Subjective symptoms and postural control during a disabled submarine simulation

A. CYMERMAN [1], A.J. YOUNG [1], T.J.R. FRANCIS [2], D.D. WRAY [2], D.T. DITZLER [1], D. STULZ [1], M. BOVILL [1], S.R. MUZA [1]

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Cymerman A, Young AJ, Francis, TJR, Wray DD, Ditzler DT, Stulz D, Bovill M, Muza SR, Subjective symptoms and postural control during a disabled submarine simulation. Undersea Hyperb Med 2002; 29(3): 204-215 - To simulate conditions aboard a disabled submarine, 7 submariners were confined for 5 d to a normobaric environment of 16.75% O_2, 2.5% CO_2, 4°C, and 85% relative humidity (RH). After 2 control days and 1 d of hypoxia, the remaining environmental conditions were imposed for the next 5 d, followed by 1 additional day of just hypoxia. Daily morning symptoms were assessed using the Environmental Symptoms Questionnaire (ESQ). Postural stability was determined on 4 occasions using a computerized balance system: control period, after 2.7 and 4.7 d of steady-state test conditions, and after 5.7 d (with return to normal ambient temp, RH, and CO_2). Three balance tests were performed: eyes open, eyes closed, and a dynamic test. Postural stability deteriorated after 2.7 d (87% eyes open, $P < 0.001$ and 26% eyes closed, $P = 0.01$). ESQ symptom subsets for acute mountain sickness, exertion, fatigue, alertness, and ear/nose/throat were not significantly different. Cold symptom subsets were increased after 3-7 d ($P < 0.001$); distress and muscle discomfort subsets after 7d ($P = 0.02$). Continued exposure to the combination of cold and hypoxia elicited subjective symptom changes and disturbances in postural stability that are statistically significant. These observations may be of practical importance when tasks aboard a disabled submarine involve balance and mobility.

hypoxia, hypercapnia, postural control, Environmental Symptoms Questionnaire

INTRODUCTION

The ambient environment of a submerged, disabled submarine can quickly become challenging to the physiological systems of a submariner. The physical environment can deteriorate with respect to temperature, humidity, carbon dioxide, oxygen, and relative darkness. The psychological environment can be one of severe confinement, inactivity, and fear. Submariners exposed to these environmental conditions must be able to perform complex tasks as part of their normal duties, as well as during crisis periods when emergency actions are required or imminent.

Exposures to the environmental and operational conditions of a disabled submarine that last from hours to several days can have specific detrimental effects on subjective symptoms and motor functions, depending on the range of hypercapnia. As early as 1945, naval researchers demonstrated reductions in physical performance and mental efficiency when submariners were exposed to 17% oxygen and 3% carbon dioxide for 50 h (1). In a classic study by Consolazio et al. (2), groups of 4 to 77 subjects were exposed to a series of 6 experiments in sealed chambers in which the carbon dioxide was not absorbed (reaching a range of 5.2 to 6.8 % while the oxygen level was either allowed to fall or maintained at above 19%). They performed a series of physiological and psychological tests to include body sway and balance and found that sway increased in all the experiments, "approaching statistical significance." Schaefer compared the effects of a 3 % carbon dioxide/15-17 % oxygen environment during actual submarine patrols lasting several months to laboratory and dockside studies of exposures to 3% carbon dioxide for 144 h on several physiological and psychomotor variables (3). More recently, Manzey and Lorenz observed that visual-motor tasks involving eye-hand coordination could be affected by carbon dioxide concentrations as low as 1.2% if subjects are chronically exposed for 26 d (4). In all of these studies, temperature was either uncontrolled and assumed normal (16-22°C) or controlled (27-32°C; RH 75%, or 16°C; RH 90% (2)).

Behavioral and psychomotor studies of shorter duration and higher carbon dioxide concentrations are sparse, as exposure to carbon dioxide levels >5% is not well tolerated. Henning et al. (5) demonstrated that breathing 6% carbon dioxide for several minutes resulted in significant changes in several behavioral tests, including body sway, after but not during the actual exposure period. Fothergill et al. (6) observed significant decrements in cognitive and psychomotor performance within minutes of exposure to approximately 7% but not 5.5% carbon dioxide.

