances in depths greater than 150 msw (16 ATA). Bennett (1) described these disturbances as nausea, vertigo, and tremor during rapid compression to 180 msw and attributed them to the helium ("helium tremor"). Brauer et al. (2) and Fructus et al. (3) have described a number of symptoms occurring during simulated dives between 300 and 365 msw. The symptoms have been termed the *high pressure nervous syndrome* (HPNS) and include tremor in the hands and arms, increased slow-wave activity (2–7 Hz) and depression of alpha waves (8–13 Hz) in the electroencephalogram (EEG), dizziness, nausea, and vomiting. The syndrome has been replicated by Bennett and Towse (4) during a dive to 457 msw, and it has also been demonstrated (5) that

lapses of consciousness may occur at depths greater than 300 msw (31 ATA). The symptoms of HPNS become more severe with increasing depth and during fast rates of compression.

The causes of the HPNS are not fully understood, but several studies, particularly in animals, have shown that HPNS can be counteracted by adding to the breathing gas a mild narcotic agent, such as an increased partial pressure of nitrogen (6–8). Bennett et al. (9) found that 25% and 18% nitrogen in a trimix breathing gas was effective in counteracting the HPNS symptoms, but the nitrogen caused symptoms of nitrogen narcosis. In 1975 they found that 10% nitrogen counteracted the HPNS and gave no narcosis according to their definitions of the two syndromes. These results were further confirmed in the Atlantis dive series (10, 11). There are, however, discrepancies between the results reported by Bennett et al. (10, 11) and the results from the CORAZ dives described by Rostain et al. (12). The results reported by Rostain et al. indicated that nitrogen only suppressed some of the HPNS symptoms, whereas other symptoms like the EEG changes were unaffected. It is, therefore, still an open question whether the HPNS is suppressed by nitrogen, as stated by Bennett et al.

In the present experiment we wanted to study effects of trimix on the central nervous system (CNS), using 10% nitrogen, as compared with heliox, during compression to 500 msw. In an earlier study (13) the same comparison was done during a dive to 300 msw (DEEP EX 80), and great care was taken in order to sample the same behavioral and neurophysiological variables.

METHOD

Subjects. Six males participated in the study. The mean age was 32 years (range = 4). Four subjects had participated in the previous dive (13) to 300 msw. Five subjects were commercial divers and one was an engineer.

Experimental design. The subjects were divided into two groups, both of which were compressed to 500 msw (51 ATA). One group ($n = 3$) breathed trimix with 10% nitrogen during the compression (trimix group), and the other group ($n = 3$) breathed heliox (heliox group). The planned and actual compression profiles are presented in Table 1. It can be seen that the holding period at 400 msw had to be extended for the trimix group because of severe symptoms (see RESULTS).

A battery of neuropsychological, neurophysiological, and performance tests and status questionnaires were used in the evaluation of signs and symptoms of HPNS and nitrogen narcosis.

Compression battery

The following 5 tests were administered repeatedly throughout compression (see Table 2). Each test block lasted about 6 min. Testing was repeated 13 times in the trimix group and 11 times in the heliox group during the compression period.

Electroencephalography (EEG). A 2-channel bipolar EEG recording was obtained from all subjects during compression. Three pairs of preamplifiers, which had been individually calibrated, were located in each chamber. All amplifiers were connected to a filter and amplifier system outside the chamber.

Beckman silver cup electrodes were located at C3, F3, C4, and F4, according to the 10–20 system, and bipolar EEG recording from both hemispheres were thus obtained (C3–F3 and C4–F4). The electrodes were secured to a cap consisting of elastic straps (after a model by

TABLE 1
TRIMIX AND HELIOX COMPRESSION SCHEDULES FOR DEEP EX 81

Depth, msw	Rate, msw/min	Planned Stop/ Travel Time, min	Actual Stop/ Travel Time, min	Elapsed Time, h:min
Trimix				
0–108	9.0	12	12	0:12
108	—	10	10	0:22
108–240	3.0	44	44	1:06
240	—	10	10	1:16
240–300	1.5	40	40	1:56
300	—	120	240	5:56
300–350	0.5	100	100	7:36
350	—	120	129	9:45
350–400	0.25	200	200	13:05
400	—	120	535	22:00
400–440	0.125	320	320	27:20
440	—	120	120	29:20
440–470	0.1	300	300	34:20
470	—	120	120	36:20
470–500	0.1	300	300	41:20
Heliox				
0–108	6.0	18	18	0:18
108–162	3.0	18	18	0:36
162–216	1.5	36	36	1:12
216	—	180	180	4:12
216–296	5.0	16	16	4:28
296–336	2.5	16	16	4:44
336–376	1.25	32	32	5:16
376	—	1174	1259	26:15
376–440	8.0	8	8	26:23
440–472	4.0	8	8	26:31
472–500	2.0	14	14	26:45

March, Duke University: personal communication, 1981). The EEG was sampled for periods of 5 min for each subject during compression, according to a fixed schedule.

The EEG signals were digitized on-line by an AD converter (Hewlett-Packard 2311, Hewlett-Packard Co., Palo Alto, CA) and stored on digital magnetic tape. These data were later analyzed with Fast Fourier Transform (FFT). The sampling rate chosen yielded power data per 0.5 Hz, and each block represented 2 s of EEG sampling. Each epoch was automatically inspected for possible noise, and samples holding more than 30% of the total power in the 0.5-to-1.0-Hz band and more than 30% in the 18-to-30-Hz band were excluded from further analysis. The power spectra were plotted on a digital plotter (Hewlett-Packard 9872A).

For back-up purpose, EEG was stored on an analog tape recorder (Tandberg, series 100, Tandberg, Norway).

Static Steadiness Test. Postural tremor in the hand was recorded with the Static Steadiness Test from the Kløve-Matthews motor steadiness battery (4605C, Lafayette Instrument Co.,

Lafayette, IN). Our definition of postural tremor was identical to the one given by Bachrach and Bennett (14): "[The tremor is observed] when the part (i.e., an arm) is voluntarily held still against the force of gravity." In order to test this type of tremor the subject was required to insert a stylus into 2 holes with diameters of 5 and 4 mm for 30 s each. The subject was not allowed to brace or rest his arm. Only the dominant hand was tested. The test equipment was connected to a data accumulation unit outside the chamber, where the total time of contacts were recorded for each trial.

Finger oscillation test. The Finger Tapping Test from the Halstead-Reitan Test battery was used. The subject was given 5 trials, each lasting for 15 s, and was required to use the index finger on his dominant hand throughout all trials.

Dynamometer test. Handgrip strength in kilograms was measured with a dynamometer (78010, Lafayette Instrument Co., Lafayette, IN).

Trails test. Visumotor speed and coordination was tested with the Trail Making Test (15). In this paper-and-pencil test the subject was asked to draw a line between circles containing letters and numbers, alternating between increasing numbers and the letters of the alphabet.

Performance tests

For testing diver performance, a battery of motor, visuomotor, and cognitive tests, in addition to a status questionnaire, was administered during intermission at 300, 350, and 440 msw for the trimix group, during the intermissions at 216 and 376 msw for the heliox group, and on reaching 500 msw for both groups. For motor and visuomotor testing the Performance Measurement System (PMS) was used. The PMS is a compact test system including a microcomputer that is programmed to control testing and log data [for further description of the PMS see Lambertsen et al. (16)].

Motor tests

Key insertion test. For evaluation of arthralgia, finger dexterity was tested. The subjects were required to insert the square and circular ends of a key insertion device alternately into

TABLE 2
TEST PROCEDURE DURING TRIMIX AND HELIOX COMPRESSION TO 500 MSW

Period	Diver 1	Diver 2	Diver 3
First 6-min period	EEG monitoring	Tremor, tapping, strength, visuomotor response	Registering the results for Diver 2
Second 6-min period	Registering the results for Diver 3	EEG monitoring	Tremor, tapping, strength, visuomotor response
Third 6-min period*	Tremor, tapping, strength, visuomotor response	Registering the results for Diver 1	EEG monitoring

*The cycle was repeated throughout the compression with about 1 min between periods.

round and square "asterisk" and "plus" cells on the PMS panel. This required rapid, controlled manipulation for 60 s, using the dominant hand.

