NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

REPORT NUMBER 992

EXCURSIONS TO THE SURFACE AS A COMPONENT OF EMERGENCY DECOMPRESSION FROM AIR OR NITROX SATURATION EXPOSURES

by

R. G. Eckenhoff and J. W. Parker

Naval Medical Research and Development Command
Research Work Unit M0099.PN.001-8013

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Commanding Officer
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SUMMARY PAGE

THE PROBLEM

To determine the feasibility and safety of performing unpressurized transfers of personnel saturated on nitrogen-oxygen breathing mixtures between pressurized environments.

FINDINGS

Unpressurized intervals of 30, 17 and 10 minutes were tolerated by 18 human subjects saturated on air at 45, 55 and 65 fsw (20, 24.5 and 29 psig) respectively with less than a 10% incidence of decompression sickness. Symptoms of DCS were generally not serious (type 1) and intravascular gas phase formation as indicated by doppler ultrasonic detection was minimal. Manipulation of the data allowed prediction of useful unpressurized intervals from depths of about 100 fswg (44.5 psig).

APPLICATION

Unpressurized transfer of sunken submarine survivors from the Deep Submergence Rescue Vehicle (DSRV) to the Deck Decompression Chamber (DDC) on the submarine rescue craft is possible. However, because of the time required to transfer the full complement of DSRV occupants, the practice is only considered safe at distressed submarine internal pressures of about 25 psig (55 fswg equivalent). A capability for pressurized transfer is recommended.

ADMINISTRATIVE INFORMATION

This study was conducted as part of Naval Medical Research and Development Command work unit No. 63713N M0099PN 001-8013 "Simulated saturation diving using nitrogen oxygen breathing mixtures". It was submitted for review on 4 Oct 1982 and approved for publication on 4 Nov 1982, and designated as Naval Submarine Medical Research Laboratory report No. 992.

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ABSTRACT

Present equipment capability precludes a pressurized transfer of personnel rescued from a pressurized, distressed submarine using either the Submarine Rescue Chamber (SRC) or the Deep Submergence Rescue Vehicle (DSRV). An unpressurized transfer risks potentially lethal decompression sickness. Experiments were conducted at this laboratory to determine the period of time available for such an unpressurized transfer to be conducted safely, with a minimal risk of decompression disease. Eighteen active duty and reserve Navy divers were saturated on air at each of 3 pressures; 20 psig (45 fswg), 24.5 psig (55 fswg) and 29 psig (65 fswg). Direct release of the pressure was followed by a "surface" or unpressurized interval of 30, 17, and 10 minutes respectively, prior to recompression. The data indicate that this procedure is safe, and carries less than a 10% risk of decompression sickness for the intervals examined. Furthermore, the data would predict that excursions to the surface from air or nitrox saturation exposures are safe from depths much greater than previously predicted.

INTRODUCTION

Military, commercial and research saturation diving operations require the occasional use of emergency decompression procedures. Frequently, this may involve direct ascent to the surface, a brief interval on the surface and finally recompression in a hyperbaric chamber to recoup the missed decompression. This is a common practice in subsaturation diving (1, 2, 3), but the feasibility and safety of its use in saturation diving has not been well established. Potential applications would include not only emergency decompression from saturation dives, but also unpressurized transfer of personnel between chambers and/or submersibles. An example of the latter is found in current U.S. Navy submarine rescue operations, where mating surface incompatibilities preclude a pressurized transfer of survivors from the Deep Submergence Rescue Vehicle (DSRV) to the Deck Decompression Chamber (DDC) (4).

