Naval Submarine Medical Research Laboratory

NSMRL REPORT 1196 5 FEBRUARY 1995

HE-N_2-O_2: ISOBARIC SHIFT AND SATURATION DECOMPRESSION

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Naval Medical Research and Development Command
Research Work Unit 63713N M0099.01A-5201

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NTIS CRA&I		☒
DTIC TAB		☐
Unannounced		☐
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Availability Codes		
Dist	Avail and / or Special	
A-1		

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Summary Page

Problem:

A disabled submarine (DISSUB) crew exposed to increased atmospheric pressures resulting from flooding, rupture of air lines, or emergency breathing apparatus use may incur a decompression obligation and will require gradual decompression to avoid decompression sickness (DCS). Decompression in a nitrogen-oxygen mixture is not always operationally feasible, and decompression from an air exposure in helium and oxygen could result in isobaric counter-diffusion DCS. An additional risk is pulmonary oxygen toxicity, especially when survivors are exposed to high partial pressures of oxygen from air at depth. These problems led to the concept of using a mixture of air and helium (trimix) for decompression of a DISSUB crew.

Findings:

The trimix experiments were designed to simulate the exposure of men in a DISSUB saturated at 5 atmospheres on air, followed by rescue in a pressurized rescue vehicle, and transfer to a surface platform for safe decompression. Trimix dives resulted in 4 cases of DCS in 62 man-dives. Three DCS cases presented after surfacing: one Type II DCS (44.5 hr schedule) and two Type I DCS (41.2 hr schedule). One case presented during decompression (Type I: 41.2 hr schedule). Only four cases of minor skin itching without rash were noted following the isobaric shift from air to trimix.

Applications:

Specific operationally relevant recommendations have been made and are also included in NSMRL report 1178, Pressurized Submarine Rescue. A manual for Undersea Medical Officers.

Administrative Information

This work was completed under Naval Medical Research Development Command Research Work Unit 63713N M0099.01A-5201, Submarine related decompression problems. The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. This report was approved for publication on 5 Feb 1995 and designated NSMRL Report 1196.

Abstract

A disabled submarine (DISSUB) crew exposed to increased atmospheric pressures resulting from flooding or other problems may incur a decompression obligation. They will then require not only gradual decompression to avoid decompression sickness (DCS), but decompression in specific gases due to operational limitations and to lower the risk for pulmonary oxygen toxicity.

Nineteen dry chamber dives were conducted at the Naval Submarine Medical Research Laboratory (NSMRL) to explore the feasibility of an isobaric shift from air at five atmospheres (ATA) to Helium-Nitrogen-Oxygen (50% He-40% N_2-10% O_2, TRIMIX) followed by decompression to the surface. These procedures parallel the potential operational scenario of returning the crew of a pressurized, disabled submarine (DISSUB) to the surface. Saturation dives were conducted by sequential experimental design, in which there was progressive shortening of the hold period following isobaric shift and/or shortening of decompression time. Initial pressurization was to 111 feet of seawater (fsw) (4.4 ATA) for 60 hours followed by compression to 132 fsw (5.0 ATA) on air for 12 hours, then the isobaric shift to TRIMIX was conducted. A hold of 24, 12, 8, or 4 hours at 132 fsw (5.0 ATA) was initiated, followed by a rapid upward excursion from 132 fsw (5.0 ATA) to 116 fsw and decompression to the surface with 57.5, 50.9, 44.5, or 41.2 hour schedules. The potential for decompression sickness (DCS) existed from both isobaric counter diffusion and also from decompression to the surface. Four cases of DCS occurred in 62 man-dives. Three cases presented after surfacing (one Type II: 44.5 hour schedule; two Type I: 41.2 hour schedule). One case presented during decompression (Type I: 41.2 hour schedule). Four cases of minor skin itching without rash were noted following the isobaric shift.

Overall, an isobaric shift of divers saturated on air at 5 ATA to trimix followed by decompression to the surface resulted in a small risk for DCS. Specific risk for isobaric counter-diffusion DCS for this switch appears to be negligible. Guidance to the fleet for DISSUB rescue scenarios has been provided.

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He-N_2-O_2: Isobaric Shift and Decompression

Introduction

Submarine safety has been of interest to the U.S. Navy since the production and launching of the first submarines. The risk of having an accident which would disable a submarine (DISSUB) is greater in the shallow waters of the continental shelf area than in much deeper waters. This is due to congested submarine and ship traffic, frequent surfacing and diving, and the fact that new submarines undergo initial sea trials in these shallower waters (Eckenhoff & Vann, 1985). If a submarine became disabled in shallow water, chances for the safe rescue of DISSUB personnel would be higher than in deep water, which might be deeper than the crush depth of the submarine.