Wrench and-cylinder test. A test was included to assess ability in manual dexterity, i.e., rapid, skillful manipulation of relatively large objects. The subject was required to use the wrench to alternately put the round and the square ends of a cylinder into alternating square "asterisk" and the round "plus" panel cells. Scores obtained were the number of responses completed in a 120-s period.

Stylus test. To test the ability of making rapid, repeated hand movements, a tapping test was used. The subject held a stylus firmly between the thumb and first two fingers of his dominant hand. The task was to tap with the stylus in a marked panel cell for 30 s as fast as possible.

Visuomotor tests

Visual reaction time test. The ability to respond to a discrete stimulus was assessed by means of a test of visual reaction time. The subject placed the stylus into the panel cell. This initiated a randomly varying delay of 1.00 to 3.00 s before the cell was illuminated. The subject withdrew the stylus from the cell as rapidly as possible upon seeing the light. There were 20 trials (600 s maximum), and the score was the mean reaction time of the completed trials.

Pursuit control test. The pursuit control test was used for evaluation of manual tracking, which is defined as follows: precise, continous adjustment of one or more axes of control to follow a target or to compensate for changes in a target's position, and speed or acceleration, or both. With his dominant hand the subject attempted to keep a dot as close as possible to a moving reference mark that moved with a constant speed diagonally on the screen on a monitor outside the chamber window. The subject's dominant hand controlled both vertical and horizontal movements of the dot. The error score was computed and expressed as the mean standard deviation of error scores for the two axes. During the 40 s of tracking, approximately 1300 samples of error scores on both axes were stored in computer memory.

Pursuit coordination test. A tracking test was included to assess coordination of both hands simultaneously. The subject was required to perform the same task as in the previous test, but now the dominant hand controlled the vertical axes and the nondominant hand the horizontal axes. Scoring was the same as for the pursuit control test.

Static control test. To test the intentional tremor in the dominant arm and hand a static control test was used. Our definition of intentional tremor was identical to the one by Bachrach and Bennett (14): Intentional tremor "is that seen as the part (i.e. an arm) is moved purposefully toward a goal." In order to test this type of tremor the subject was required to use his dominant hand to control a round knob without supporting his arm or hand. The task was to keep a tracking dot within a larger stationary target on the screen for 1 min. Scoring was the same as for the pursuit tests.

Cognitive tests

Arithmetic. The subjects were presented with a sheet of mathematical statements (additions) for 1 min. The statements were randomized: half were wrong and half were correct. The subjects were required to mark as many as possible as F (False) or C (Correct).

Reasoning. The subjects were presented with sheets of verbal assertions for 1 min (17); example: "A precedes B-BA." Half of the assertions were correct and half false, and they were randomized. The subjects were required to rate the statements as true or false.

Long-term memory. The subjects were given 30 s to memorize a list of 10 pairs of words (Where: bay; depth:50msw, etc.). The first word of each pair was presented 15 min later, and memory for the paired word was tested.

Perceptual speed. Forty pairs of numbers were presented on a sheet. The subjects were given 1 min to compare the numbers and mark pairs having different numbers.

Hidden patterns. The subjects were given 30 s to recognize in 25 different figures a figure presented at the top of a sheet. As many as possible were to be marked with plus or minus signs.

Visual digit span. Within each presentation of the visual digit span test a trial began as a series of one-digit numerals ordered randomly. They were shown on the top panel cell on the PMS at the rate of one numeral per second. The series length increased in one-digit steps. The subject was asked to reproduce the numerals using the stylus and the display-response panel.

Operational test. The operational test was a test of the subject's ability in rapid selection of the correct arithmetic operation for solving a problem without taking time to do the actual computation. A trial began by showing a number at the upper left on the panel, a number at the upper right, and a number in the center of the panel. The task was to indicate the required operation to go from the number at the upper left, using the number on the panel, to arrive at the number at the upper right. The score was the number of trials correct during a 120-s test session.

Test procedure

The test procedure was the same for both groups. Predive testing, including all tests, was done repeatedly during the six weeks before the dive started. This was done in order to familiarize the subjects with the test procedures to be used in the pressure chamber and to reduce learning effects. A minimum of five predive samples were collected. During compression the subjects rotated between the different test setups (Table 2). This rotation was repeated throughout the compression with about 1 min between periods of testing. The procedure was administered at fixed schedules throughout the compression.

RESULTS

Compression on trimix and heliox

Electroencephalogram (EEG). The FFT analysis of the EEG records revealed a marked increase in the power of slow waves (2–7 Hz) during compression to 500 msw for the trimix group. There was, however, considerable variance between subjects, and hemispheric differences were also found within subjects. The power spectrum was calculated in two different ways: both percentage of power in each frequency band and absolute power in each frequency band were calculated. The percentage of power measure showed a decrease in the alpha frequency band and an increase of slow waves. The absolute power measure gave a somewhat different picture. Power in the alpha band did not decrease in all subjects, but the increase of slow-wave activity was seen in all subjects.

For Trimix-Diver 1 there were some changes at 156 msw, particularly in the right hemisphere. There was an inhibition of the center frequency at 10.5 Hz and increase of slow-wave activity. During compression to 300 msw there were major changes in both hemispheres. On Day 2 at 435 msw some recovery was seen, but further compression to 500 msw caused great changes in the EEG (see Fig. 1). In analyzing the ratios of the theta and alpha activity (see Fig. 2) it was found that the major changes occurred around 300 msw. At that depth, and farther down to 500 msw, there was significant increase in relative theta activity and inhibition in the 8-to-

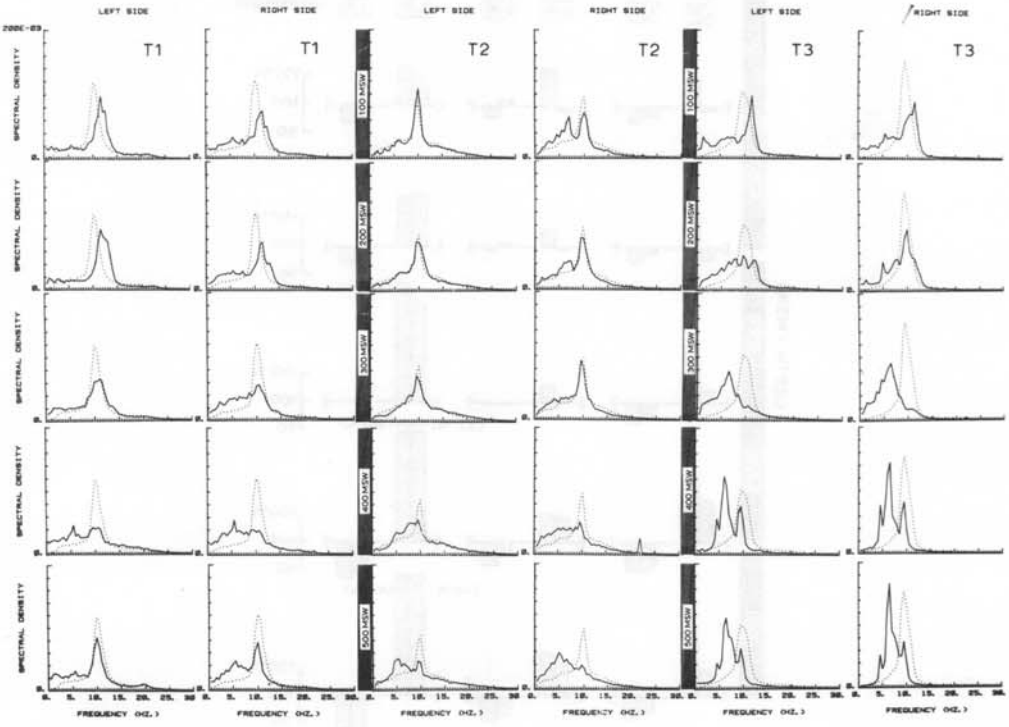

Fig. 1. Power spectrum EEG during trimix compression. *Stippled* curve is the mean predive power spectrum EEG.

13-Hz alpha frequency band. On reaching 500 msw there still were differences between the two hemispheres.