The literature contains several reports of saturation-excursion diving experiments which describe ascending excursions to or near the surface in small numbers of subjects. In one of these studies, two subjects surfaced directly from saturation at 26 fswg and underwent no decompression at all (5). No symptoms were reported. In establishing emergency procedures for accidental surfacing in the Tektite experiments, Edel studied surface intervals from a 42 fswg nitrogen-oxygen (nitrox) saturation depth, and concluded that an interval of 15 minutes was safe (6). This conclusion was based on the appearance of a serious decompression symptom in one subject after 19 minutes on the surface. A surface interval of 3 minutes from air saturation at 65 fswg was accompanied by finger pain in one of two subjects in a Russian study (7). No symptoms were observed in 25 divers subjected to a 2 minute surface interval after air saturation at 45 fswg (5), however, in this study pure oxygen was breathed for 20 minutes prior to ascent. Several other studies have included ascending excursions from either air or nitrox saturation at 50 to 90 fswg to 5-30 fswg for intervals of up to 30 minutes (5). The only symptoms produced were pruritus, and occasionally joint niggles (fleeting pains). Venous gas emboli (VGE) data are not available for any of these human studies. However, in goats ascending directly from air saturation at 50 fswg, VGE were first detected at 5-10 minutes, increasing to a peak at about 25 minutes. Decompression symptoms were not observed prior to about 20 minutes (8).

Hamilton et al., condensed a portion of this background information into a predictive graph for use in planning the ascending excursion profiles for a series of nitrox saturation diving experiments in the early 1970's (9). Although no decompression symptoms resulted, this curve is based on scanty systematic data. Additional human studies are required prior to operational use. Furthermore, due to the paucity of symptoms in the preceding studies, longer excursions from greater depths than suggested by this curve may be safe for human application.

This report describes the effect of direct ascent to the surface from air saturation in 18 human subjects, and offers a revised predictive curve from which to base this practice in the future.

MATERIALS AND METHODS

I. Facility

All saturation exposures were performed in the main hyperbaric chamber of the Environmental Simulation Facility located at the Naval Submarine Medical Research Laboratory in Groton, Ct. The chamber was of double lock design, steel construction and man-certified to 350 fswg. The chamber measured 9 feet in

TABLE I
SUBJECT VITAL STATISTICS

mean, standard deviation
(range)

AGE, yrs	HEIGHT, cm	WEIGHT, kg	BODY FAT, %
26 $\pm$ 5.0 (20-38)	147.6 $\pm$ 7.3 (163.6-190.5)	74.3 $\pm$ 8.3 (56.5-92.3)	12.4 $\pm$ 3.2 (7.3-18.7)

diameter and about 25 feet in length. Separate life support systems for each lock controlled CO2, temperature and humidity. CO2 was monitored continuously in each lock by Beckman 864 analyzers, and maintained at 0.80 $\pm$ 0.05%. Temperature was adjusted to subject comfort and averaged 23.6 $\pm$ 2.0 degrees C. Oxygen was monitored by Beckman 755 analyzers and maintained at 20.9 $\pm$ 0.2% by means of two Teledyne 323 controllers. CO2, O2, pressure and temperature were recorded hourly in permanent logs.

II. Subjects

The subjects for these experiments were reserve and active duty military divers with varying degrees of diving/chamber experience. All had been in hyperbaric chambers previously. No subjects had been exposed to elevated pressure for at least two weeks prior to these experiments. Eighteen subjects were used in this study (3 in each of 6 separate exposures). No subjects were used twice. Subjects began predive testing and training about one week prior to the actual pressurization, and were generally retained for a week postdive. Vital statistics data for the subjects are shown in Table 1.

III. Experimental design

The excursion profiles to be used in this study are based on the previously mentioned curve from Hamilton, et al (9), which is an exponential plot of additional ascent above M-value limitations in feet sea water absolute (fswa) versus time in minutes. Three representative points from this curve were chosen, and converted to give three air saturation depth - surface excursion duration combinations by forcing the additional ascent limitation to coincide with 0 fswg (the surface)*. The pressurization and excursion profile for these experiments is given in Figure 1. Air is used as the breathing media

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#1. For example: from the curve, an ascent of 34 fsw above M-value limitations is allowed for 10 minutes. If this ascent is to terminate at the surface, the M-value limitation would occur at 34 fswg, and assuming that the 480 minute tissue is limiting, the M-value would be approximately 74 fswa. Since at saturation, the tissue nitrogen tension is roughly equivalent with that of the breathing gas, this M-value is an estimate of the nitrogen saturation partial pressure in fswa. Converting to air saturation depth in gauge pressure (74 fswa/0.79 - 33 fsw) yields 61 fswg. Therefore, this curve would predict that a 10 minute surface interval from air saturation at 61 fswg is safe.