There are few psychomotor performance studies of the long-term effects of mild hypoxia (16.75% oxygen) without the confounding effects imposed by unique temperature and carbon dioxide levels, probably because this level of hypoxia is not sufficiently severe. Many research studies suggest that there is little or no disruption of psychomotor performance below altitudes of 10,000 ft (>14.4% O_2). However, equivocal results have been obtained on several mental and psychomotor tests that may depend on factors such as the specific tasks being measured, the length of exposure time, and the degree of training (7,8). Because symptoms such as dizziness and disequilibria may be sensitive indicators of hypoxia, tests associated with these phenomena may provide functional correlates that reflect physiological mechanisms that are affected by a small change in ambient oxygen levels. Studies by Fraser et al. (9) and Nordahl et al. (10) found significant detrimental effects with exposures to 5,000 ft for 30 min and 8,000 ft for 14 min, respectively. Only anecdotal evidence is available on balance and postural stability during relatively longer exposures to moderate and high terrestrial altitudes (11). The effect of possible additive or synergistic combinations of the stress conditions cold, hypoxia, hypercapnia, and inactivity on postural control is unknown.

Effects of whole-body cold exposure and hypercapnia on postural stability are few. Magnusson et al. exposed feet to cold temperatures for several minutes and found that body-sway velocity increased significantly during hypothermia when compared to normothermic conditions (12,13). There are no publications on postural stability that have incorporated the conditions of mild hypoxia, hypercapnia, and total-body cold exposure for 5 d. Nevertheless, it is quite likely that some component(s) of the postural control system, whether it is the visual, vestibular, and proprioceptive feedback and/or reflexive and voluntary muscle responses, will be detrimentally affected.

In order to simulate the potential environmental conditions that may develop aboard a disabled 688-class submarine, ambient, steady-state conditions of hypoxia (16.75%), hypercapnia (2.5%), and cold (4ºC) were produced and maintained for 5 consecutive days in a hypobaric chamber at normal barometric pressure (760 mmHg) (DISSUB conditions). This experimental design allowed us to examine the effects of the combined stresses as well as the initial and final effects of hypoxic exposure per se on subjective symptomology and postural control. This research effort was part of a larger effort designed to accurately estimate the carbon dioxide production of survivors aboard a disable submarine by measuring metabolic rate and respiratory exchange parameters in healthy male submariners to conditions that simulated, as close as possible, those expected to prevail on a disabled, submerged submarine. This research was a collaborative effort between the Naval Submarine Medical Research Laboratory (Groton, CT) and the US Army Research Institute of Environmental Medicine (Natick, MA), involving staff and resources from both laboratories.

METHODS

Subjects: Eight military subjects who were submariners were recruited from the U.S. Naval Submarine Base, New London, CT. Physical exams and medical histories were considered normal. Each subject was fully informed of the nature of the study, gave written consent, and was made aware of his right to withdraw without prejudice at any time.

Experimental Design: This study used a repeated measures design and was conducted in 7 consecutive atmospheric phases as described below and in Table 1:

1. Pre-exposure control phase (48 h) with normal ambient conditions (21% oxygen, 0.04% carbon dioxide, 50% RH, and 22°C)
2. Acute hypoxia (16.75%) with other ambient conditions normal
3. Environmental transition to DISSUB conditions
4. Steady-state DISSUB phase
5. Environmental transition (5 h) back to 0.04% carbon dioxide, 50% RH, and 22°C
6. Continued hypoxia (16.75%) with other ambient conditions normal
7. Post-exposure control phase

Except for specific clothing to be worn for specific tests, submariners were issued US Navy regulation clothing: a pair of boots; socks; a pair of long johns; a pair of blue dungaree trousers; a pair of blue overalls; a woolen sweater; a heavy cotton jacket and a blue woolen hat. They were provided with a bunk with: a mattress; a pillow; pillowslip; two sheets; a blanket and a quilt. When not involved in testing, they remained resting in their bunks. There was constant, diffuse lighting in the chamber. Television, radios, videos, personnel stereos, smoking, washing, showering, newspapers, and telephone calls were not allowed.