For Trimix-Diver 2 there were only minor changes before reaching 300 msw (see Fig. 1). After that there were major changes with a total inhibition of activity at the previous center frequency (10 Hz). Analysis of the ratios of the theta and alpha activity (see Fig. 2) revealed no consistent changes before 300 msw. At 400 and 500 msw, however, there was a 50% increase in theta activity and nearly a 50% decrease in relative alpha band power.

For Trimix-Diver 3 there were major changes in the EEG at 140 msw (see Fig. 1). At stable depth at 300 msw this diver had severe HPNS symptoms (see SUBJECTIVE SYMPTOMS). After some hours there was a recovery in symptomatology, and the EEG became normal to some extent. During compression to 500 msw there were again considerable changes in the power spectrum, with a change in the center frequency from 9 Hz at 1 ATA to a center frequency around 6.5 Hz. Analysis of the ratios of the theta and alpha activity showed a steady increase in theta activity for both hemispheres down to 400 msw and a marked inhibition of the alpha band frequency. At 500 msw there was some recovery, but still more than a 200% increase in theta and a 60% decrease in alpha band power (see Fig. 2).

The FFT analysis revealed a marked increase of power for slow waves during compression to 500 msw for the heliox group. As for the trimix group, there was considerable variance as well as hemispheric differences between the subjects.

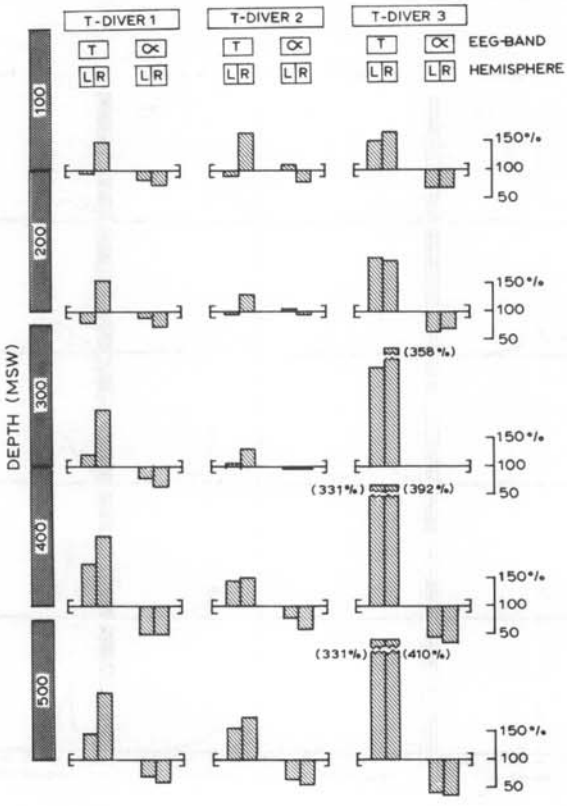

Fig. 2. Relative changes in theta (T) and alpha (α) band frequencies during trimix compression.

For Heliox-Diver 1 no major changes in the EEG were seen before reaching 300 msw (see Fig. 3). From that depth to 500 msw there was a marked increase in the EEG slow-wave activity. On reaching 500 msw there was some normalization. Analysis of the ratios for theta and alpha band activity showed minor changes down to 300 msw (see Fig. 4). Around 400 msw, however, there was a clear inhibition of the alpha band power (30%), but only the right hemisphere showed an increase in theta activity (30%). At 500 msw the theta activity was at predive control values, but the alpha band power was still reduced.

For Heliox Diver 2 there were no major changes before reaching 440 msw (see Fig. 3), but some slight changes were observed at 280 msw. On reaching 300 msw this diver experienced severe dizziness. From that depth and down to 500 msw the ratio of theta activity was markedly increased and a 40% reduction of the alpha band activity was seen (see Fig. 4). For Heliox-Diver 3 there was some increase in slow-wave activity on reaching 200 msw, but major changes did not occur before reaching 376 msw (see Fig. 3). From that depth, the center frequency at 10 Hz was totally inhibited. Analysis of the ratios of the theta and alpha bands showed no inhibition of relative alpha band power before reaching 376 msw (see Fig. 4). At 500 msw there was a 25%–30% alpha band inhibition, similar to the changes seen in the other two heliox divers.

The graphs presented in Fig. 5 show mean EEG power values for the two groups. As can be seen, predive values did not differ between the two groups. The mean EEG values at 100 msw showed marked differences between the groups. This was primarily due to the EEG changes in Trimix Diver 3 (see Fig. 1). Both groups, however, showed marked changes in

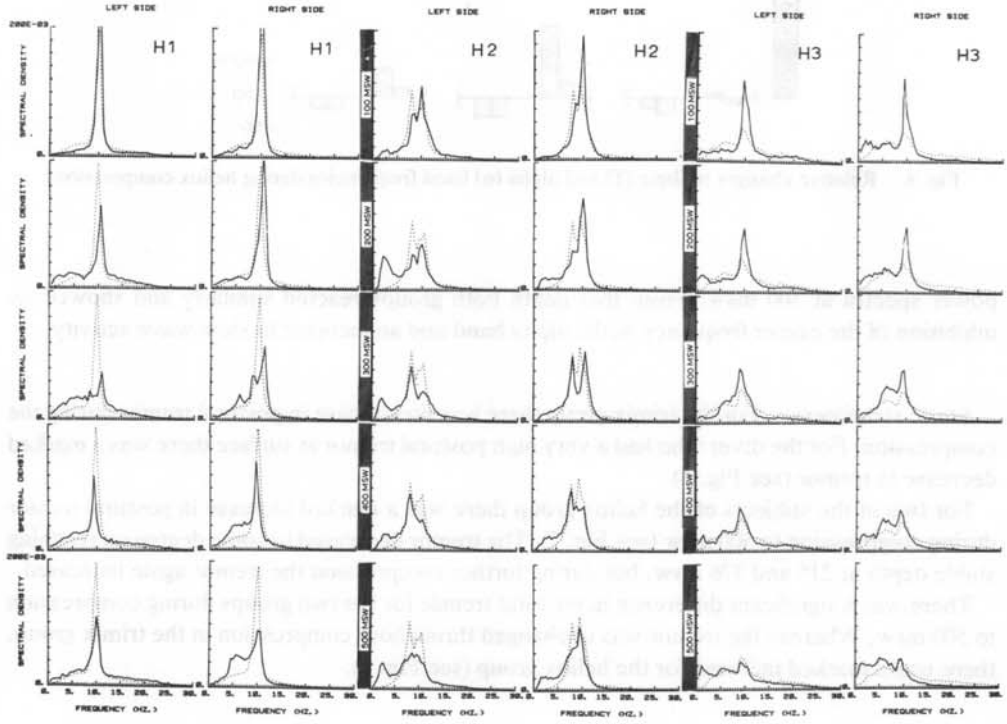

Fig. 3. Power spectrum EEG during heliox compression. Dotted *curve* is the mean predive power spectrum EEG.

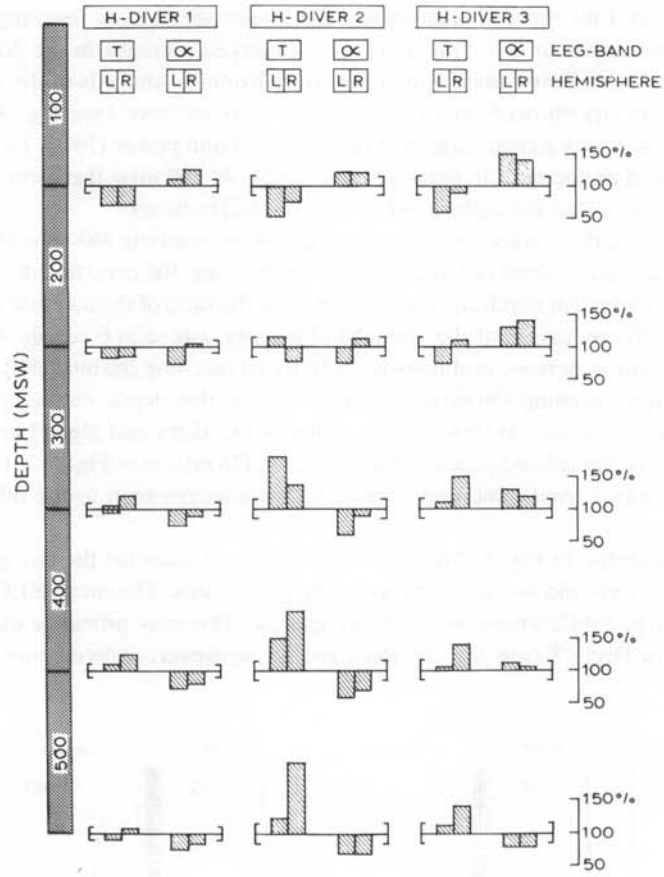

Fig. 4. Relative changes in theta (T) and alpha (α) band frequencies during heliox compression.

power spectra at 300 msw. From that depth both groups reacted similarly and showed an inhibition of the center frequency in the alpha band and an increase in slow-wave activity.