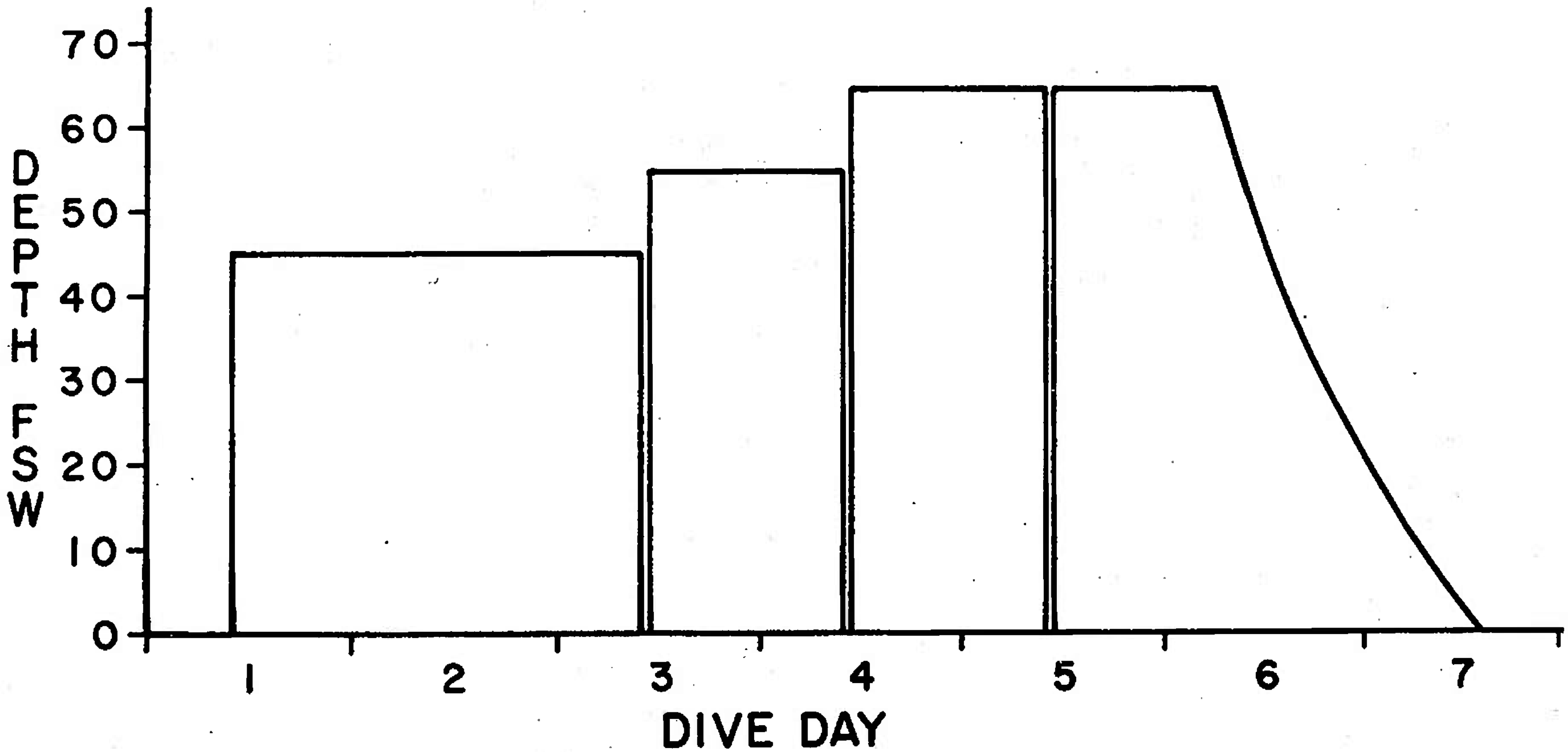

Figure #1
Pressurization profile for these experiments. Note that all three excursions are performed on a single exposure. The excursion from 45 and 55 fswg were 30 and 17 minutes, respectively. The excursion to the surface from 65 fswg was 7 minutes in duration in the first three runs (8 subjects) and 10 minutes in final three runs (9 subjects).