The Navy has technology to rescue DISSUB crews. The Deep Submergence Rescue Vehicle (DSRV), designed to operate deeper than U.S. submarine hull crush depth, is capable of conducting rescues from a DISSUB at depths too great for safe direct buoyant ascent escapes. The DSRV was also designed to conduct rescues with DISSUB internal pressures up to 5 atmospheres absolute (ATA) (132 feet of sea water (fsw)) (5.0 ATA) (Eckenhoff & Vann, 1985).

During normal operations the internal air pressure of a submarine is maintained at approximately 1 ATA. Several events, however, can cause DISSUB internal pressure to rise well above 1 ATA: rupture of air lines, flooding with ocean water which causes compression of the remaining air spaces; planned pressurization of compartments to prevent or slow further ocean flooding; or exhaust from the Emergency Air Breathing (EAB) face masks.

A DISSUB crew exposed to increased atmospheric pressure may incur a decompression obligation. Specifically, the exposure of DISSUB crew to increased atmospheric pressure for some period of time results in the uptake of inert nitrogen (N_2) into the blood stream and tissues. If an individual is exposed for an extended period of time, the blood then becomes "saturated" (N_2 in the blood is equilibrated with the higher partial pressure of N_2 in the submarine). Once this happens, the crew should be gradually returned to 1 ATA. This decompression process allows the excess inert gas to be eliminated while it is still in a dissolved state to avoid decompression sickness (DCS) (Hallenbeck & Andersen, 1982).

In most cases a DISSUB crew will probably be exposed to increased pressure for at least 48 hours while waiting for the arrival of rescue crews (Eckenhoff & Vann, 1985). This delay will result in saturation of the survivors with higher pressure inert gas. Although safe decompression time is exposure dependent, numerous hours of decompression can be anticipated even if the DISSUB crew was exposed to relatively low atmospheric pressures.

In a DISSUB scenario the survivors would be transferred dry to the DSRV and then transported onto the deck of a submarine rescue ship (ASR-21 class) with saturation diving chambers or to the forward compartment of a mother submarine (MOSUB) (Figure 1).

The recovery and decompression problem is complicated by the fact that ASRs and MOSUBs do not carry large supplies of N_2. Normally, the best atmosphere for decompression would be a mix of N_2-O_2, but this is not feasible without a large source of stored N_2. ASRs carry only large sources of air, oxygen (O_2), and helium (He), while MOSUBs carry air only. Shifting survivors from the air

(N_2-O_2) atmosphere to Heliox (He-O_2), could result in isobaric counter-diffusion phenomenon which creates a risk for DCS-like symptoms (D'Aoust & Lambertson, 1982). Briefly, this process involves the movement of two inert gases (He, N_2) in opposing directions through tissues without a change in pressure, but can allow locally high total inert gas partial pressure. This supersaturation can cause gas phase formation and result in clinical DCS symptoms such as bubbles in superficial tissues including skin and subcutaneous tissue (Bove & Davis, 1990).

It is also likely that survivors breathing air at up to 5 ATA for a prolonged period will have increased risk of pulmonary oxygen toxicity (Harabin, Homer, Weathersby, & Flynn, 1987). It would, therefore, be advantageous to dilute the O_2 in the breathing mixture with an inert gas (N_2 or He) as soon as possible.

These problems led to the concept of using a mixture of air and He for decompression of DISSUB crews. The best option for DISSUB rescue on-board an ASR would be decompression on a trimix combination of He-N_2-O_2. This would: a) be operationally feasible, b) decrease O_2 partial pressure, and c) lessen risk for DCS.

The TRIMIX experiments were designed to simulate the exposure of men in a DISSUB saturated at 5 ATA on air, followed by rescue under pressure in the DSRV, and transfer to an ASR for "safe" decompression.

The focus of this paper is to explore the feasibility and safety of an isobaric shift from saturation on air to TRIMIX followed by decompression. Specifically, the TRIMIX series used a sequential experimental design and examined the following problems: 1) establish the practical safety of an isobaric shift from air at 5 ATA to He-N_2-O_2; 2) establish a minimum safe holding period on trimix breathing gas before decompression is initiated; and 3) establish a safe, yet expedient, trimix saturation decompression schedule.