Static steadiness. For the trimix group there was no increase in postural tremor during the compression. For the diver who had a very high postural tremor at surface there was a marked decrease in tremor (see Fig. 6).

For two of the subjects of the heliox group there was a marked increase in postural tremor during compression to 500 msw (see Fig. 7). The tremor decreased to some degree on reaching stable depth at 215 and 376 msw, but during further compression the tremor again increased.

There was a significant difference in postural tremor for the two groups during compression to 500 msw. Whereas the tremor was unchanged throughout compression in the trimix group, there was a marked increase for the heliox group (see Fig. 8).

Finger oscillation. There was no significant change in finger tapping speed during compression on trimix and heliox.

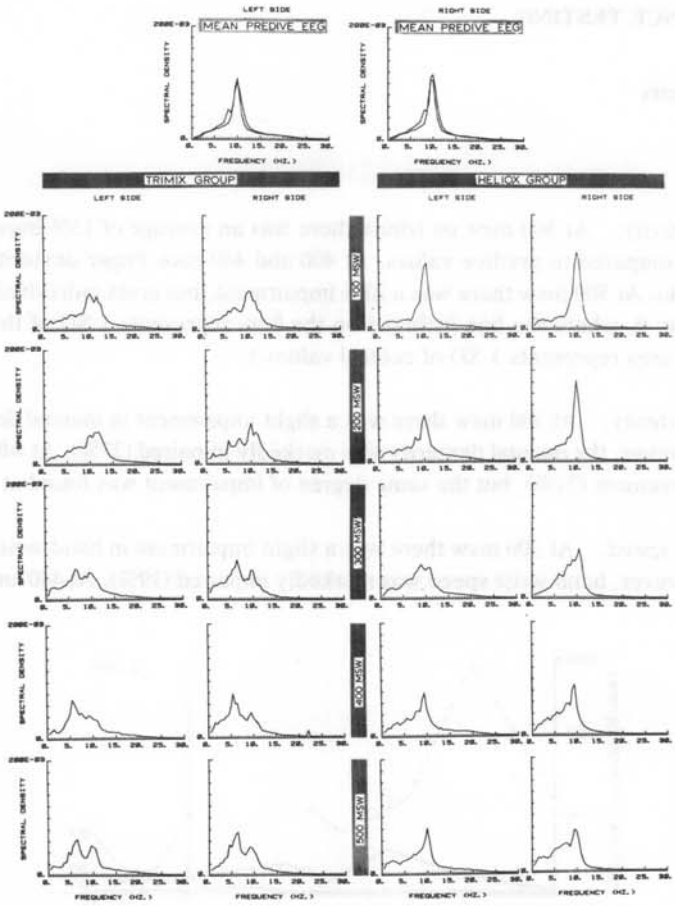

Fig. 5 Power spectrum EEG, mean value for 3 trimix divers and 3 heliox divers, respectively, during compression to 500 msw.

Dynamometer test. For the trimix group there was no reduction in handgrip strength during compression (see Fig. 6). In the heliox group there was a reduction in handgrip strength on reaching 100 msw. This impairment of about 15% lasted throughout the whole compression (see Fig. 7). Comparison of the two groups showed a marked difference in percentage of reduction in handgrip strength during compression to 500 msw. For the trimix group there seemed to be a slight impairment at stable depth (see Fig. 8).

Trails test. There was a slowdown of performance on the trails test (a visuomotor speed test) during compression on trimix. This impairment was pronounced when reaching 500 msw (see Fig. 6). In the heliox group there was a slowing of visuomotor speed performance during compression to about 400 msw for one diver. On reaching 500 msw on the second day, the performance was recorded to predive values (see Fig. 7).

Comparison of the two groups showed no marked difference in visuomotor speed during the compression. On reaching 500 msw, however, the trimix group was markedly impaired, whereas the heliox group performed at predive levels (see Fig. 8).

PERFORMANCE TESTING

Testing on trimix

Motor tests

Finger dexterity. At 300 msw on trimix there was an average of 13% impairment in finger dexterity as compared to predive values. At 400 and 440 msw finger dexterity was markedly impaired (19%). At 500 msw there was a 23% impairment, but great individual variations were found (see Fig. 9, where the line included on the bars represents 1 SD of the mean, and the crosshatched area represents 1 SD of control values.)

Manual dexterity. At 300 msw there was a slight impairment in manual dexterity (6%). At 400 msw, however, the manual dexterity was markedly impaired (27%). At 440 msw there was a slight improvement (21%), but the same degree of impairment was found at 500 msw.

Hand wrist speed. At 300 msw there was a slight impairment in hand-wrist speed (7%). At 400 msw, however, hand wrist speed was markedly impaired (19%). At 440 and 500 msw there

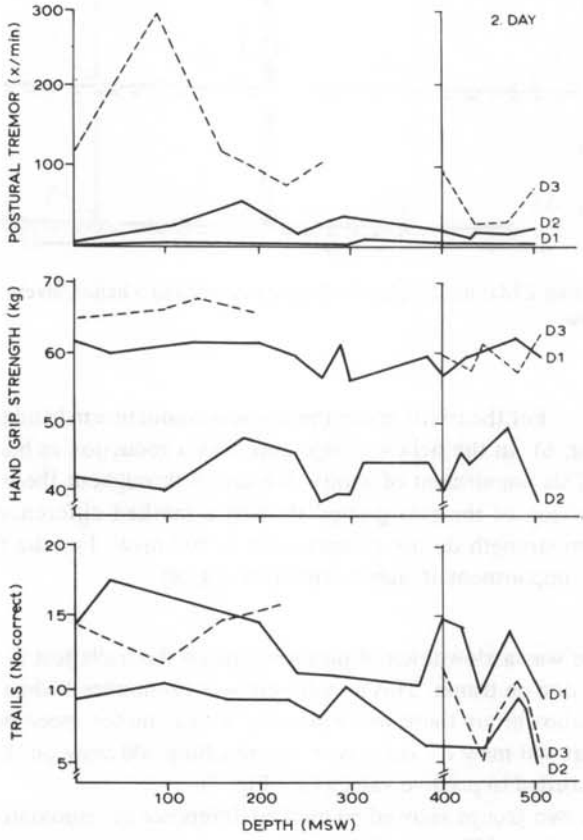

Fig. 6. Postural tremor, handgrip strength, and visuomotor speed (trails) during trimix compression.

was a slight improvement (14% and 12%, respectively), but the hand-wrist speed was 1 SD below predive values (see Fig. 9).

Visuomotor tests

Visual reaction. At 300 msw there was a mean impairment of 12% in visual reaction, but with great individual differences. At 400 msw the performance had returned to predive levels. At 440 and 500 msw, however, there was impairment of 12% and 14%, respectively (see Fig. 9).

Pursuit control. There was a marked impairment in manual tracking at 300 msw with 71% increase in error score. At 400 msw there was a slight improvement (53%). At 440 msw there was a marked improvement (18%), but after the compression to 500 msw manual tracking was again impaired, with 50% increase in error score (see Fig. 9).

Static control. At 300, 440, and 500 msw there were marked increases in error scores on the static control test, with 107%, 79%, and 86%, respectively; the results from 400 msw were missing for two subjects (see Fig. 9).