throughout the experiment. Initially, the subjects were compressed to 45 fswg, where they remained for 48 hours. At 1000 on dive day 3, an excursion to the surface at 30 fpm was made. The duration of this first excursion was 30 minutes, which includes the ascent time. The subjects were then recompressed directly to 55 fswg, where they remained for 24 hours. A second excursion to the surface was made on day 4, lasting 17 minutes. Recompression back to 65 fswg was followed by another 24 hour hold and then a third excursion lasting 7 minutes in the first 8 subjects and 10 minutes for the final 9 subjects. Compression back to 65 fswg was followed by a 20 hour wait prior to initiation of the final decompression. The decompression was accomplished on a 32 hour and 6 minute schedule and is the subject of a separate report (10).

During and after the excursions and final decompression, the subjects were interviewed and examined. In addition, the precordium of each subject was monitored with doppler ultrasound at regular intervals for the entire duration of the excursion or decompression. A Sodelec D.U.G. bubble detector with probe was used for signal generation. The signals were recorded on cassette tapes and the Kisman-Masurel system (11) of grading was used to score the recordings. In this system, grade 0 indicates the absence of VGE and grade 4 is maximal. Two scores are reported, one at rest and the other with movement (deep knee bends).

Additional medical monitoring included daily vital signs (pulse, blood pressure, respiratory rate and temperature), daily weights, pulmonary function (FVC, FEV1, PEFR, PIFR), audiograms and electrocardiograms. Daily blood draws for hematology and chemistry will be the subject of a separate report.

RESULTS

Symptoms and venous gas emboli scores for each of the excursions are presented in Table 2. Although the significance of pruritus as a symptom of decompression stress is not clear, it is included here because it seemed to correlate in both timing and degree with the other indicators of decompression stress. Results following each excursion are as follows:

TABLE 2
SUMMARY OF SYMPTOMS AND VGE DATA

EXCURSION NO	1	2	3	
EXCURSION DURATION (min)	30	17	7	10
TOTAL NO. SUBJECTS	18	17	8	9
NO. SUBJECTS WITH:				
-PRURITUS	15	16	0	7
-DCS TYPE 1 SYMPTOMS	1	1	0	0
-DCS TYPE 2 SYMPTOMS	0	1	0	0
NO. SUBJECTS WITH VGE				
-AT REST	5	2	0	1
-WITH MOVEMENT	10	8	1	2
MEAN VGE SCORE (KM CLASS.)				
-AT REST	0.44	0.18	0	0.22
-WITH MOVEMENT	0.97	0.72	0.13	0.36

Excursion 1 (30 minutes after 48 hours at 45 fswg). The majority of the subjects exhibited both pruritus and VGE, the mean time of appearance for both is shown in Table 3. The mean VGE grades are low; 0.44/0.97 (rest/movement). One subject had the onset of DCS type I symptoms (knee pain) at 15 minutes into the excursion, and was treated by compression at 18 minutes. No VGE were detected in this subject. Relief was obtained prior to reaching the bottom. This subject was not used in the subsequent excursion, but was in the last. No DCS type II symptoms occurred on this excursion.

Excursion 2 (17 minutes after 24 hours at 55 fswg). Sixteen of 17 subjects complained of pruritus (subjectively more intense on this excursion), whereas only about half had detectable VGE. The mean appearance times are again shown in Table 3. Mean VGE grades are 0.18/0.72. Towards the end of the excursion, one subject noted hip pain, and another noted axillary pain. Neither admitted to symptoms until after recompression. The pain was relieved in both subjects shortly after leaving the surface, but on examination, the subject with axillary pain had a mild to moderate motorsensory deficit in the ipsilateral arm. This deficit cleared completely after 2 hours on intermittent oxygen breathing, but the subject was not used in the subsequent excursion. Neither subject with DCS symptoms had detectable VGE.