Food intake was *ad libitum* on control days, but strictly regimented during DISSUB conditions with unrestricted access to water and caffeinated beverages. The menu was derived based on normal inventories carried aboard submarines but nutrient composition and energy content of the subject's diet was individually calculated (using the Harris Benedict Formula). An additional 10 % was added to account for the thermic effect of food.

Chamber Description: The study was conducted in the hypobaric chamber at the U.S. Army Research Institute of Environmental Medicine, Natick, MA. The chamber complex consists of a large study chamber (18.5 m^2) in which the subjects were housed and a small study chamber (10 m^2) in which most tests were conducted. A connecting, sealable airlock (6.0 m^2) served as an entrance and exit for study personnel and as a sanitary facility for the subjects. Normoxic, normocapnic conditions were achieved by circulating normal, air-conditioned, ambient air through the chambers. When hypoxic, hypercapnic, cold, and humid conditions were required, the fractional contents of N_2 and CO_2 at normobaric pressures were adjusted with

TABLE 1 DISSUB Environmental Conditions and Testing Schedule

Phase	Hour	Environmental Conditions and Test Performed	Duration Hypoxia*	Duration DISSUB**
Pre-exposure Control (1a,b,c)	1600	ESQ	A	
	0600	ESQ	B	
	1400	Postural Instability		
	0600	ESQ	C	
	1400	Postural Instability		A
Acute Hypoxia (2)	0215-0530	Ramp down to 16.75% O_2		
	0600	ESQ	1	
Transition to DISSUB (3)	1500	24-h Ramp to 2.5% CO_2, 4ºC, 85% RH		
	0600	ESQ	24	
	1500	Start of Steady-State DISSUB Conditions		
Steady-State DISSUB Conditions (4)	0600	ESQ	48	
	1500			
	0600	ESQ	72	
	1500			
	0600	ESQ	96	
	0930	Postural Instability		66
	1500			
	0600	ESQ	120	
	1500			
	0600	ESQ	144	
	0900	Postural Instability		114
End DISSUB Conditions (5)	1500	End 2.5% CO_2, 4ºC, 85% RH		
Continued Hypoxia (6)	0600	ESQ	168	
	0800	Postural Instability		135
	1300	End 16.75% O_2		
Post-exposure Control (7)	0600	ESQ	Post	B
	1245	Postural Instability		

* Letters and numbers indicate elapsed exposure hours when ESQ was administered.

** Letters and numbers indicate when balance instability tests were performed. Numbers also indicate elapsed hours from the beginning of steady-state DISSUB conditions. The last balance measurement (1400 h) was used for Control A values in Table 3.

appropriate mixing systems (14). Required temperature and humidity were controlled by standard hypobaric chamber air conditioning and humidity systems.

Subjective Symptoms: Subjective symptoms to environmental stressors were assessed using the ESQ. The questionnaire was developed to determine the effects of exposure to environmental extremes such as heat, cold, and high terrestrial elevation (15,16,17,18). Questionnaire weighted scores (factor scores) have been developed and validated for Acute Mountain Sickness-cerebral, Acute Mountain Sickness-respiratory, ears-nose-throat, cold stress, distress, alertness, exertion, muscle discomfort, and fatigue. Using these factor scores, the ESQ is ideal for the measurement of subjective multistress-induced symptoms. The ESQ was administered every morning at approximately 0600 h.

Postural Instability: **S**ubjects were screened for any significant lower extremity injury or equilibrium dysfunction. Postural instability was assessed using a computer-controlled unstable platform balance system (K.A.T. 2000, O.E.M. Medical, Carlsbad, CA 92008). The balance consisted of a 60-cm circular platform (15 cm above the floor) whose ease of tilting was controlled by varying the pressure in a pneumatic bladder situated around a central pivot point. The bladder pressure was normalized for each subject by adjusting the degree of balance instability for ambient pressure, subject weight, and balancing ability. It was not changed throughout the study. A balance index score was automatically derived from a tilt sensor that measured the absolute distance between the tilted position and a reference point. These vectors were summed every 0.1 sec. The balance score was thus inversely proportional to balancing skill. A handrail was situated about 45° to the left and right of the subject's midline.

