USAFSAM-TP-88-10R

AN ANNOTATED BIBLIOGRAPHY OF HYPOBARIC DECOMPRESSION SICKNESS RESEARCH CONDUCTED AT THE CREW TECHNOLOGY DIVISION, USAF SCHOOL OF AEROSPACE MEDICINE, BROOKS AFB, TEXAS FROM 1983 TO 1988

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NOTICES

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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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This revision to USAFSAM-TP-88-10 includes updated information (Appendix A, etc.) with information on the last study initiated during the period covered.

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

Four major protocols, one of which includes five studies, have been initiated or completed in the 5-year period from 1983 to 1988. The studies have resulted in numerous publications which are listed as the references for this review. The purpose of this review is to provide an accessible summary of these extensive efforts and document the history of their accomplishments. The cross-reference information contained in this review is intended to simplify data accession within both published and data base records. A listing of the abbreviated title, protocol approval information, sponsorship information, computer database (HYPOB) retrieval numbers/titles, dates of exposure, and information about subjects, prebreathe, and exposure parameters for each study is followed by the published abstracts from each publication. 25

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AN ANNOTATED BIBLIOGRAPHY OF HYPOBARIC DECOMPRESSION SICKNESS RESEARCH CONDUCTED AT THE CREW TECHNOLOGY DIVISION, USAF SCHOOL OF AEROSPACE MEDICINE, BROOKS AFB, TEXAS FROM 1983 TO 1988

INTRODUCTION

Four major decompression sickness (DCS) protocols, one of which includes five studies, have been initiated or completed in the period from 1983 to 1988. Data from these experiments have been entered on the USAFSAM VAX computer under the various study titles accessible via the menu-driven HYPOB retrieval program. The studies have resulted in numerous publications which are listed as the references for this review. The purpose of this annotated bibliography is to provide an accessible summary of these extensive efforts and document the history of their accomplishments. The cross-reference information is intended to simplify data accession within both published and database records.

The studies are presented in chronological order of their first exposure date. The abbreviated title, protocol approval information, sponsorship information, computer database (HYPOB) retrieval numbers/titles, dates of exposure, and information about subjects, prebreathe, and exposure parameters for each study are followed by the published abstracts from each publication. In some cases, the original protocol approval was used as authority to begin a study and later amendments provided for more efficient acquisition of subjects or extension of protocol parameters.

Appendix A is a table of results by pressure in which percentage bends is reported in two formats. One format indicates the percentage of subjects in the study who had Grade 2 bends during any of the exposures. The other format indicates the percentage of subjects in the study who had Grade 2 bends during the first of the exposures. Presenting both formats should provide some basis of comparison between studies in which there was only one exposure and studies with multiple exposures per subject. Comparisons between studies should be done with the understanding that other experimental parameters were variable in addition to pressure and number of exposures per subject (e.g., duration of exposure, exercise level, and breathing mixture). Appendix B is a current bibliography of published works which used data from any of the studies.

METHODS

Prebreathe was with 100% O_2 unless otherwise specified. Subjects were monitored for intravenous gas bubbles, graded by the method of Spencer[1] as follows: Grade 0, no bubbles; Grade 1, an occasional bubble signal, with the majority of the cardiac cycles being bubble free; Grade 2, bubbles in many but less than one-half of the cardiac cycles; Grade 3, bubbles in most of the

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[1] Spencer MP. Decompression limits for compressed air determined by ultrasonically detected blood bubbles. J Appl Physiol 1976;40:229-35.

cardiac cycles; and Grade 4, numerous bubbles that obscure the heart sounds. Grades 1 and 2 bubbling were classified as "not severe" and Grades 3 and 4 were classified as "severe".

Bends screening exercises (Krutz and Dixon, 1987) consisted of five upward extensions of the arms while holding 5-lb weights and five chair-height knee bends. During doppler monitoring, joint flexion aided in releasing bubbles from extremities and increasing the reliability of precordial bubble detection.