Excursion 3 (7, 10 minutes after 24 hours at 65 fswg). Due to the lack of signs and symptoms during the 7 minute excursion in the first 8 subjects, the excursion time was extended to 10 minutes for the final 9 subjects. Again, the majority of the subjects had pruritus, but now only 2 of the 9 subjects had detectable VGE at 10 minutes. The grades are again low, with a mean of 0.20/0.36. No symptoms of DCS occurred in this excursion.

This disappearance of VGE, like the appearance, required a finite period of time after recompression. In several subjects with detectable VGE on the surface, VGE continued to be detected for as long as 40 minutes (mean about 10 minutes) after recompression to the original depth plus 10 fsw. Both pruritus and DCS symptoms were generally relieved long before the disappearance of VGE. Sufficient cases of decompression sickness were not generated in these experiments to allow a meaningful correlation with the VGE scores, but it is interesting to note that none of the 3 subjects with DCS symptoms had detectable VGE at the time. Throughout the exposures, no significant changes were noted in the blood pressure, resp. rate, temperature, body weight, pulmonary function or cardiac rhythm.

DISCUSSION

The results of the surface excursions from 45 and 55 fswg probably indicate that the durations of each are maximal for routine operational use, yet probably leave some flexibility for the true emergency application, depending on the incidence and type of decompression sickness acceptable under the prevailing circumstances. It is not known whether longer surface intervals from each of these depths would produce a greater incidence of the type of symptoms observed in this study, an increased severity of symptoms (more type II), or both. It seems likely that, with an increasing volume of intravenous gas phase being formed with time, more serious symptoms may be observed due to the increased chance of venous obstruction and arterial embolization. This may explain the occurrence of the "marked neurocirculatory symptoms" in what was probably a particularly susceptible subject, possibly with a right-to-left circulatory defect, in Edel's preTektite study (see Introduction). Otherwise, the incidence and type of symptoms reported in the literature are similar to the results of this study.

The seven and ten minute excursion from 65 fswg had a significantly lower incidence of pruritus, decompression sickness and venous gas emboli than the two previous excursions. Therefore, extension of the excursion duration seems possible. Based on the increase in signs and symptoms observed on prolonging this excursion from 7 to 10 minutes, it is estimated that an additional 2 minutes would produce results which are similar in degree as the excursions from 45 and 55 fswg. Therefore, we believe that an excursion of at least 12 minutes from air saturation at 65 fswg will be tolerated with an acceptable level of DCS (defined here as 1-10% incidence).

In an attempt to use this information to predict safe excursion durations from nitrogen-oxygen saturation at other depths, the excursions performed in this study are plotted as the nitrogen partial pressure reduction ratio* versus the excursion time in minutes. A power curve is drawn through the points as shown in Figure 2. The correlation coefficient demonstrates that the power function is fairly representative of the relationship between pressure reduction and excursion duration. This is consistent with the work of Spencer (12) in subsaturation diving. Fitting this data with either a linear or exponential function would result in curves that intersect the y-axis at ratios of about 0.70-0.73, and since it is reasonable to assume that a ratio as high as 1.0 will produce no symptoms at zero time, these mathematical approaches are probably not valid. Likewise, the logarithmic approach is a poor candidate as it would intersect the x-axis in several hours, when it can be assumed that a ratio of 0 will produce no symptoms in an infinite period of time. Therefore, we believe that the power function adequately represents the relationship between pressure reduction and symptom onset.