Methods and Materials

All dives were conducted in the "Genesis" hyperbaric chamber at NSMRL in Groton,

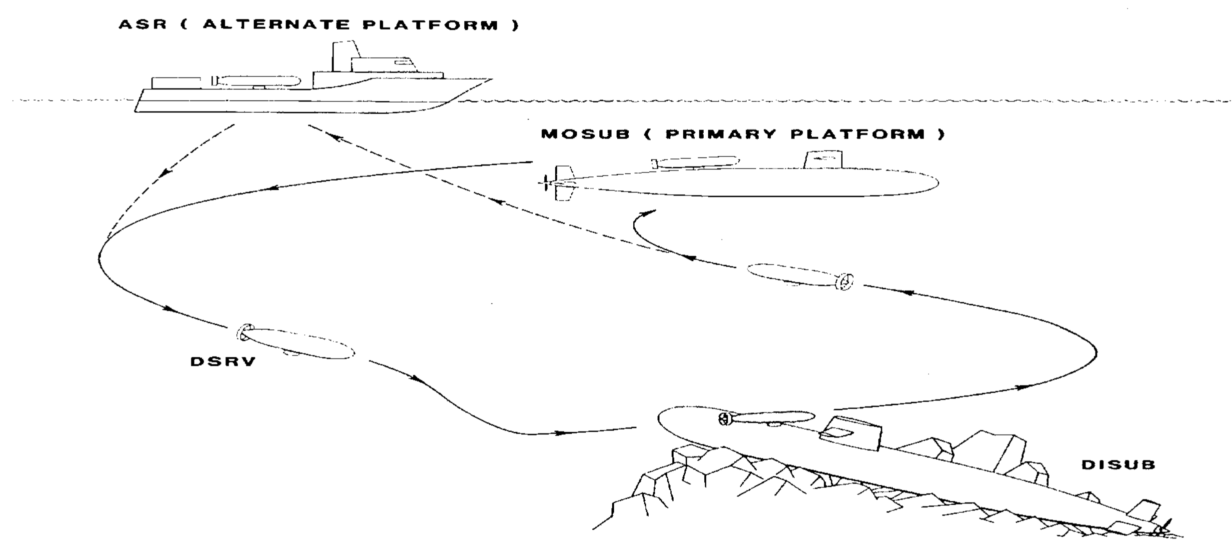

Figure 1

Connecticut. Depth was maintained within +/- 0.5 fsw. Beckman 864 analyzers were used to continuously monitor CO_2, which was maintained at or below 0.5% surface equivalent (SEV). Temperature and humidity were adjusted to suit subject comfort. Oxygen was continuously monitored by dual Beckman 755 analyzers and maintained within +/- 0.2% of prescribed values by two Teledyne 323 controllers. Nitrogen and helium concentrations were also monitored by a mass spectrometer (Perkin Elmer 1100 Medical Gas Analyzer) and were maintained within $\pm$ 0.5% by manual addition of the appropriate inert gas. Diet was not limited or monitored. The use of medications was minimized, and confined to topical preparations, antacids, acetaminophen and rare use of decongestants and non-steroidal anti-inflammatory drugs. Ancillary scientific studies during some or all of the exposures included spirometry, audiometry, doppler ultrasonic monitoring, and breathing resistance/exercise studies.

Subjects

All subjects for the TRIMIX series were active duty or reserve Navy trained male divers or submariners. Subjects' ages ranged from 20 to 42 years (Mean = 31.5 years). At least one Navy qualified diver was present during each dive. None of the subjects had hypo/hyperbaric exposures for at least 48 hours preceding their dive. Informed consent was obtained from all subjects after thorough briefs with the investigators. All subjects had current physical examinations. Sixty-two man-dives were conducted during nineteen dry chamber dives. The design of the experiment allowed for multiple dives by a single subject. No subject, however, was allowed to repeat the exact same dive profile.

Dive Profiles

Trimix dives were conducted by sequential experimental design in which there was a) progressive shortening of the hold period following the isobaric shift and b) shortening of decompression time.

The rules for progression of the profile risk specified that the hold time and, separately, the decompression time would be shortened if there were: no cases of DCS in at least 10 man-dives, no more than 1 case in 15 man-dives, or no more than 2 cases in 20 man-dives. A third case of DCS in any profile required a return to more conservative procedures (Table 1). These rules were applied separately to either DCS-like cases resulting from the isobaric shift and hold or DCS cases resulting from decompression.