Extravehicular Activity (EVA) exercises as described by Dixon et al. (1986) were similar, both quantitatively and qualitatively, to light workloads expected during actual EVA. The exercise workloads consisted of a different activity at each of three work stations and were designed to emphasize upper body stress. All exercise was performed in synchrony with a 5-s audible signal transmitted to headsets worn by the subjects who rotated sequentially from one station to another every 4 min. The subject at station 1 operated a cycle ergometer set at 0.5 kiloponds (kp) at the rate of 2 revolutions per 5 s, simulating manual closing of the Shuttle bay doors. At station 2, the subject operated a torque wrench while seated, at the rate of one tightening movement per 5 s to simulate operational tool use while weightless. The subject at station 3 pulled a Mini-Gym rope, at a resistance of 7.7 kg, using alternate hands, simulating translation along a cable in the Shuttle bay. Inderbitzen and DeCarlis (1986) found that these exercises required a mean of 148 kcal/h (1.8 kcal/h/kg) for males and 105 kcal/h (2.0 kcal/h/kg) for females.

CHRONOLOGICAL PRESENTATION OF PROTOCOLS

Sample Format

(Study #) Name of Protocol
Short Name (SGOR #; SAM ACHE #)
(Approval authority and date)
(Addenda with approval authority and dates)
Sponsorship:
VAX Title Code #: Name on VAX
(first - last exposure dates)
Number of subjects, gender
    # Exposures/subject
    # Subjects/Chamber Run
Prebreathe information
Exposure information
    Exercise information

Abstracts

Previous and Current Protocols

1. Bends Screening Index

Bends Screening Index (SGOR 83-001; SAM ACHE 82-19)
(SGP approval, 7Apr83)
(Addendum, blood drawing; SGP approval, 26Apr85; SAM ACHE #85-8)
Sponsorship: This research was supported in part by USAF Contracts F33615-81-C-0600 and F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 17: Bends Screening Index
(May83-Aug87)
Male Subjects
6 Exposures/Subject, > 4 days between exposures
3 Subjects(max)/Chamber Run
Prebreathe: 1 h
8 h/Exposure @ 4.37 psia (30,000 ft; 14 subjects w/o exercise; 31 subjects with exercise), 4.89 psia (27,500 ft; 33 subjects), 5.46 psia (25,000 ft; 29 subjects), 6.08 psia (22,500 ft; 19 subjects); breathing 100% oxygen
Bends screening exercises (4 cycles/h)

Abstract - Bends Susceptibility (Adams et al., 1984):
"Introduction. The purpose of this study was to develop a method of producing a broad spectrum of bends symptom onset times to differentiate between bends-prone and -resistant individuals. A pilot study was conducted to determine the optimal altitude to produce this differentiation. Methods. Ten male subjects were exposed to 3 altitudes: 25K, 27.5K, and 30K ft, for a maximum of 8 hrs. Each flight, conducted at least 1 week apart, was preceded by 1 hr of prebreathing 100% O_2. An exercise regimen--consisting of 5 knee bends and the lifting of two 5-lb weights, 5 times each 15 min--was performed. The subjects were monitored for intravascular bubbles and subjective symptoms. The onset times were recorded. The subjects were removed from the chamber if continuous symptoms were reported, or at the end of 8 hrs. Results. All subjects developed symptoms at 30K ft, with an average onset time of 93.5 min and a range of 42 to 172 min. At 27.5K ft, only 6 subjects developed symptoms. The average onset time was 127 min with a range of 59 to 204 min for those who developed symptoms. Eight subjects reported symptoms at 25K ft; the mean onset time was 133 min, ranging between 82 and 234 min. A high tolerance to decompression stress was exhibited by 3 subjects, and 2 exhibited high susceptibility at all altitudes. Conclusions. The data suggest that, under the stated parameters, an altitude of 27.5 K ft allows the greatest differentiation of bends susceptibility, although more data are necessary for validation."