Although the significance of pruritus remains unclear, it is more than an artifact of dry hyperbaric exposures (13). The relationship between the mean onset time of pruritus and VGE was consistent across the three excursions, with pruritus appearing first, VGE next and finally, symptoms of decompression sickness. This progression, however, was not observed in all subjects, as the three subjects with DCS did not have detectable VGE prior to symptoms. However, they did have pruritus beforehand. Because of the low incidence of DCS produced by these excursions, it was not possible to compute a mean appearance time of decompression sickness symptoms. Therefore, the curve in Figure 2, represents the appearance of DCS symptoms in approximately 1-10% of the subjects, which we believe to be an acceptable level for the intended use of this practice. Note that this curve would suggest that a 5 minute excursion to the surface from air saturation at 110 fswg or from nitrox (pO_2=0.30 ATA) saturation at 90 fswg would result in an acceptable level of decompression sickness. This is in contrast to a previous prediction of 7 minute safe interval from nitrox saturation at only 55 fswg. However, the curve remains speculative in this area, and further information is required for substantiation.

In the practical application of this technique, it should be recalled that the excursion duration values include the time required for ascent. Thus, excursions from deeper than 90 fswg nitrox saturation are probably not practical due to the necessary ascent time. However, it may be possible to accelerate ascent to allow more time on

#2. The change in nitrogen partial pressure divided by the saturation nitrogen partial pressure.