Subjects performed three 30-s balance tests that they had practiced two times previously. Each test was performed while barefooted (or in socks) with arms akimbo and feet approximately 25 cm apart, equidistant from a central pivot point. Subjects received computer feedback by way of a moving X that indicated the position of the platform. They were instructed to keep the platform as level as possible by keeping the X in the center of a bulls-eye (eyes-open static test). The second test was the same except that the subject's eyes were closed (eyes-closed static test). During the third test (dynamic test), subjects stood as before but were required to move the platform in a circular pattern so as to "chase" a computer-controlled moving object. Tests were performed in the same order for all subjects. Subjects were tested a total of 5 times: once prior to entering the chamber (phase 1, A), after 66 and 114 h of exposure to DISSUB conditions (phase 4), after returning to normal environmental conditions except for continued exposure to 16.76% O_2, and after returning to completely normal conditions (phase 7, B) (See Table 1).

Core Body Temperature: Core body temperatures were recorded each minute throughout the exposure using an FDA-approved temperature sensing "pill" (CorTemp™, Human Technologies, INC., Palmetto, FL) which transmitted a 260 kHz signal to a body core temperature monitor and data logger (BCTM 3, Personal Electronic Devices, Inc., Wellesley, MA). To ensure volunteer safety, real-time temperatures were documented manually using the digital display on the BCTM every two hours.

Statistics: Data were analyzed using repeated-measures ANOVA followed by a Tukey *post-hoc* test for critical differences. A statistical probability value of $P \leq 0.05$ was accepted as significant. Values are presented as mean ± standard deviation (sd).

RESULTS

Chamber Conditions: Pre-DISSUB chamber conditions were set for thermal comfort at 22.2 ± 1.1°C and 50.4 ± 5.2% RH. Environmental conditions for the DISSUB phase were 4.5 ± 0.6°C, 80.5 ± 5.3 RH, 16.73 ± 0.06% O_2, and 2.49 ± 0.04% CO_2.

Subjects: Of the 8 military subjects that were initially recruited from the U.S. Naval Base, New London, CT, 1 withdrew voluntarily for personal reasons. The subjects' initial physical characteristics were 31.8 ± 6.1 yrs old, 174.4 ± 4.1 cm tall, and 82.9 ± 9.8 kg.

Caloric Intake and Core Body Temperature: Energy intake was 1976 ± 173 kilocalories from phases 2- 5 (see Table 1). Although normal diurnal rhythms were noted throughout the exposure period, with peaks between 1600-2000 h each day with the nadirs at ~ 0400 h, there were no differences in core body temperature measured during the cold exposure and control periods. Thus, despite the visual observation of shivering, core temperatures remained normal. The mean pill temperature throughout the testing period was 36.82 ± 0.43°C.

ESQ Results: The 68-item ESQ is factored into nine different symptom complexes or factor scores. Mean scores and standard deviations for seven of these symptom complexes that showed no significant differences at any time during DISSUB conditions are shown in Table 2. Questionnaires administered during control periods A and B were not used in the statistical calculations and are not included in the Table 2. The symptom course for 2 scores, cold stress and muscle discomfort, were statistically significant and are shown in Figure 1. The cold stress factor scores began to increase after 24 h (P = 0.06), continued to increase at 48 h (P = 0.001), and declined thereafter (P = 0.123). Muscle discomfort score increased steadily reaching a maximum at 144 h (P = 0.023), after which the score declined.