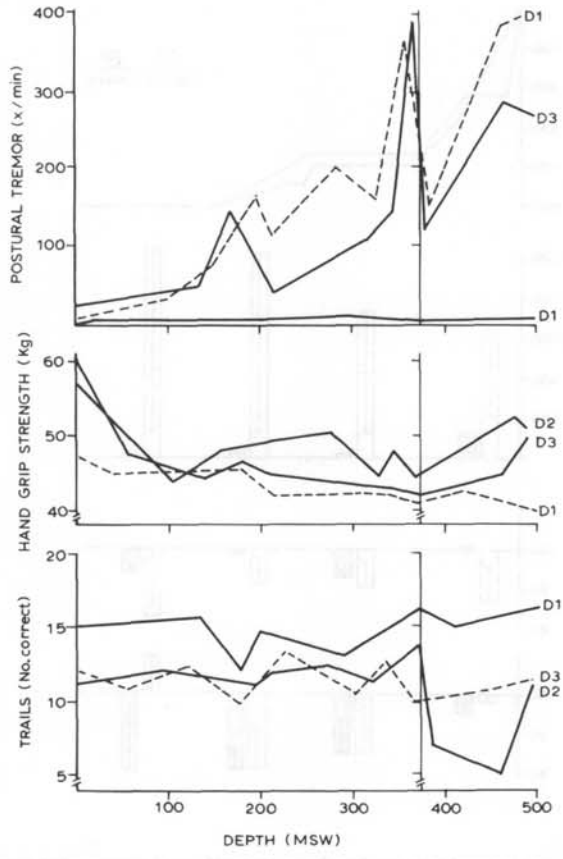

Fig. 7. Postural tremor, handgrip strength, and visuomotor speed during heliox compression.

Cognitive tests

Arithmetic. Arithmetic performance at 300 and 350 msw was at predive level. On reaching 440 msw there was a marked impairment (17%) that further worsened (23%) on reaching 500 msw (see Fig. 10).

Reasoning. Reasoning capacity showed a marked impairment (25%) at 300 msw; on reaching 350 msw there was a marked improvement (7%). At 440 msw, however, the impairment was 60%, and on reaching 500 msw there was still more than 40% impairment (see Fig. 10).

Hidden patterns. The ability to evaluate spatial patterns was minimally impaired. At 300 and 350 msw the subjects performed at predive levels, while there was a moderate impairment (11% and 10%) on reaching 440 and 500 msw (see Fig. 10).

Long-term memory. There was a marked and progressive impairment in long-term memory at depth. On reaching 300 and 350 msw the impairments were 42% and 48%. At 440 and 500 msw the impairment stayed below 50% (52% and 56%) (see Fig. 10).

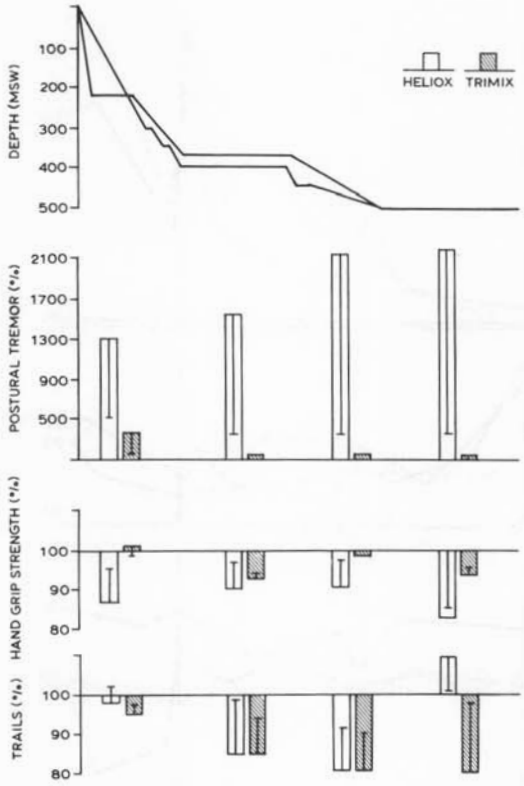

Fig. 8. Mean changes in postural tremor, handgrip strength, and visuomotor speed during trimix and helium compression.

Perceptual speed. On reaching 300 and 350 msw there was some impairment in perceptual speed (9% and 11%). At 440 msw, however, there was marked impairment (26%) with some improvement on reaching 500 msw (see Fig. 10).

Visual digit span. On reaching 300 msw there was a marked impairment in short-term memory (42%) as measured on the Performance Measurement System (PMS), which was used on this and the operational test. At 400 and 440 msw there was a progressive improvement (30% and 3%), but on reaching 500 msw there was a 23% impairment in short-term memory (see Fig. 10).

Operational test. At 300, 400, and 440 msw operational performance was within 1 SD of predive control. On reaching 500 msw, however, there was a 10% impairment (see Fig. 10).

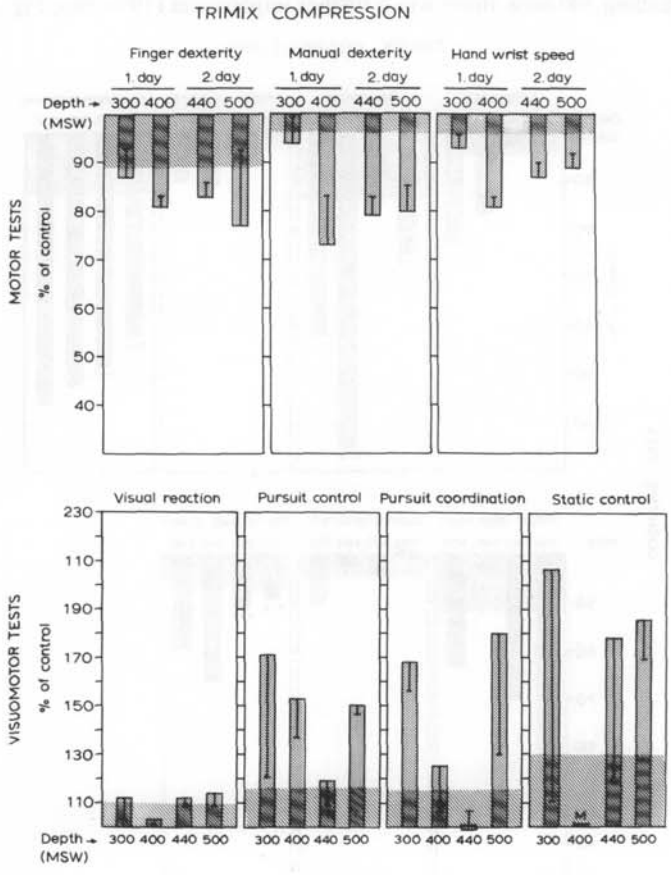

Fig. 9. Motor and visuomotor performance at stable depths during trimix compression. *Line* included on bars represents 1 SD of the mean; the *crosshatched area* represents 1 SD of control values. Results from 2 subjects at 400 msw missing from static control results.

Testing on heliox

Motor tests

Finger dexterity. At 216 and 376 msw there was no impairment in finger dexterity; there was a 10% impairment, however, on reaching 500 msw (see Fig. 11).

Manual dexterity. At 216 and 376 msw there was slight impairment in manual dexterity (12% and 15%). There was a further decrease (18%) at 500 msw (see Fig. 11).

Hand-wrist speed. At 216 msw there was a slight decrease in hand-wrist speed (4%). There was a further impairment (13%) on reaching 376 msw and more (18%) on reaching 500 msw (see Fig. 11).

Visuomotor tests

Visual reaction. At 216 and 376 msw there was some impairment on visual reaction (10% and 9%). On reaching 500 msw there was a further impairment (19%) (see Fig. 11).