Abstract - Validity of Ultrasonic Monitoring at Altitude for Bends Detection (Olson et al., 1986):
"Introduction. The ultrasonic precordial bubble detector (UPBD) is an inexpensive, portable device used to detect intravascular bubbles associated with bends. Its value as a device to warn of impending bends is controversial. This paper will present precise, well established numerical estimates of the sensitivity and specificity of the UPBD based on data from over 100 subjects at various altitudes.

Methods. Eighty-nine male and thirty female subjects were taken to simulated altitudes of 16,000 to 30,000 ft after prebreathing 100% oxygen for all but the lowest level flights. At altitude, the subjects performed mild exercise and were monitored with a continuous wave, 5 MHz Doppler bubble detector. They were returned to ground level after 6 to 8 hours or when they developed bends. UPBD sensitivity, defined as: number of bubblers who also bend/number of benders, as calculated from high altitude data where bends was prevalent. Specificity, defined as: Number of bubble-free subjects who also are bends-free/number of bends-free subjects, was determined at low altitudes where there were many non-benders. Results. The results showed that the specificity of the UPBD was 64% at 16,000 ft and 50% at 27,500 ft. The sensitivity was 86% at 30,000 ft and 80% at 27,500 ft. Conclusions. It was concluded that the UPBD, as a warning device for impending bends, is reasonably sensitive and can be expected to predict the majority of cases. It is, however, not very specific and will yield many false positives."

Abstracted from The relationship of intravascular bubbles to bends at altitude (Krutz et al., 1986):
"The detection and monitoring of intravascular bubbles using Doppler ultrasonic techniques has been a valuable tool in decompression sickness (bends) research for a number of years. This paper describes a series of studies at both low (less than or equal to 16,500 ft) and high (less than or equal to 30,000 ft) altitudes in which intravascular bubbles were monitored and correlated with the subsequent development of bends. Results have shown an excellent correlation between the occurrence of severe bubbling and the subsequent development of bends at high altitudes; however, many cases of severe bubbling occurred at low altitudes with no symptoms. Reasons for the large number of "false positives" at lower altitudes will be discussed."

Abstract from The Effects of Exercise on Bubble Formation and Bends Susceptibility at 9,100 m (30,000 ft; 4.3 psia) (Krutz & Dixon, 1987):
"This study assessed the value of controlled exercise in a bends susceptibility test. Healthy male subjects were exposed to a pressure altitude of 9,100 m (30,000 ft; 4.3 psia) for a period not exceeding 8 h on two separate days at least 1 week apart. During one exposure, subjects performed five deep knee bends followed by five upward arm extensions with 5-lb weights every 15 min; during the other exposure, they remained sedentary. Exercise and no-exercise altitude exposures were randomized between subjects. A precordial Doppler monitoring technique was used to record venous bubbling at 15-min intervals. Bends was diagnosed from subjective symptoms. Results have shown that controlled exercise decreases time to maximum venous bubbling and increases the incidence of Grade 2 bends compared to no-exercise conditions. Exercise also appears to increase the validity of precordial Doppler monitoring as a method to predict bends onset."

Abstract from Preliminary Findings: Bends Screening Index Study (Smead, 1987):
"Objective: To determine the extent of the relationship between intravascular bubbling at altitude and the development of limb bends.

Such data could be used to develop a test for bends susceptibility based on the timing and/or intensity of intravascular bubbling. An additional purpose of the investigation was to identify characteristics which might predispose an individual to bends. Methods: Forty-eight male volunteers made a total of 190 man-flights to four selected altitudes (30000, 27500, 25000, and 22500 ft pressure equivalent) in a hypobaric chamber. The subjects' ages ranged from 19 to 48, and all were in good health. Subjects denitrogenated for one hour prior to the flight, and continued breathing 100% oxygen at altitude. Light periodic exercise was performed during the flight, which continued for eight hours unless terminated sooner by the development of grade 2 limb bends (constant moderate pain which resolved on descent). Intravascular bubble grade was determined by ultrasound every 15 minutes: 0 to 4 on the Neuman scale with grades 3 and 4 classified as significant. Results: Altitude (25000 ft and above) did not significantly affect the incidence of limb bends which ranged from 70% to 74% (43% at 22500 ft), but did affect the time of onset, with increased time to bends at each successively lower altitude. Incidence of significant intravascular bubbling varied erratically between 66% and 78% at and above 25000 ft (51% at 22500 ft), but time to onset was similar to the bends pattern. Although the association between bends and bubbling was strong (Chi Square = 9.404, p = 0.002), and intravascular bubbling preceded limb bends in 93 of 126 cases, significant bubbling was correctly negative in only 31 of 64 flights without bends (sensitivity = 0.738, specificity = 0.484). Age stood out as the most significant predeterminate for bubble susceptibility (t = 3.13, p = 0.002)."