TABLE 2 Environmental Symptoms Questionnaire Responses

Symptom Complex	Time Course of Environmental Conditions									
	1c	2	3	4	4	4	4	4-5	6	7
	Control C	Hypoxia	SS Transition	SS 15h	SS 39h	SS 63h	SS 87h	SS 111h SS End	Hypoxia	Post Exposure
		1h	24h	48h	72h	96h	120h	144h	168h	
ESQ-C	0.1±0.1	0.0±0.1	0.1±0.1	0.4±0.9	0.2±0.1	0.28±0.2	0.1±0.1	0.4±0.7	0.1± 0.1	0.2±0.2
ESQ-R	0.2±0.2	0.2±0.2	0.1±0.1	0.3±0.2	0.2±0.2	0.2±0.2	0.2±0.2	0.3±0.3	0.2±0.2	0.2±0.2
ENT	0.3±0.4	0.1±0.1	0.1±0.2	0.2±0.2	0.4±0.4	0.3±0.4	0.3±0.5	0.4±0.6	0.5± 0.6	0.5±0.6
Distress	0.2±0.2	0.1±0.1	0.1±0.1	0.2±0.2	0.2±0.2	0.3±0.4	0.2±0.3	0.5±0.5*	0.2±0.3	0.2±0.3
Alertness	1.9±0.9	2.0±0.4	1.7±0.8	1.8±0.9	1.9±0.5	1.9±0.5	1.8±0.5	1.9±0.6	2.2±0.5	1.9±0.4
Exertion	0.0±0.1	0.1±0.1	0.1±0.2	0.2±0.4	0.2±0.3	0.2±0.3	0.2±0.3	0.3±0.5	0.1±0.2	0.1±0.1
Fatigue	0.4±0.3	0.2±0.2	0.2±0.2	0.3±0.4	0.3±0.3	0.4±0.6	0.3±0.4	0.6±0.8	0.5±0.8	0.3±0.6

Data represent the mean ± s.d. from 7 subjects. See Table 1 for environmental conditions. SS indicates transition to or achievement of steady-state DISSUB conditions. * P < 0.02.