Table 1
Decompression Rate (fsw/Hr)

Depths (fsw)	Trimix-I	Trimix-II	Trimix-III	Trimix-IV	Trimix-V
116-100	3.00	3.00	3.33	3.33	3.33
100-50	2.50	2.50	3.00	3.00	3.33
50-40	2.33	2.33	2.66	2.66	3.00
40-30	2.00	2.33	2.33	2.33	2.66
30-20	1.66	2.00	2.00	2.00	2.33
20-10	1.33	1.66	2.00	2.00	2.00
10-0	1.05	1.66	2.00	2.00	2.00
Total Decompression (Hrs)	57.5	50.9	44.5	44.5	41.2
Hold Time (Hrs)	24	12	8	4	4

The dive profiles consisted of: a) initial pressurization to 111 fsw (4.4 ATA) on nitrox (ppN_2= 4 ATA, ppO_2= 0.4 ATA) for 60 hours to provide a saturated N_2 partial pressure equivalent to that of 132 fsw (5.0 ATA) on air while minimizing the potential for pulmonary oxygen toxicity; b) pressurization to 132 fsw (5.0 ATA) with a simultaneous shift to air (ppN_2= 4 ATA, ppO_2= 1.05 ATA), followed by a 12 hour stay; c) an isobaric shift to trimix (50% He, 40%, N_2, 10% O_2) with subsequent holds for 24, 12, 8, or 4 hours; and d) an upward excursion to 116 fsw and decompression to the surface with 57.5, 50.9, 44.5, or 41.2 hour schedules (Table 2) and (Figure 2). The 16 fsw upward excursion was set to equal the oxygen partial pressure (0.50 ATA) which is thought not to incur any risk of decompression sickness (Behnke, 1947).

Table 2
Trimix Dive Series - DCS Incidence

TRIMIX	Hold Hrs	Decompression Time Hrs	# of Divers	DCS Cases	Itching Cases	% DCS
I (Series)	24	57.5	19	0	0	0.0
II (Series)	12	50.9	11	0	0	0.0
III (Series)	08	44.5	12	1	4	8.3
IV (Series	04	44.5	04	0	0	0.0
V (Series)	04	41.2	16	3	0	18.8

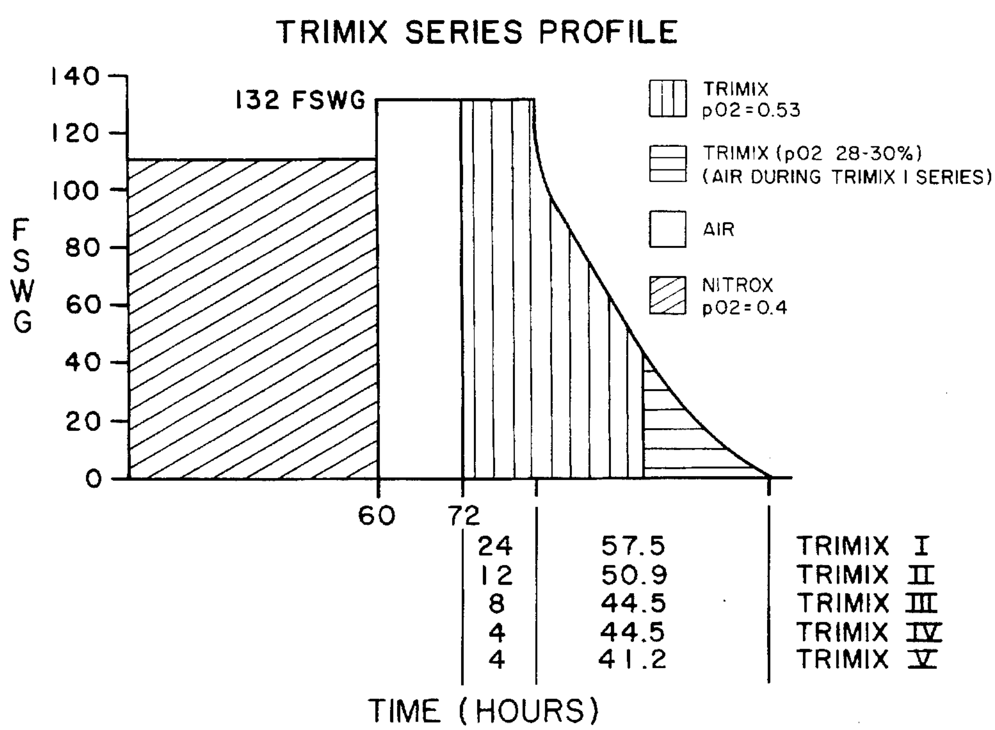

Figure 2

Trimix I. The first 19 man-dives did not use the sequential design rules. After the isobaric shift was conducted, the subjects remained on trimix for 24 hours before commencing decompression. Decompression was initiated with a 16 fsw upward excursion. A switch of chamber atmosphere to air occurred at 46 fsw for the remaining decompression time. The decompression schedule was from previous nitrox schedules used during the AIRSAT series (Eckenhoff & Vann, 1985). The 57.5 hour schedule was considered a conservative starting point for the TRIMIX series (Table 1).