Abstract from An Evaluation of Precordial Ultrasonic Monitoring to Avoid Bends at Altitude (Olson et al., 1988):
"Several investigators have reported that intravascular bubbles can be detected in decompressed subjects before they develop bends. The altitude exposures were generally of short duration with a limited number of subjects. This important preliminary finding needed to be verified in a larger sampling of long duration altitude exposures. In this experiment, 32 subjects in 82 flights were taken to 27,500 ft simulated altitude for 8 h or until the subject developed mild but steady joint pain (bends). Many subjects took more than one flight. At altitude, the subjects were monitored for circulating bubbles by a team of well-trained, experienced technicians. It was determined that bubbles, clearly audible even to untrained observers, occurred in 77% of the flights in which the subjects developed bends. On the other hand, no bubbles were found in 61% of the flights in which the subjects remained bends free even though the subjects were monitored by more than one experienced technician. Therefore, at 27,500 ft ultrasonic monitoring will miss about 25% of the subjects who developed bends (false negatives) and will incorrectly identify a little less than half of the subjects who do not develop bends as potential benders (false positives)."

Abstract - Bubble Detection with an Echo-Image/Doppler Combined Probe Versus Separate Probes: A Comparison of Results. (Webb et al., 1989b):

"The ability to monitor a subject for intravascular bubbles during decompression using precordial Doppler and 2-D echo-imaging in a single probe offers the advantage of simultaneous visual and audio observation. This advantage should result in better detection and fewer false negatives (cases where decompression sickness, DCS, occurred without detection of bubbles). Better methods of bubble detection should increase understanding of the bubble-DCS relationship. Records of decompression exposures from ground level to simulated altitudes of 22,500 and 25,000 ft from combined probes (112 subject exposures) or separate probes (65 subject exposures) have provided information on the sensitivity and specificity of each method. Sensitivity is defined here as the number of bubblers who had DCS divided by the total number with DCS. With separate probes, the sensitivity was 79% (31/39) and with the combined probes, the sensitivity was 90% (36/40). Specificity is defined here as the number of bubble-free subjects without DCS divided by the total number of subjects without DCS. The specificity was 33% (9/27) with separate probes and 31% (22/72) with combined probes. The combined probe allows higher sensitivity as a result of fewer false negatives compared to the single probes. The greater detection capability with the combined probe also increases the number of false positives (cases where bubbles were detected but DCS did not occur). While this refinement in equipment reinforces the theory that those who exhibit DCS also have bubbles, it does little to refine the value of bubble detection as a tool for DCS prediction."

2. Decompression Sickness Protection Using an 8 psia Suit Environment

7.8 psia Male Study (SGOR 83-010; SAM ACHE #83-14)
1st study within this protocol
(SGP approval, 21Oct83)
Sponsorship: This research was supported in part by USAF Contracts F33615-81-C-0600 and F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 18: 7.8 psia Male Study
(Oct83-Jun84)
30 Male Subjects
3 Consecutive Daily Exposures/Subject,
3 Subjects(Max)/Chamber Run
Prebreathe: None
6 h/Exposure @ 7.8 psia (16,500 ft); breathing 50% O_2, 50% N_2
EVA exercises

Abstract from Decompression Sickness and Intravenous Bubble Formation Using a 7.8 psia Simulated Pressure-Suit Environment (Dixon et al., 1986):