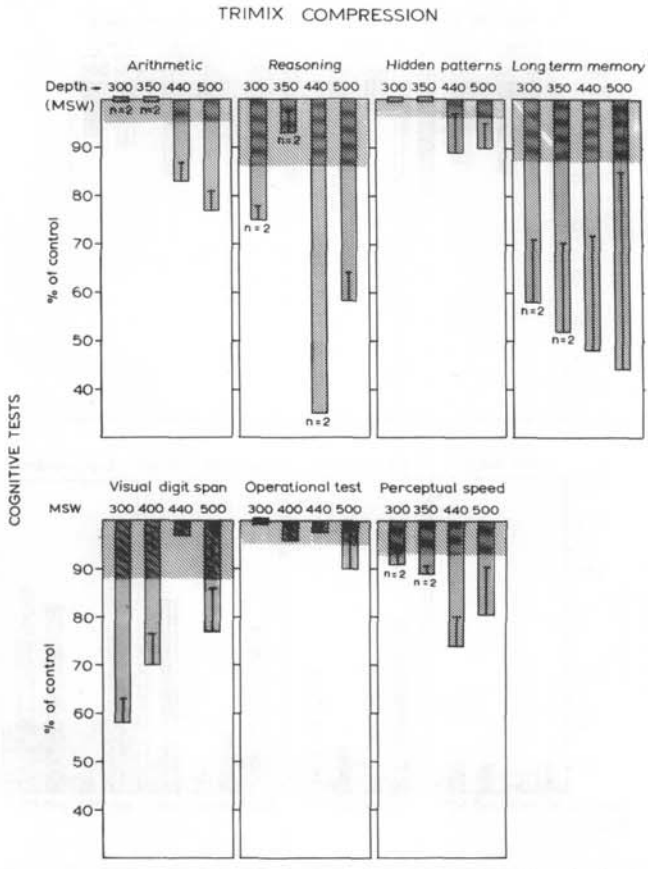

Fig. 10. Cognitive performance at stable depths during trimix compression. *Line* included on bars represents 1 SD of the mean; *crosshatched area* represents 1 SD of control values.

Pursuit control. At 216 msw there was a marked impairment in manual tracking with 28% increase in error score. This impairment continued at 376 and 500 msw with minor improvements (25% and 19%).

Pursuit coordination. The test showed the same degree of impairment as for pursuit control, with 23%, 35%, and 26% increase in error scores.

Static control. There was a marked increase in error scores on the static control test with a 130% increase at 216 msw, 82% at 376 msw, and 101% at 500 msw (see Fig. 11).

Cognitive tests

Arithmetic. In arithmetic performance there was a progressive impairment correlated with depth. While there was only a 10% impairment at 216 msw, the impairments were 17% and 22% at 376 and 500 msw, respectively (see Fig. 12).

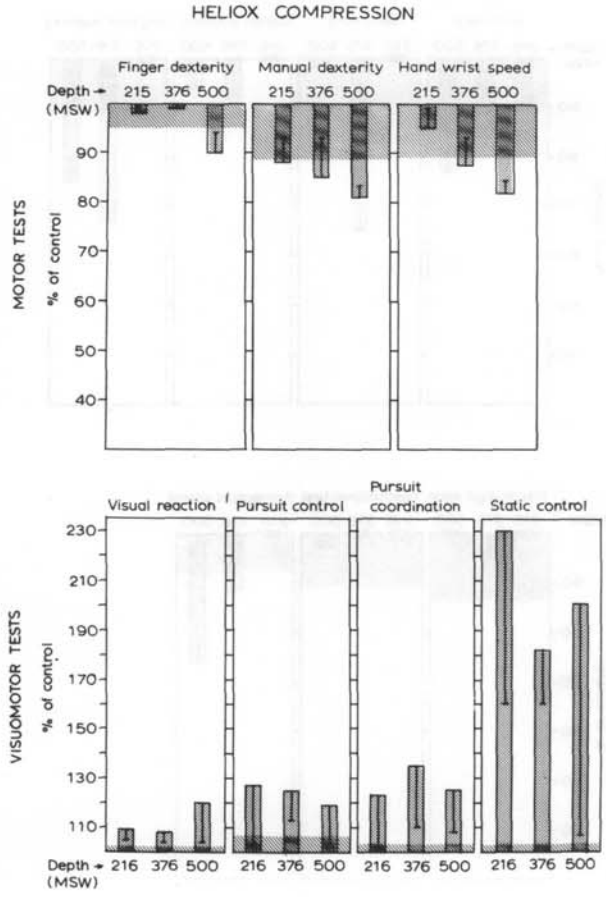

Fig. 11. Motor and visuomotor performance at stable depths during heliox compression. *Line* included on bars represents 1 SD of the mean; *crosshatched area* represents 1 SD of control values.

Reasoning. Reasoning capacity was at predive level at 216 msw. On reaching 376 msw there was a 35% impairment, but on reaching 500 msw this function returned to predive level (see Fig. 12).

Hidden patterns. There were slight impairments in evaluating spatial patterns. While it was at predive value on reaching 216 msw, there were 8% and 6% impairments at 376 and 500 msw (see Fig. 12).

Long-term memory. On reaching 216 msw, long-term memory functioned at predive level. At 376 msw, however, there was a 33% impairment, with some improvement (25%) on reaching 500 msw (see Fig. 12).

Perceptual speed. At 216 msw perceptual speed functioned at predive level. On reaching 376 and 500 msw there was a progressive impairment (12% and 26%) (see Fig. 12).

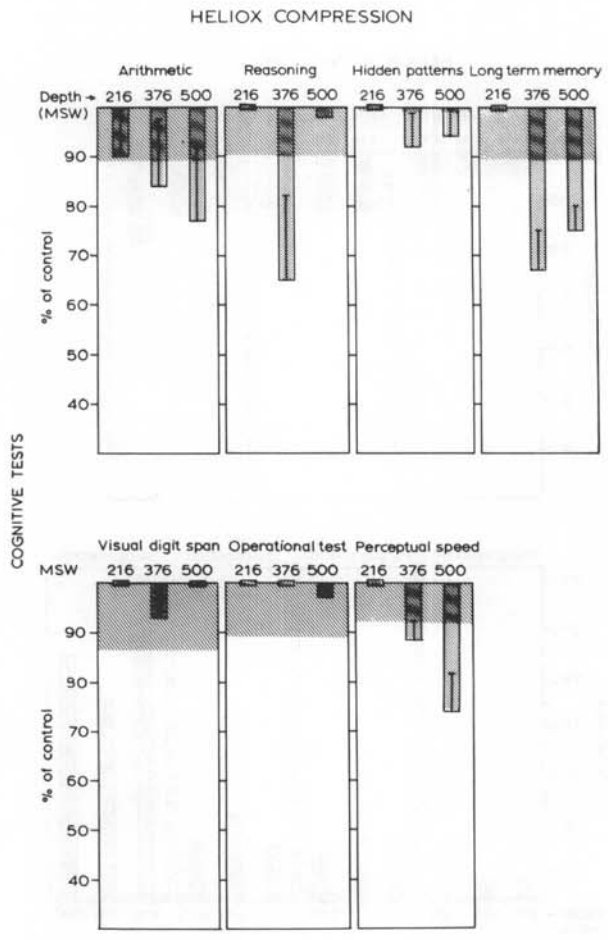

Fig. 12. Cognitive performance at stable depths during heliox compression. *Line* included on bars represents 1 SD of the mean; *crosshatched* area represents 1 SD of control values.

Visual digit span. There was a slight impairment in short-term memory on reaching 376 msw (7%), but short-term memory had returned to predive level by 500 msw (see Fig. 12).

Operational test. At 216, 376, and 500 msw operational performance was essentially unchanged from control values (see Fig. 12).

SUBJECTIVE SYMPTOMS

Subjective symptoms during trimix compression to 500 msw

On reaching 300 msw Trimix Diver 3 reported euphoria, concentration difficulties, poor appetite, vomiting attacks, visual disturbances, depression, and clumsiness. All divers reported euphoria of varying degree. Trimix Diver 1 reported knee pain, poor appetite, vomiting attacks, irritability, headache, perspiration, and shortness of breath (see Table 3).

At 350 msw Trimix Diver 3 was unable to fill in the questionnaire because of severe symptoms. Trimix Diver 2 did not report any symptoms, while Trimix Diver 1 experienced some dizziness (reported as spinning and unsteadiness), euphoria, numbness, knee pain, and vomiting attacks, and he felt very sleepy (see Table 3). Later referrals to dizziness refers to spinning and unsteadiness.