FIGURE 1

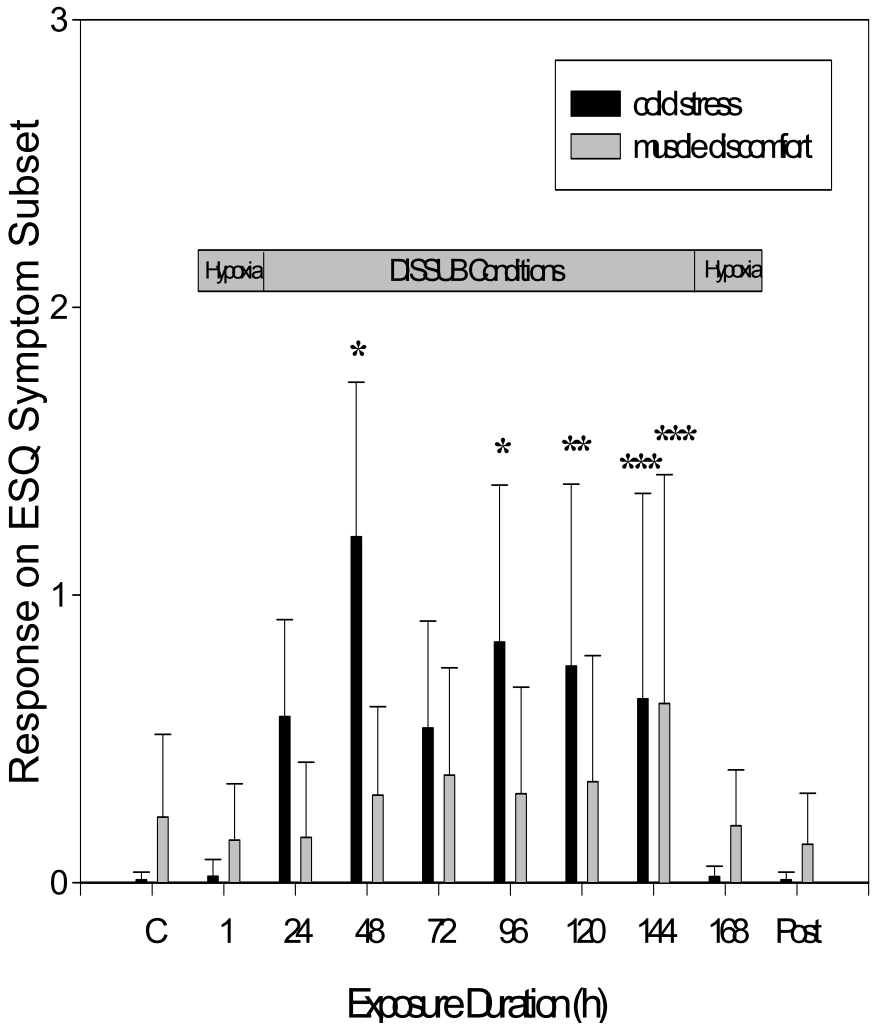

Fig. 1. Time course for the development of symptoms of cold stress and muscle discomfort as reflected by the specific ESQ symptom subset. Environmental conditions are described in Table 1. * $P < 0.001$, ** $P < 0.003$, *** $P < 0.03$ in *post hoc* comparisons with the post exposure period.

Postural Balance: An increase in numerical values in Table 3 represents a decrease in postural control (an increase is indicative of a greater postural instability). With the eyes-open test, there is an increase in postural instability after 66 h of steady-state DISSUB conditions compared to the post exposure Control B period ($P<0.001$). This increase declined after 114 h ($P=0.04$) and returned after DISSUB conditions were discontinued, with the exception of the 16.75% oxygen condition. A similar change occurred in the eyes-closed test except that the increase in instability after 135 h did not occur. Significant differences were also found in the ratio of eyes closed/eyes open as noted in the table. There were no differences in the results of the dynamic test during any of the testing times. The power of the dynamic test was only 0.14 with $\alpha = 0.05$ (a value of 0.80 is traditionally desirable to achieve an 80% chance of detecting a difference with 95% confidence). In addition, there were no differences in either the left-to-right or anterior-posterior postural control indices on any of the three balance modes during any of the test times.

TABLE 3 Postural Instability Responses during the Disabled Submarine Protocol

Test	Control A	SS66	SS114	H135	Control B
Eyes Open	30.9±9.1	39.1±12.7*	27.2±10.3*	35.9±14.2*	20.8±9.1*
Eyes Closed	187.0±46.3	226.4±46.1‡	183.2±45.5‡	178.3±36.1‡	179.6±50.7‡
Ratio EC/EO	6.4±2.04^{+}	6.04±1.14^{+}	7.2±1.8	5.5±1.9 $^{+}$	9.6±3.0 $^{+}$
Dynamic	88.3±20.1	106.4±48.6	74.9±17.5	102.3±24.8	86.5±35.9

SS 66 = 66 h of exposure to DISSUB steady state conditions (16.75% oxygen, 2.5% carbon dioxide, 85% rel. hum., 4°C). SS114 = 114 h and H135 = 135 continuous hours of 16.75% oxygen but a return to normal temperature, carbon dioxide level and RH.
* Eyes Open main effects repeated measures ANOVA, P < 0.001 (post hoc Tukey: Control B vs. SS66, P<0.001; Control B vs. H135, P=0.006; SS66 vs SS114, P=0.04).
‡ Eyes Closed main effect repeated measures ANOVA, P<0.011 (post hoc Tukey: Control B vs. SS66, P=0.022; SS66 vs. H135, P=0.018; SS66 vs. SS114, P=0.038).
$^{+}$ main effect repeated measures ANOVA, P =0.003 (post hoc Tukey: Control B vs. Control A, P=0.024: Control B vs. SS66, P=0.011; Control B vs. SS135, P=0.003)
N= 7 subjects; values are means ±sd.

There were no correlations between subjective symptomology (cold stress or muscle discomfort) and postural control measurements when the highest symptom scores were used with postural measurements closest in time to the ESQ. The probability closest to significance (P = 0.08) was obtained after 15 h of DISSUB conditions, and the balance measurements taken after 66 h.