"The purpose of this study was to determine the minimum spacesuit pressure required to prevent decompression sickness (DCS) during operational conditions in a 50% oxygen/50% nitrogen environment. In this study, 30 male volunteer subjects were exposed in groups of three, to three consecutive daily extravehicular activity (EVA) simulations at 7.8 psia (5,031 m altitude equivalent) for a continuous

period of 6 h. During each altitude exposure, the subjects participated in similar exercise workloads expected to be experienced by astronauts during a typical EVA scenario. Precordial Doppler monitoring revealed that 73.3% of the subjects had intravenous bubbling during at least 1 d of the 3 d of exposure, with 26.7% remaining bubble-free during the entire study. No correlation was found between either body fat or age and incidence of bubble formation. One case of DCS occurred during the study indicating that 7.8 psia is not sufficient pressure to totally preclude DCS in a 50% oxygen/50% nitrogen environment. The necessary pressure awaits further study."

Abstract - Determining a Bends-Preventing Pressure for a Space Suit (Krutz et al., 1988):
"It is desirable that a pressure suit used for extravehicular activity (EVA) (1) eliminate the threat of decompression sickness (bends) and (2) require no preoxygenation prior to EVA. This paper chronicles the definition of a pressure to prevent bends during EVA without preoxygenation and subsequent studies to test and evaluate this pressure using both male and female subjects with different breathing gas mixtures. METHODS. Initially, a study was conducted at 7.8 psia using a 50:50::O_2:N_2 breathing gas mixture without prebreathing O_2 and simulated EVA workloads. Since this pressure did not totally eliminate bends, a subsequent study was conducted using step-wise increases in pressure to determine a suit pressure at which both significant intravascular bubbles and bends were eliminated without preoxygenation. The results indicated that 9.5 psia met the aforementioned criteria in male subjects. To validate 9.5 psia, subsequent studies were conducted using both males and females and 40:60::O_2:N_2 and 100% O_2 breathing gases. RESULTS AND CONCLUSIONS. No cases of significant bubbling, bends, or any other detrimental physiologic effects were noted during any exposure. It appears then, from a physiologic viewpoint, that a minimum pressure of 9.5 psia should be considered as the standard for EVA from a 14.7 psia space station."

See the abstract of Olson et al. (1986) under Bends Screening Index, (1), for additional information about this study.

See the abstract of Krutz et al. (1985) under Bubble Threshold Study, (4), for additional information about this study.

See the abstract of Krutz et al. (1986) under Bends Screening Index, (1), for additional information about this study.

3. Decompression Sickness Protection Using an 8 psia Suit Environment

7.8 psia Female Study (SGOR 83-010; SAM ACHE #83-14)
2nd study within this protocol
(SGP approval, 21Oct83)
(Addendum 2; use contractor-procured female subjects; ACHE review, 14Aug84; SAM/CC review/approval, 7Sep84; SG approval, 15Mar85; SGP approval, 22Mar85; SAM ACHE #84-15)
Sponsorship: This research was supported in part by USAF Contracts F33615-81-C-0600 and F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 20: 7.8 psia Female Study
(Nov83-Jul85)
30 Female Subjects
3 Consecutive Daily Exposures/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: None
6 h/Exposure @ 7.8 psia (16,500 ft); breathing 50% O_2, 50% N_2
EVA exercises

Abstract - Female Susceptibility to Decompression Sickness and Bubble Formation Using a Simulated 7.8 psia Suit Environment (Dixon & Krutz, 1986):
"Introduction. The purpose of this study was to determine female susceptibility to decompression sickness (DCS) during simulated extravehicular activity (EVA). Methods. Thirty female volunteer subjects were exposed in groups of three to three consecutive daily EVA simulations at 7.8 psia (5031 m altitude equivalent) for a continuous period of 6 h. During each altitude exposure, the subjects breathed a gas mixture of 50% oxygen/50% nitrogen and participated in exercise workloads similar to those expected to be experienced by astronauts during a typical EVA scenario. Results. Precordial Doppler monitoring revealed that 43.3% of the subjects had intravenous bubbling during at least one of the three days of exposure. Seventeen of the thirty subjects (56.7%) were bubble free during the entire study. Five of the thirty subjects (16.7%) developed DCS as a result of exposure to these study conditions and two of these developed delayed symptoms. Three of these five subjects underwent hyperbaric oxygen treatment. Conclusion. Female subjects appear to suffer more delayed DCS symptoms necessitating more hyperbaric oxygen treatment than male subjects under the same experimental conditions. Female subjects do not appear to bubble as frequently as male subjects when exposed to these study conditions."