Trimix II. The sequential design was initiated in this series. The next 11 man-dives used a 12 hour hold after the isobaric shift, the same 16 fsw upward excursion, and a shortened decompression schedule. This schedule was 50.9 hours and was intermediate between the TRIMIX I schedule and a linearized USN He-O_2 saturation decompression rate (NAVSEA, 1987).

Trimix III. The hold period on trimix was shortened to 8 hours in addition to shortening of the decompression schedule to 44.5 hours. Sixteen man-dives were completed on this schedule.

Trimix IV. The hold period on trimix was shortened to 4 hours while the decompression schedule was held at 44.5 hours. Four man-dives were conducted in this phase.

Trimix V. Sixteen man-dives were completed with a hold following the shift of 4 hours. The decompression schedule was also shortened to 41.2 hours. The schedule is slightly faster than the linearized Navy He-O_2 saturation decompression rate (NAVSEA, 1987).

Decompression Monitoring: The potential for DCS or DCS-like symptoms existed from both the isobaric shift and the upward excursion with subsequent decompression to the surface. The adequacy of the decompression procedures was assessed by the presence or absence of specific symptoms of DCS (doppler ultrasonic recordings were not used for diagnosis since they were being recorded in a double-blind fashion for other research). A qualified USN diving medical officer (DMO) made the diagnosis in accordance with conventional diagnostic categories as outlined in the US Navy Diving Manual (NAVSEA, 1988). Evaluation of subjects was based on spontaneous reporting of symptoms, regular (twice daily) interviews with the DMO, and thorough post-dive examinations. All divers were examined within 2 hours of surfacing, and again at 24 and 48 hours post-dive.

The data generated from this dive series will be included in a master data base at Naval Medical Research Institute (NMRI). This information will allow mathematical models to be developed to perform maximum likelihood analysis to assess DCS risk (Weathersby, Survanshi, Nishi, & Thalmann, 1992).

Results

Sixty-two man dives were conducted between 1987 and 1992. The overall incidence of DCS for the entire TRIMIX series was 6.5% (4 of 62), which was attributed to the actual decompression based on the time of DCS symptom occurrence. The fastest decompression schedule resulted in a DCS risk of 18.8% (3 of 16). One Type II DCS case and three Type I DCS cases were diagnosed. Only four cases of minor skin itching without rash were noted following the isobaric shift (Table 2).

The first case of DCS involved a 28 year old subject who completed TRIMIX III (8, 44.5). The subject reported increasing right knee pain (dull ache below patella) to the

DMO 14 hours post surfacing (at 2225 hr). The subject stated that the pain began earlier (1200 hr). This knee pain was soon followed by lower back (L4/L5 level) and elbow pain. The back pain was mostly a dull ache, poorly localized and not affected by range of movement. The left elbow pain was an intermittent, poorly localized dull pain which began soon after the back pain. The pain gradually increased in the left elbow. US Navy Treatment Table 6 (TT6) was initiated immediately (2230 hr) for these Type I symptoms. At the end of the first 20 minute O_2 breathing period (followed by 5 minutes air breathing), the subject's left elbow pain resolved, the right knee pain decreased in severity, and no change was noted in the back pain. Several hours into the treatment (0045), the subject's back pain also decreased in intensity to a rating of 3 out of 10 (initially 10/10) and only slight knee pain was noticed. The subject completed five O_2 breathing periods (20 minutes O_2 / 5 minutes air) (3 extensions) at 60 fsw. Travel was then commenced to 30 fsw, however at 45 fsw the diver complained of increasing back pain (4/10) and a slight increase in knee pain. The diver was then returned to 60 fsw for three more 20 minute O_2 / 5 minute breathing periods as per the U.S.N. Diving Manual Chapter 8 (NAVSEA, 1988). Approximately 2 hours and 40 minutes later, the diver reported complete resolution of knee pain, and only a "slight twinge" in his back, but significant relief. The diver was then allowed to travel to 30 fsw on O_2 where TT6 was continued. During the first O_2 breathing period at 30 fsw, the subject reported complete relief of all symptoms. Upon reaching the surface, the patient reported some back soreness that he explained was different than his original symptoms.