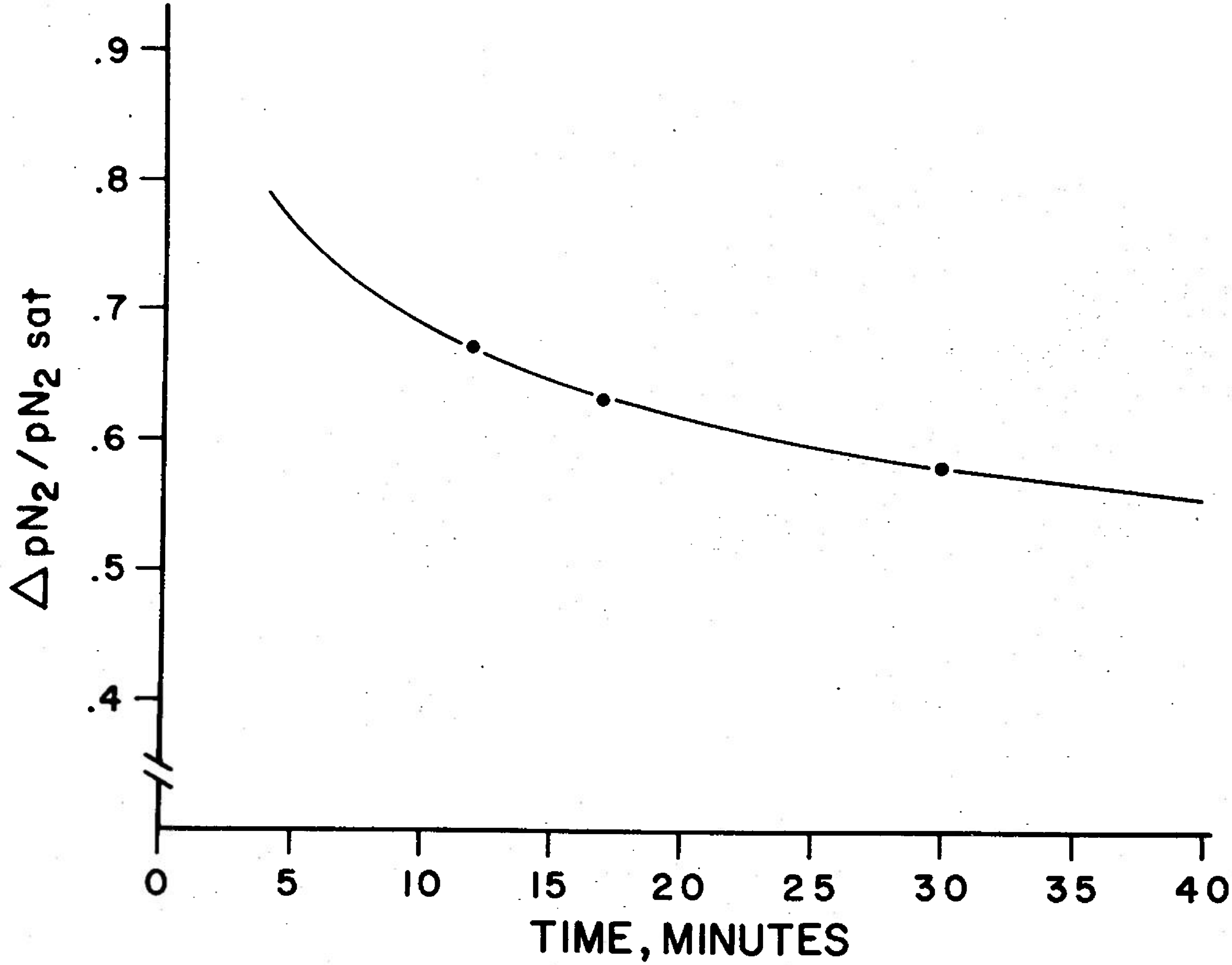

Figure #2

This curve represents the appearance of decompression sickness symptoms in 1-10% of subjects as a function of pressure reduction and excursion duration. The correlation coefficient for this power curve is 0.999.

the surface.

Application of this technique to submarine rescue entails other considerations. The DSRV holds 28 personnel, some of which could be sick or injured. The time to decompress and transfer these personnel will require a minimum of 15-20 minutes. Therefore, this study suggests that this practice can be safely employed only when the distressed submarine's internal pressure is less than 24.5 lbs/square inch gauge (PSIG) (55 fswg equivalent). If internal pressures are greater than this, an increasing morbidity and mortality from DCS can be expected. Although probably not realistic, loading less passengers at a time onto the DSRV may speed transfer to the DDC allowing transfer from greater pressures.

We recognize at least three potential sources of controversy in the experimental design. First, the time allowed for saturation at the 55 and 65 fswg level was 24 hours, which some investigators believe to be insufficient for body tissue saturation. However, this amount of time will result in saturation of all tissues with half times of less than 360 minutes, which account for the vast majority of dissolved inert gas. It seems unlikely that tissues with half times greater than 360 minutes would be responsible for either symptoms or gas phase formation in rapid decompressions. Furthermore, most tissues half times are derived from inert gas elimination, rather than uptake, and a few studies have suggested that uptake may be significantly faster (14, 15). Although other factors could be responsible for a difference between 24 and 48 hours of exposure, such as redistribution of inert gas after uptake, no studies to date have demonstrated a significant differnce in either the type or incidence of DCS after identical decompression from exposures of 24 and 48 hours breathing either nitrox or air.

Secondly, the excursions from 55 and 65 fswg follow earlier decompression/compression cycles. Possible outcomes of this are: a) the early excursions have no effect on the latter, b) the early excursions imparted a protective effect of tolerance of the latter (acclimatization), and c) the early excursions imparted a detrimental effect of tolerance of the latter. Although the results of this study do not appear to fit either b) or c), discrimination between the possibilities was not possible.

Finally, our study used a small number of subjects, although larger than other similar studies to date. Because of the well-known individual, and day to day variation in response to decompression, eighteen subjects may not allow a true estimate of the incidence. On the other hand, the type of symptoms observed in a given decompression is probably subject to less variation, and thus is believed to be fairly representative in this study.

In conclusion, the data indicate that temporary violations of established decompression requirements can occur safely, permitting either emergency decompression and/or transfer between pressurized nitrogen-oxygen environments. Furthermore, the results of this study suggest that surface excursions from air or nitrox saturation exposures are safe from depths much greater than previously predicted.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Present equipment capability precludes a pressurized transfer of personnel rescued from a pressurized, distressed submarine using either the Submarine Rescue Chamber (SRC) or the Deep Submergence Rescue Vehicle (DSRV). An unpressurized transfer risks potentially lethal decompression sickness. Experiments were conducted at this laboratory to determine the period of time available for such an unpressurized

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