Abstract from Decompression Sickness and Bubble Formation in Females Exposed to a Simulated 7.8 psia Suit Environment (Dixon et al., 1988):
"The purpose of this study was to measure female susceptibility to decompression sickness (DCS) during simulated extravehicular activity (EVA) at a candidate (7.8 psia) suit pressure. Thirty female volunteer subjects in groups of three, were exposed to three consecutive daily EVA simulations at 7.8 psia (5031 m altitude equivalent) continuously for 6 h. During each altitude exposure, the subjects breathed a gas mixture of 50% oxygen/50% nitrogen, and participated in exercise workloads similar to those expected to be experienced by astronauts during a typical EVA scenario. Precordial

Doppler bubble monitoring was accomplished after each cycle of exercise workload simulations. During at least one of the three days of exposure, 43% of the subjects experienced intravenous bubbling. Of the 30 subjects, 17 (57%) did not experience detectable bubbling on any of the three days of exposure and 5 (17%) developed decompression sickness (DCS) during the study. Two cases were delayed, occurring after recompression to ground level; and three subjects required hyperbaric oxygen treatment. The results of this study suggest that female subjects may suffer more delayed DCS symptoms, necessitating hyperbaric oxygen treatment, than their male counterparts under the same experimental conditions. Female subjects did not experience intravenous bubbling as frequently as male subjects when exposed to these study conditions."

See the abstract of Olson et al. (1986) under Bends Screening Index, (1), for additional information about this study.

See the abstract of Krutz et al. (1986) under Bends Screening Index, (1), for additional information about this study.

See the abstract of Krutz et al. (1988) under Decompression Sickness Protection Using an 8 psia Suit Environment (2), for additional information about this study.

4. Decompression Sickness Protection Using an 8 psia Suit Environment

Bubble Threshold Study (SGOR 83-010; SAM ACHE #83-14)
3rd study within this protocol
(SGP approval, 21Oct83)
(Addendum; use bubble-prone subjects at higher pressures; ACHE review, 17Aug84; SAM/CC approval, 7Sep84; SAM ACHE #84-19)
(Addendum 3; add more male subjects, alter the purpose, add new altitudes, and use contractor-procured subjects; ACHE review, 14Aug84; SAM/CC review/approval/referral, 7Sep84; SGP approval, 22Mar85; SAM ACHE #84-16)
(Amendment to Addendum 3; blood drawing; SGP approval, 26Apr85; SAM ACHE #85-7)
Sponsorship: This research was supported in part by USAF Contracts F33615-81-C-0600 and F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 19: Bubble Threshold Study
(Apr84-Apr85)
Male Subjects
1 Exposure/Subject at a given pressure
3 Subjects(Max)/Chamber Run
Prebreathe: None
6 h/Exposure @ 8.0 psia (25 subjects), 8.5 psia (10 subjects), 9.0 psia (22 subjects), 9.5 psia (6 subjects), 10.0 psia (9 subjects), 10.5 psia (2 subjects); breathing 50% O_2, 50% N_2
EVA exercises

Abstract from Minimum Pressure for a Zero-Prebreathe Pressure Suit (Krutz et al., 1985):
"There are two current approaches to reducing the risk of decompression sickness during repeated extravehicular activity (EVA)