At 400 msw Trimix Diver 3 was again able to fill out the status questionnaire and then reported euphoria, concentration difficulties, poor appetite, dizziness, short-term memory impairment, visual disturbances, fatigue, and sleepiness. Again Trimix Diver 2 did not report any symptoms, while Trimix Diver 1 had about the same symptoms as at 350 msw. In addition he now reported sore eyes and lack of initiative, and he felt sleepy (see Table 3).

At 440 msw no divers reported any severe symptoms. Two divers reported reduced appetite and some dizziness, euphoria, nausea, and concentration difficulties (see Table 3). On reaching 500 msw two divers reported symptoms. For one diver these were euphoria and dizziness, and for the other, reduced appetite; both had concentration difficulties, whereas their dizziness and sleepiness were reduced.

Subjective symptoms during heliox compression to 500 msw

Two divers reported symptoms on reaching 216 msw: these were dizziness and perspiration. One diver reported concentration problems, short-term memory impairment, upset stomach, and tremor (see Table 4).

On reaching 376 msw the same two divers had more severe symptoms—dizziness, nausea, and perspiration. One diver reported concentration difficulties, poor appetite, dizziness, visual disturbances such as trouble focusing, and fatigue. After 4 h at 376 msw no divers reported severe symptoms, but all felt dizzy. After 18 h at 376 msw one diver reported severe tremor. Two reported much dizziness, perspiration, concentration difficulties, and poor appetite. At 500 msw only Heliox Diver 1 reported severe concentration difficulties, dizziness, and tremor. Heliox Diver 2 had reported slightly reduced appetite, dizziness, and perspiration, and he felt tired. Heliox Diver 3 reported a mild shoulder pain and minor concentration difficulties.

DISCUSSION

Compression to 500 msw in 41 h 20 min with a trimix breathing gas containing 10% nitrogen did not prevent signs and symptoms of HPNS. Power spectrum analysis of EEG showed

TABLE 3
SUBJECTIVE SYMPTOMS AT STABLE DEPTHS DURING TRIMIX COMPRESSION

Depth, m	Diver No.	Symptom Severity	Symptoms
300	1	Some	Dizziness, numbness, euphoria, concentration trouble, stomach trouble, memory disturbances
		Much	Knee pain, poor appetite, vomiting attacks, irritability, headache, perspiration, euphoria, shortness of breath
	2	Some	Numbness, tremor
		Much	Euphoria
	3	Some	Headache
		Much	Sleep disturbances, memory disturbances
		Severe	Euphoria, concentration trouble, poor appetite, visual disturbances, vomiting attacks, depression
350	1	Some	Dizziness, euphoria, numbness, knee pain, headache, sleepiness, vomiting attacks
		Much	Inactivity
	2		(No symptoms reported)
	3		(Was not able to fill out the questionnaire)
400	1	Some	Dizziness, nausea, euphoria, headache, fatigue, poor appetite, visual disturbances, stomach trouble
		Much	Sleepiness, sore eyes, inactivity
	2		(No symptoms reported)
	3	Severe	Euphoria, concentration trouble, poor appetite, visual disturbances, memory disturbances, fatigue, sleepiness
440	1	Some	Euphoria, concentration trouble, dizziness, sleepiness, stomach trouble, fatigue, visual disturbances
		Much	Poor appetite
	2		(No symptoms reported)
	3	Some	Inactivity, sleep disturbances, perspiration, memory disturbances, dizziness
		Much	Poor appetite
500	1	Some	Poor appetite, dizziness, sleepiness, inactivity
	2	Much	Concentration trouble
		Severe	Euphoria, dizziness
	3	Some	Dizziness, euphoria, memory disturbances, perspiration, sleep disturbances, clumsiness
		Much	Concentration trouble, inactivity, tremor
		Severe	Poor appetite

changes from base-line EEG recordings for all trimix divers. There was a slowdown of visuomotor speed during compression, and this impairment was pronounced on reaching 500 msw. The performance testing at intermediate depths showed pronounced impairment, particularly in cognitive functions. On the motor and visuomotor tests, manual dexterity and static control were impaired. Postural tremor and handgrip strength, however, were unaffected.

Compression to 500 msw in 26 h 45 min with a heliox breathing gas also caused signs and symptoms of HPNS. Power spectrum analysis of EEG showed increased theta activity and inhibition of activity in the alpha band during compression. There was significant increase in

TABLE 4
SUBJECTIVE SYMPTOMS AT STABLE DEPTHS DURING HELIOX COMPRESSION

Depth, m	Diver No.	Symptom Severity	Symptoms
216	1	Much	Concentration trouble, activation, memory disturbances, upset stomach, trembling
		Severe	Dizziness, perspiration
	2	Some	Clumsiness, headache, inactivity, concentration trouble, poor appetite, fatigue, tiredness, nausea, trembling
		Much	Dizziness, perspiration
	3	Some	Clumsiness, shoulder pain
376	1	Some	Perspiration, trembling
		Severe	Dizziness, activation
	2	Much	Concentration trouble, poor appetite, fatigue, tiredness, dizziness, visual disturbances
		Severe	Nausea, perspiration
	3	Some	Activation, shoulder pain
376*	1	Some	Activation, concentration trouble, perspiration, trembling
		Much	Dizziness
	2	Some	Poor appetite, upset stomach
		Much	Clumsiness, inactivity, dizziness, perspiration
	3	Some	Shoulder pain
		Much	Dizziness
376**	1	Some	Activation, visual disturbances, sleep disturbances
		Much	Dizziness, concentration trouble, perspiration
		Severe	Trembling
	2	Some	Clumsiness, tiredness
		Much	Poor appetite, dizziness, perspiration
	3	Some	Shoulder pain
500	1	Much	Activation, memory disturbances, visual disturbances
		Severe	Concentration trouble, dizziness, trembling
	2	Some	Clumsiness, inactivity, fatigue
		Much	Poor appetite, tiredness, dizziness, perspiration
	3	Some	Shoulder pain, concentration trouble

*For 4 h. **For 18 h.

postural tremor and reduction of handgrip strength. The performance tests showed impairment in reasoning and long-term memory and increased error score on the static control test. There was, however, some tendency of recovery in EEG and in visuomotor and cognitive tests during the late phase of heliox compression. Whereas poor performance on the static control test was caused by increased postural tremor in the heliox group, the poor performance on the same test in the trimix group clearly was caused by narcosis.

The subjective symptoms reported by the divers differed between and within groups. One diver in the trimix group experienced severe HPNS symptoms. The two others reported dizziness, stomach trouble, and euphoria. The most commonly reported symptoms in the heliox group were dizziness and tremor. One diver felt very dizzy, but the impaired diver in the trimix group was clearly more affected. One diver in each group was relatively symptom

free, one diver showed some symptoms, and one showed severe symptoms at times. For both groups the severe symptoms occurred below 300 msw with recovery after 3–4 h at stable depth.

Comparing the data from the trimix and heliox compression it was not possible to separate the groups with regard to EEG changes. On a group level, more pronounced changes were found in the trimix group, but this was due to very pronounced changes in only one of the trimix divers. In addition to the differences in tremor a different pattern was found for motor, visuomotor, and cognitive functions: the trimix group was more impaired at greater depths, while there was a tendency in the heliox group to recover on reaching 500 msw.

How do these data fit in with previous data from the DEEP EX dive to 300 msw (13), in which four of the same divers participated?

In the DEEP EX dive to 300 msw there were minor changes in the EEG during the trimix compression. This is in accordance with the 500-msw data, where the changes were minor before reaching 300 msw. In the 300-msw dive major changes in the EEG were observed in the heliox group. An important point to consider is that the trimix diver who was severely impaired in the present dive was the same diver who was sick in the 300-msw heliox dive. The change from heliox to trimix obviously did not help him.

On the other compression tests, the results were more or less similar. In both the 300- and 500-msw heliox compressions there were increased postural tremor and reduction of handgrip strength. In both trimix compressions the tremor as a symptom of HPNS was inhibited, while there was a marked narcotic effect on the different performance tests.

The results obtained are different from those reported by Bennett et al. (9): In the DEEP EX 81 dive to 500 msw it was the heliox that tended to give less symptoms during compression than the trimix mixture. Bennett et al. (9) reported opposite results. The different results obtained during the trimix dive to 300 msw (DEEP EX 80; see Ref. 13) with HPNS-free subjects and the CORAZ dive to the same depth (12) may be explained as a result of individual differences in sensitivity to high pressure.