The second DCS case involved a 30 year old (TRIMIX V (4, 41.2)) who reported left knee pain (intensity 1-2/10) at 22 fsw, 2355. The pain had started the night before after the subject slipped and banged his knee. The subject denied any change in initial pain severity during decompression so he did not report it at that time. It was not until later (22 fsw, 2355 hours) that he reported it because the pain had become more persistent. No DCS treatment was initiated at this time because the DMO was not convinced the symptoms were DCS related. At 6 fsw (0730) the subject reported no change in the pain (intensity still 1-2/10). He found that the intensity of the pain was lessened with massage and movement. Approximately 5 hours (1600) post-surfacing, the subject reported a gradual increase in pain on the medial aspect of the left knee. The pain was steady with occasional episodes of throbbing and severe pain lasting 15-30 seconds (intensity 6/10). Treatment Table 6 was then initiated, and after the first 20 minute O_2 breathing period (followed by 5 minutes air) (1700), the pain decreased to an intensity of about 2/10. Following the second O_2 treatment, the patient was able to stand, bear full weight, and reported feeling remarkably better. TT6 was continued, and the subject continued to improve. At 1750 hr, the subject had mild residual medial pain and mild tenderness in his left knee. At 30 fsw (1820 hr) and again at the surface, the diver reported only minor residual soreness. Forty-eight hours post-surfacing, the diver still had very minor soreness which eventually resolved.

The third case of DCS (TRIMIX V (4, 41.2)) was the only case to be diagnosed and treated before surfacing. A 31 year old reported (day 5 of dive) left knee pain at 88 fsw (0130 hr) which woke him from sleep (intensity=2/10). The chamber was pressed 5 fsw deeper where the subject reported some relief of pain (1/10). The chamber was then pressed another 5 fsw and the subject was treated with two periods of 20 minute O_2 breathing (PO_2 = 2.8 ATA) with 5 minutes of air breathing between O_2 treatments. Following this, the subject reported that the pain was entirely resolved. Assessment by the DMO was Type I DCS. The subject also reported fleeting "ache" symptoms in the same knee several times during the last day of the dive (various depths). These aches were mild and did eventually resolve; however, following the first two episodes of achiness, the subject was given three 20 minute periods of pure O_2 (23 fsw) each followed by 5 minutes air breathing. The subject again experienced two more episodes of fleeting aches before decompression was complete, a single episode just as the chamber surfaced, and one more while walking to his barracks (2 hours post-surface). No O_2 treatment was given for these symptoms. Thirty-six hours after surfacing, the subject reported a residual "stiffness" in his left knee which had gradually diminished during the last 24 hours and was absent at the time of the interview. The final diagnosis was Type I DCS, full resolution after treatment during saturation decompression with episodic knee pain (spontaneously resolved).

The last case of DCS (TRIMIX V (4, 41.2)) was not treated until 3 hours post surfacing. The 33 year old subject had reported right knee pain (both sides of patellar tendon, not within joint) at 5 fsw following twisting his knee earlier at 19 fsw (2300). During the remainder of decompression and upon surfacing the subject stated that the pain was present only during movement with no weakness or numbness. Approximately three hours post surfacing the subject noted pain at rest as well, but had no weakness or numbness. Decompression sickness was considered possible so the DMO initiated recompression (1300 h). No relief was noted after the third session of 20 minutes O_2 / 5 minutes air breathing at 60 fsw (1410 hr). Although it was thought that DCS was unlikely, TT6 was continued. Later, at 30 fsw (1600) the subject reported a significant decrease in discomfort when at rest and during movement. Treatment on Table 6 was completed and the subject reported feeling much improved with less discomfort at rest and during movement. Fourteen hours post TT6 (0900), the subject felt "100% better" than he did immediately post treatment. Twenty-four hours post dive, the subject admitted the pain had actually worsened during the experimental decompression but he failed to report. The case was documented as DCS Type I.

The four cases of skin symptoms resulting from isobaric counter diffusion (TRIMIX III) consisted of itching, blotching and redness (no rash). The cases were quite similar in severity (minor), time of onset, and duration. Two cases occurred 2.5 hours after the shift and lasted until 6.5 hours after the shift. The other two cases both started approximately 75 minutes post shift. One case lasted about 40 minutes; the other about 2 hours. All four cases resolved spontaneously without treatment.

Discussion

The TRIMIX test series was designed specifically to simulate the extended exposure of men in a DISSUB to air at a pressure of 5 ATA followed by rescue under pressure in the DSRV.