Abstract from Minimum Pressure for a Zero-Prebreathe Pressure Suit (Krutz et al., 1985):
"There are two current approaches to reducing the risk of decompression sickness during repeated extravehicular activity (EVA) without prebreathing 100% oxygen. One approach suggests the use of different pressures in the transfer vehicle, the station, and the suit. The other would use advanced pressure-suit technology to build a suit that will make different pressures unnecessary provided the bends-free suit pressure is reasonable and can be readily determined. Research at the USAF School of Aerospace Medicine since November 1982 has been directed at determining this suit pressure using human subjects at simulated altitudes of 16,500 to 10,000 feet (7.8 to 10 psia). An earlier report of this ongoing research showed that bends is not totally eliminated at 7.8 psia. The present study is a continuation of this effort to define a "bends-free" suit pressure with the initial results suggesting that this pressure begins at around 9.5 psia (from a 14.7 psia station)."

See the abstract of Krutz et al. (1986) under Bends Screening Index, (1), for additional information about this study.

See the abstract of Krutz et al. (1988) under Decompression Sickness Protection Using an 8 psia Suit Environment (2), for additional information about this study.

5. Decompression Sickness Protection Using an 8 psia Suit Environment

9.5 psia Bubble Threshold Validation (SGOR 83-010; SAM ACHE #83-14)
4th study within this protocol
(Addendum 4; validate 9.5 psia with additional subjects; ACHE review, 16May85; SAM/CC approval, 12Jul85; SAM ACHE #85-13)
Sponsorship: This research was supported in part by USAF Contracts F33615-81-C-0600 and F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 21: 9.5 psia Bubble Threshold Validat.
(Aug86-Nov86)
20 Male & 10 Female Subjects
1 Exposure/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: None
6 h/Exposure @ 9.5 psia (11,500 ft); breathing 40% O_2, 60% N_2
EVA exercises

Abstracted from Evaluation of 9.5 psia as a Suit Pressure for Prolonged Extravehicular Activity (Dixon and Krutz 1985):
The present study was undertaken to determine if a pressure of 9.5 psia would serve to prevent the occurrence of DCS in both males and females, without the requirement of prebreathing or the use of stage decompression, during a typical simulated Extravehicular Activity (EVA) scenario. Four of the twenty (20%) male subjects experienced Grade 1 or 2 bubble formation. None of the females exhibited any bubble formation. The study conditions of 40% O_2, 60% N_2 at 9.5 psia for 6 h did not result in the development of bends among any of the subjects. Thus, this pressure (9.5 psia) appears to protect the

See the abstract of Krutz et al. (1988) under Decompression Sickness Protection Using an 8 psia Suit Environment (2), for additional information about this study.

6. Decompression Sickness Protection Using an 8 psia Suit Environment

8.3 psia Study (SGOR 83-010; SAM ACHE #83-14)
5th study within this protocol
(Addendum 5; test proposed space suit pressure; ACHE review, 29Aug85; SAM/CC approval, 13Sep85; SAM ACHE #85-25)
Sponsorship: This research was supported in part by USAF Contracts F33615-81-C-0600 and F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 24: 8.3 psia Study
(Aug86-Nov86)
20 Male & 11 Female Subjects
1 Exposure/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: None
6 h/Exposure @ 8.3 psia (15,000 ft); breathing 50% O_2, 50% N_2
EVA exercises

Abstract from Decompression Sickness and Venous Gas Emboli at 8.3 psia (Smead et al., 1986):
"This study sought to determine the bends risk on decompression from sea level to 8.3 psia. On the basis of several prior studies by NASA and the Air Force, this differential was expected to result in a minimal (about 5%) incidence of mild decompression sickness, and may be the pressure of choice for the next generation NASA extravehicular activity (EVA) pressure suit. Thirty-one volunteer subjects, performing light work characteristic of EVA, were exposed to 8.3 psia (4572 m) pressure altitude for six hours in an altitude chamber. Limb bends incidence was 3.2%, and 25.8% of the subjects demonstrated significant intravascular bubbling. Those who bubbled were significantly older than the bubble-free group, but differed in no other aspect. An 8.3 psia advanced pressure suit design was considered insufficient to totally preclude the risk of decompression sickness."