DISCUSSION

Confinement, cold, high carbon dioxide levels, low oxygen levels, and high humidity can all combine to produce physiological dysfunction in otherwise normal individuals. When these environmental stressors occur in unison aboard a disabled submarine, there is a finite time in which submariners can be expected to perform sophisticated cognitive and dexterous procedures. Exposures to high carbon dioxide, low oxygen, and cold have been studied individually and extensively over the years, but relatively few studies have looked at the combination of the three. It was expected that the combination could seriously hamper performance of crucial tasks and perhaps endanger individual and crew lives. It was hypothesized that the subjective effect of the combination of stressors would become evident on the self-administered ESQ in both severity and temporal (exposure duration) aspects. In addition, it was hypothesized that the combination of stresses would also affect balance control.

ESQ scores showed significant increases in three areas: total score (data not shown), cold stress, and muscle discomfort. As expected, the cold stress symptom subset increased after 24 h, reached a peak after a further 24 h, and stabilized thereafter. Symptoms disappeared immediately after termination of DISSUB and hypoxic conditions. Muscle discomfort scores throughout the study were higher than usually observed in past chamber studies. It is possible that the confinement and inability to perform normal physical activities accounted for the higher muscle discomfort score baseline. Muscle discomfort scores were slightly higher during the DISSUB conditions, reached a significant peak 144 h after initiation of environmental conditions, and returned to original baseline levels after cessation of environmental conditions. It is likely that cold exposure (and possibly hypercapnia) exacerbated muscle discomfort as symptoms returned to pre-exposure levels 24 h after return to normocapnia and normal ambient temperature.

There were no indications that the submariners exhibited any symptoms of Acute Mountain Sickness, either the cerebral or respiratory variety, with several days' exposure to 16.75% oxygen at ambient pressure. Exposure to only hypoxic conditions 24 h prior to initiation of the transition to DISSUB conditions resulted in no significant ESQ symptom scores. Likewise, after termination of DISSUB conditions but with continuation of hypoxia for another 24 h, there were no significant ESQ symptom scores related to Acute Mountain Sickness.

Balance is the culmination of afferent feedback from the visual, vestibular, and proprioceptive senses and efferent reflexive and voluntary muscle responses. The relative importance of each of these varies in different individuals and can be modified with appropriate training. Nordahl et al. (19) found the measurement of postural stability to be both objective and reproducible using a static balance system with a learning effect observable primarily in the most difficult test conditions (subject standing with eyes closed on a foam pad and with short time periods between tests. By eliminating the visual input on the two-legged static balance tests, we attempted to gauge how much a submariner relied on vision to maintain postural stability, and whether this ability changed during exposure to DISSUB environmental conditions. In other words, in a darkened or dark submarine, how much worse would balance be when combined with environmental stressors? Submariners were 5-7 times worse in a cold, dark, and humid room with above normal carbon dioxide levels than when visual cues were present. There was no change observed in this relationship (eyes-closed/eyes-open ratio) during the course of DISSUB exposure conditions. A change was observed only when compared to the Control B condition. We felt that this was due in part to the slight improvement (not statistically significant) in the eyes-open scores during the exposure relative to the eyes-closed condition. There does not appear to a practice effect for either of these tests. Although vision is one of the first of the special senses to be affected by hypoxia, the eyes-open stability scores did not deteriorate or approach the scores obtained with the eyes-closed condition during exposure to the combined stresses or when hypoxia was the sole stressor. With regard to the dynamic postural stability test, no significant differences were found at any time period. Even though the greatest dynamic instability scores were obtained at the 66 h of exposure to steady-state conditions, similar to the eyes-open and eyes-closed tests, the variability was unusually large at this time (coefficient of variation = 45.6% as compared to 22.8% during the control A period. The power of this test was only 0.14 due primarily to the large underlying variability and insufficient differences in treatment effects). It may be that the complexity of muscular coordination in trying to use body motion and changes in center of gravity to chase a computer-generated target requires a longer practice period. Also, there may be a learning effect associated with static stabilometry measured with eyes open, eyes closed, and standing on a soft foam pad, a situation similar but not exactly the same as standing on a centrally-pivoting platform trying to track a moving target (19). The foam pad may bear some similarity to movement of an unstable platform. Nordahl et al. (19) tested subjects 10 times with intervals ranging from 11-117 days.