Three DCS cases were diagnosed and treated post-dive while one occurred during decompression. All involved either the right (1 case) or left (3 cases) knees. The site of the symptoms was consistent with air and NITROX saturation dive results reported by Eckenhoff and Vann (1). Knee pain has also been noted in the majority of DCS symptoms in heliox saturation decompressions (Hanson, Vorosmarti, & Banard, 1987; Summitt & Berghage, 1971; Summitt and Kulig, 1970).

In a DISSUB situation the most senior survivior is given responsibility for the decision to either await rescue or attempt an escape.

This individual must take into consideration the survival potential in the DISSUB and the time that can be spent in a pressurized environment without incurring an unacceptable decompression obligation and/or risk of DCS. Escape may be desirable yet impossible if conditions are not correct (e.g. severe surface envirnoment).

In the case where escape is not feasible, the senior survivor must also be responsible for evaluating the risk of possible DCS versus the risk associated with escape. He then makes a decision based on all available information. Several tables are provided in the manual titled, "Pressurized Submarine Rescue, A manual for Undersea Medical Officers" (Harvey et al. 1992), which outline alternative schedules for saturation decompression from various depths. The more conservative lengthy schedules are associated with a 1% or less predicted incidence of DCS. Less conservative schedules provide an alternative means to decompress survivors when time and resources are limited or not available. These schedules have faster overall decompression times, at the cost of higher expected risk for DCS; in some cases risk may be almost as high as 80%. Currently, the incidence rates over 30% reflect more a numerical ranking of schedules than a reliable estimate of actual predicted DCS rates. In these higher risk ranges, some very serious and possibly fatal DCS cases may occur. The tables in the Pressurized Submarine Rescue Manual allow a senior survivor to make informed decisions regarding the risks and benefits associated with the selection of riskier decompression schedules. These tables (which include the Trimix decompression) have not all been directly tested. They are statistically derived from 1,992 well documented saturation man dives and represent a highly informed, yet unconfirmed, estimate of the risks associated with their use.

It is likely that during a real DISSUB rescue scenario, a Commander and/or rescue team may choose to accept a DCS risk much greater than the 18.8% resulting from the fastest trimix decompression schedule. However, it should be emphasized that it would be unethical to expose volunteer subjects to any greater risk than is absolutely necessary, even in a controlled research setting. Consequently, attempts to directly test a decompression schedule to be used for rescue purposes may be less than ideal, resulting in relatively conservative schedules. Many more trimix decompressions with faster schedules would be needed to directly determine a faster schedule for DISSUB rescue with a higher acceptable DCS risk.

Decompression testing yielding a substantial degree of confidence in the results is also not practical for another reason. The number of replicate exposures required on a single procedure is very large. For example, to be 95% confident that the underlying incidence of DCS is below 10% DCS, 35 test dives with no DCS or only one case of DCS in 54 replicated exposures are required.

The authors realize that the obvious shortcoming of this research is the small number of replicate tests conducted. However, resource economics and ethical concerns prohibit direct, statistically useful testing of more than a few candidate decompression schedules.

A more powerful and practical approach is to combine many, i.e. thousands, of well described test dives into probabilistic models fitted by maximum likelihood (Weathersby, Homer, & Flynn, 1984). That approach produced controlled risk decompression tables for air diving (Weathersby et al., 1985), and has been invoked in the submarine rescue scenario (Harvey et al., 1992). It is not, however, yet ready for the trimix problem.

Probabilistic models can never be better than the data on which they are developed and calibrated. The bulk of published studies have considered N_2 as the only inert gas. Only a single pilot study (Tikuisis, Weathersby, & Nishi, 1991) has examined probabilistic models allowing for both helium and nitrogen inspiration. Work is now in progress to extend the compilation of primary decompression data (Weathersby, Survanshi, Nishi, & Thalmann, 1992) to include helium-oxygen and TRIMIX dives. In addition to the present data, about 2000 more dives are being reviewed. Of those, this series has the only well-described TRIMIX saturation dives available.

Conclusions:

The conclusions drawn from this study are:

1. Overall, an isobaric shift of divers saturated on air at 5 ATA to TRIMIX (50% He, 40% N_2, 10% O_2) followed by decompression to the surface is feasible. Specific isobaric counter diffusion DCS risk for this switch appears to be negligible;

2. A 4-hour hold period following the shift from 5 ATA air to TRIMIX is believed to be adequate. A 4-hour hold did not present greater DCS risk than longer hold periods because we believe the temporal proximity of the DCS cases reported for all dives precludes any relationship to hold time;

3. Trimix decompression time of 44.5 hours or greater creates only a slight risk of DCS (1 DCS case of 46 dives, 95% C.L. on rate 1%-10%); and

The information and experience gained from these TRIMIX dives has permitted NSMRL to provide guidance to the fleet for DISSUB rescue scenarios.