The trimix mixture seemed to have beneficial effects on some clinical symptoms: it reduced the postural tremor and minor myoclonic jerks. This finding is in agreement with observations made by other investigators (6, 7, 18–20). Severe myoclonic jerks, however, seem to be one of the withdrawal symptoms when the nitrogen is eliminated (21). The trimix gas caused unwanted behavioral changes and increased drowsiness. In some cases it had been reported to accentuate the EEG changes (12). The dissociation between postural tremor and EEG changes have been reported earlier (22), and this dissociation suggests different CNS origins of these phenomena. Previous reports have also shown that, similar to high pressure nitrogen, narcotic agents as such reduce postural tremor (6, 20).

From the results obtained during DEEP EX 80 and DEEP EX 81 dives to 300 and 500 msw, it may be concluded that the HPNS observed with the trimix mixture is different from that observed with the heliox mixture. Therefore the high pressure nervous syndrome does not seem to be a homogenous entity. Ten percent nitrogen did not inhibit HPNS effects during compression to 500 msw and the nitrogen narcosis complicated the individual reaction pattern further. The considerable variance between subjects in both groups, however, further underscores the importance of research on individual susceptibility to compression, regardless of composition of the breathing gas.

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Værnes R, Hammerborg D, Ellertsen B, Peterson R, Tønjum S. Réactions du système nerveux central pendant des plongées à l'héliox et trimix jusqu'à 51 ATA, DEEP EX 81. Undersea Biomed

Res 1983; 10(3):169–192.—Deux groupes de plongeurs ont été comprimés jusqu'à une profondeur équivalente à 500 mètres d'eau salée (msw) avec des mélanges respiratoires d'héliox ($n = 3$) et trimix ($n = 3$). Les sujets furent soumis à des tests neuropsychologiques et neurologiques à maintes reprises durant la compression, à des profondeurs intermédiaires stables, et à 500 msw. Une augmentation marquée du tremblement et des ondes lentes de l'électroencéphalogramme (EEG) et une diminution de la force de préhension furent observées chez le groupe à l'héliox. Aucun effet sur le tremblement, mais des changements de l'EEG semblables à ceux du groupe à l'héliox furent obtenus chez le groupe trimix. Les tests de la motricité ont révélé une détérioration de la dextérité digitale et manuelle chez le groupe trimix seulement. Un effet similaire fut détecté dans la coordination visuomotrice fine, tandis que le tremblement intentionnel était augmenté dans les deux groupes. La même différence est apparue avec les tests cognitifs. Une détérioration marquée des facultés de raisonnement et de la mémoire à long terme fut trouvée dans le groupe trimix, comparativement à une légère déficience chez le groupe héliox. Des signes de vertige et d'autres symptômes du syndrome nerveux des hautes pressions (SNHP) étaient présents dans les deux groupes. *Conclusion:* Des effets marqués du SNHP furent observés durant la compression chez les deux groupes. Le tremblement seulement fut inhibé par l'azote. De plus, la narcose à l'azote contribue à la détérioration du groupe trimix. Ces résultats indiquent que la présence de 10% d'azote dans le mélange respiratoire ne réduit pas les effets du SNHP durant la compression à 500 msw, et les différences considérables entre les sujets révèlent que la susceptibilité à la compression doit constituer un sujet très important de recherches futures.

trimix
héliox
SNHP
narcose à l'azote
EEG
performance

REFERENCES

1. Bennett PB. Performance impairment in deep diving due to nitrogen, helium, neon, and oxygen. In: Lambertsen CJ, ed. Underwater physiology. Proceedings of the third symposium on underwater physiology. Baltimore: Williams and Wilkins, 1967:327–340.
2. Brauer RW, Dimov S, Fructus X, Gosset A, Naquet R. Syndrome neurologique et electrographique des hautes pressions. Rev Neurol 1969; 121:264–265.
3. Fructus X, Naquet R, Gosset A, Fructus P, Brauer RW. Le syndrome nerveux des hautes pressions. Mars Med 1969; 6:509–512.
4. Bennett PB, Towse EJ. The high pressure nervous syndrome during a simulated oxygen-helium dive to 1500 ft. Electroencephalogr Clin Neurophysiol 1971; 31:383–393.
5. Bennett PB, Roby J, Simon S, Youngblood D. Optimal use of nitrogen to suppress the high pressure nervous syndrome. Aviat Space Environ Med 1975; 46:37–40.
6. Lever MJ, Miller WD, Paton WDM, Smith EB. Pressure reversal of anesthesia. Nature 1971; 231:368–371.
7. Brauer RW, Goldman SM, Beaver RW, Sheehan ME. N_2, H_2, and N_2O antagonism of high pressure neurological syndrome in mice. Undersea Biomed Res 1974; 1:59–72.
8. Zaltsman GL. Hyperbaric epilepsy and narcosis. I.M. Sechenov Institute Evolutionary Physiology Biochemistry. Leningrad: Academy of Sciences USSR, 1968.
9. Bennett PB, Blenkarn GD, Roby J, Youngblood D. Suppression of the high pressure nervous syndrome in human deep dives by He-N_2-O_2. Undersea Biomed Res 1974; 1:221–237.
10. Bennett PB, Coggin R. Relationship between compression rate and trimix 10 in amelioration of HPNS in man. Undersea Biomed Res 1981; 8(Suppl):15.
11. Bennett PB, Coggin R, Roby J. Control of HPNS in humans during rapid compression with trimix to 650 m (2132 ft). Undersea Biomed Res 1981; 8:85–100.
12. Rostain JC, Gardette-Chauffour MC, Naquet R. HPNS during rapid compressions of men breathing He-O_2 and He-N_2-O_2 at 300 m and 180 m. Undersea Biomed Res 1980; 7:77–94.
13. Vaernes R, Bennett PB, Hammerborg D, Ellertsen B, Peterson RE, Tønjum S. Central nervous system reactions during heliox and trimix dives to 31 ATA. Undersea Biomed Res 1982; 9:1–14.
14. Bachrach AJ, Bennett PB. Tremor in diving. Aerosp Med 1973; 44:613–623.
15. Reitan RM. Validity of the Trail Making Test as an indicator of organic brain damage. Percept Mot Skills 1958; 8:271–276.
16. Lambertsen CJ, Gelfand R, Clark JM. Predictive studies IV. Work capability and physiological effects in He-O_2 excursions to pressures of 400, 800, 1200, and 1600 feet of sea water. Institute for Environmental Medicine, Philadelphia: University of Pennsylvania Medical Center, 1978.

17. Baddeley AD, DeFiguerdo JW, Hawkwell-Curtis JW, Williams AN. Nitrogen narcosis and underwater performance. Ergonomics 1968; 11:157–164.
18. Rostain JC, Charpy JP. Effects upon the EEG of psychometric performance during deep dives in helium-oxygen atmosphere. Electroencephalogr Clin Neurophysiol 1976; 40:571–584.
19. Brauer RW, Way RO, Jordan MR, Parrish DE. Experimental studies on the high pressure hyperexcitability syndrome in various mammalian species. In: Lambertsen CJ, ed. Underwater physiology. Proceedings of the fourth symposium on underwater physiology. New York: Academic Press, 1971:487–500.
20. Miller KW, Paton WDM, Smith RA, Smith EB. The pressure reversal of general anesthesia and the critical volume hypothesis. Mol Pharmacol 1973; 9:131–143.
21. Vaernes R, Hammerborg D, Ellertsen B, Peterson R, Tønjum S. Saturation at 51 ATA on heliox and trimix with gas-change from trimix to heliox. An analysis of recovery from HPNS and narcosis at depth. In: Elliott D, ed. Proceedings of European Undersea Biomedical Society. Lubeck/Travemunde: 1982:213–248.
22. Rostain JC, Naquet R. Human neurophysiological data obtained from two simulated heliox dives to a depth of 610 meters. In: Shilling CW, Beckett MW, eds. Underwater physiology VI. Proceedings of the sixth symposium on underwater physiology. Bethesda: Federation of American Societies for Experimental Biology, 1978:9–19.