They found reproducible results that exhibited a learning effect, especially using the foam pad. The subjects in this study were not given the opportunity to practice more than 3 times. These three sessions served more to acquaint the subjects with the balance procedure than to train their responses. Thus, any training effect would be minimized but variability of the data would probably be increased.

With increases in muscle discomfort and cold stress ESQ scores, we surmise that the root of a stability problem could be peripheral at the muscle level. The eyes-closed/eyes-open ratio did not change over the course of exposure, indicating that the relative importance of visual input did not change with respect to the total postural control input-output. With an increase in instability, the lack of change in this ratio would support the hypothesis that the problem arises in the periphery. We do not believe that the importance of vision in the maintenance of balance is changed by these environmental conditions and the short time period involved

Previous studies of environmental stressors such as hypercapnia, cold, and hypoxia on postural control may be difficult to relate to this study due to the imposition of the three stressors at the same time. Nevertheless, an indication of the sensitivity of postural control can be discerned from studies that have imposed singular stresses. Exposure to acute, mild, simulated altitude (5,000-8,000 ft) has been shown to result in a decreased static postural stability (i.e., the subjects were required to stand as still as possible on a stable force plate)(9,10). Our subjects were at simulated 6,000-6,500 ft altitude, but carbon dioxide-induced hyperventilation effectively lowered the equivalent altitude to ~5,000 ft or less (~98% saturation using pulse oximetry). Although the significant detrimental effects previously observed have been attributed to effects on the central nervous system, we don't believe that a central cause was operative during DISSUB.

To our knowledge, the effects of whole body cold exposure and postural control have not been studied previously. Magnusson et al. (12,13) demonstrated the importance in postural control of mechanoreceptors in the soles of hypothermic feet. They concluded that sensory inputs from mechanoreceptors in the feet were important in maintaining postural control. The results during exposure to DISSUB conditions are explainable if subjects' feet and leg muscles were cold, stiff, and hypothermic. Subjects were made to remain as immobile as they could when measurements were not being made. During these times visual evidence of shivering was obvious in all subjects despite evidence that core body temperatures remained normal.

There is also a paucity of previous studies on hypercapnia and postural control. Most studies of psychomotor performance involved levels of carbon dioxide much higher than those imposed in DISSUB. Levels of carbon dioxide exposure in the range of 4%-8% have been shown to significantly impair performance on a number of tasks such as a modified Stroop test, an arithmetic test, figure-copying tasks, a pegboard speed test, tracking, eye-hand coordination, and problem-solving ability (20,6). Henning et al. studied the behavioral effects of short-term exposure (5-7 min) to 6% carbon dioxide produced by using gas mixtures and found a significant effect on body sway after exposure (5). They did not measure sway during exposure. Manzey and Lorenz found significant impairment in a tracking performance when 4 subjects were exposed to 1.2% carbon dioxide for 26 days (4). However, they attributed the effect to a possible change in alertness and the performance of only 2 of the subjects. Their results were significantly lower on the first day of exposure; only one subject's performance remained consistently lower during the entire exposure. Sayers studied the mental performance of subjects during 20 min exposures of 4.5%-7.5% carbon dioxide and found reductions in performance on a reasoning task at a threshold of 5.5% (21). Longer exposures at these levels were not studied.

From the above, we can conclude that the level of carbon dioxide used on DISSUB should not affect psychomotor or mental performance, including postural control.

The continued exposure to the combination of cold and hypoxia elicited measurable subjective symptom changes and disturbances in postural stability. These observations may be of practical importance when tasks aboard a disabled, submerged submarine involve balance and mobility, but they should not hamper or impede individuals in performing their duties when participating in any rescue efforts.

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The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

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