Recommendations:

The results from these dives have been incorporated in operationally relevant recommendations as follows (Harvey et al., 1992):

1) For decompression of submarine rescue survivors a mixture of air and He with an O_2 partial pressure of 0.5 ATA and a N_2/He ratio of 4/5 has been found effective. The trimix decompression procedure offers the advantage of a lower partial pressure of O_2 but does not produce isobaric counter-diffusion symptoms at depth (132 fsw) (5.0 ATA).

2) A required, yet conservative, hold of 8 hours is recommended after switching the survivors to trimix before beginning decompression. A hold time of 4 hours is suggested as sufficient if time is crucial.

3) A decompression time of 44.5 hours is recommended.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 074-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF THE REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NSMRL Report 1196	5. MONITORING ORGANIZATION REPORT NUMBER(S) NA
6a. NAME OF PERFORMING ORGANIZATION Naval Submarine Medical Research Laboratory 6b. OFFICE SYMBOL *(If Applicable)*	7a. NAME OF MONITORING ORGANIZATION Naval Medical Research and Development Command
6c. ADDRESS *(City, State, Zip Code)* Box 900, Naval Submarine Base NLON, Groton, CT 06349-5900	7b. ADDRESS *(City, State, Zip Code)* 8901 Wisconsin Avenue Bethesda, MD 20889-5606
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Same as 7a 8b. OFFICE SYMBOL *(If Applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS *(City, State, Zip Code)* Same as 7b	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
63713N	M0099	.01A	DN 242606

11. TITLE *(Include Security Classification)*
(U) $He-N_2-O_2$: Isobaric shift and saturation decompression

12. PERSONAL AUTHOR(S)
C. L. Shake, P. K. Weathersby, B. G. Caras, and J. W. Parker

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Interim	FROM ____ TO ____	95 February 5	10

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	Decompression; Decompression sickness;

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

A disabled submarine (DISSUB) crew exposed to increased atmospheric pressures resulting from flooding or other problems may incur a decompression obligation. They will then require not only gradual decompression to avoid decompression sickness (DCS), but decompression in specific gases due to operational limitations and to lower the risk for pulmonary oxygen toxicity.

Nineteen dry chamber dives were conducted at the Naval Submarine Medical Research Laboratory (NSMRL) to explore the feasibility of an isobaric shift from air at five atmospheres (ATA) to Helium-Nitrogen-Oxygen (50% He-40% N_2-10% O_2, TRIMIX) followed by decompression to the surface. These procedures parallel the potential operational scenario of returning the crew of a pressurized, disabled submarine (DISSUB) to the surface. Saturation dives were conducted by sequential experimental design, in which there was progressive shortening of the hold period following isobaric shift and/or shortening of decompression time. Initial pressurization was to 111 feet of seawater (fsw) (4.4 ATA) for 60 hours followed by compression to 132 fsw (5.0 ATA) on air for 12 hours, then the isobaric shift to TRIMIX was conducted. A hold of 24, 12, 8, or 4 hours at 132 fsw (5.0 ATA) was initiated, followed by a rapid upward excursion from 132 fsw (5.0 ATA) to 116 fsw and decompression to the surface with 57.5, 50.9, 44.5, or 41.2 hour schedules.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT [X] UNCLASSIFIED/UNLIMITED [ ] SAME AS REPORT [ ] DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Susan D. Monty, Publications	22b. TELEPHONE *(Include Area Code)* (203) 449-3967 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 *Previous editions are obsolete.*

S/N 0102-LF-014-6603

SECURITY CLASSIFICATION OF THIS PAGE

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19. cont.

The potential for decompression sickness (DCS) existed from both isobaric counter diffusion and also from decompression to the surface. Four cases of DCS occurred in 62 man-dives. Three cases presented after surfacing (one Type II: 44.5 hour schedule; two Type I: 41.2 hour schedule). One case presented during decompression (Type I: 41.2 hour schedule). Four cases of minor skin itching without rash were noted following the isobaric shift.

Overall, an isobaric shift of divers saturated on air at 5 ATA to trimix followed by decompression to the surface resulted in a small risk for DCS. Specific risk for isobaric counter-diffusion DCS for this switch appears to be negligible. Guidance to the fleet for DISSUB rescue scenarios has been provided.