Abstract - Blood Factors and Venous Gas Emboli: Surface to 429 mmHg (8.3 psia) (Webb et al., 1988b; short version of Webb et al., 1987):
"Analyses of 43 parameters were performed on blood obtained from 30 volunteer subjects before and after a 6-h chamber decompression from the surface to 429 mmHg. Eight subjects (5 male, 3 female) were bubble-prone (bubble grades 3 and 4), and 22 (15 male, 7 female) were resistant (bubble grade 0) to forming bubbles as detected with precordial Doppler. Significant ($P<.05$) differences include the following: Higher levels of cholesterol in the bubble-prone males and combined subjects (males and females) than in their resistant counterparts; higher magnesium in the bubble-prone males; shorter pre-exposure prothrombin time in bubble-prone males and combined subjects; increased partial thromboplastin time in bubble-prone females versus the resistant females who showed a decrease during exposure; higher pre-exposure hemoglobin, hematocrit, and red blood cell count in the bubble-prone females; and significant reduction in hemoglobin, red

blood cell count, and serum osmolality in the bubble-prone females during the exposure relative to changes in the resistant females. In this study, high cholesterol and hemoconcentration appear to be characteristics of bubble-prone subjects."

See the abstract of Krutz et al. (1986) under Bends Screening Index, (1), for additional information about this study.

See the abstract of Krutz et al. (1988) under Decompression Sickness Protection Using an 8 psia Suit Environment (2), for additional information about this study.

7. Pulmonary Tolerance to 100% Oxygen at 9.5 psia

9.5 psia Oxygen Toxicity Study (SGOR 86-007; SAM ACHE #86-05)
(SG approval, 26Mar87; SGPT approval, 30Mar87)
(Addendum; change investigators and define test subject physical; SGPT approval, 21Jan88)
Sponsorship: This research was supported in part by USAF Contract F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 22: 9.5 psia Oxygen Toxicity Study
(Sep87-May88)
12 Male & 12 Female Subjects
5 Consecutive Daily Exposures/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: None
8 h/Exposure @ 9.5 psia (11,500 ft); breathing 100% O_2
EVA exercise (4 cycles/h)

Abstract from Oxygen Toxicity During 5 8-h Exposures to 100% Oxygen at 9.5 psia (Webb et al., 1988a):
"We conducted a study to determine if oxygen toxicity occurs in a proposed extravehicular activity (EVA) pressure suit environment. Twelve male subjects were exposed to 100% oxygen at 9.5 psia for five consecutive days, 8 h/day while performing moderate exercise. No decompression sickness or venous gas bubbles were detected. Pulmonary function tests, physical exams, blood analyses, arterial oxygen saturation monitoring, and x-rays showed no evidence of oxygen toxicity. These results suggest that a 100% oxygen, 9.5 psia pressure suit environment could avoid both decompression sickness and oxygen toxicity during EVAs of comparable duration and physical activity."

Abstract from Human Tolerance to Five Daily Simulated Eight-hour EVA Exposures to 100% Oxygen at 9.5 psia (Webb et al., 1989c):
"Extravehicular Activity (EVA) currently involves decompression to 4.3 psia. This degree of decompression carries a significant potential for decompression sickness (DCS) which could be alleviated if a pressure of 9.5 psia could be maintained in the pressure suit. Previous research has not evaluated the potential for oxygen toxicity at 9.5 psia. Twenty-one subjects were exposed to 100% oxygen at 9.5 psia for five consecutive days, 8 h/day while performing moderate exercise to simulate a typical work-week in the proposed pressure suit environment. No DCS or venous gas bubbles were detected. Pulmonary function tests, physical exams, blood analyses, arterial oxygen

saturation monitoring, and x-rays showed no evidence of oxygen toxicity under these conditions. These results suggest that a 100% oxygen, 9.5 psia pressure suit environment could avoid both DCS and oxygen toxicity during EVAs of comparable duration and physical activity."

See the abstract of Krutz et al. (1988) under Decompression Sickness Protection Using an 8 psia Suit Environment (2), for additional information about this study.

8. Effect of Carbon Dioxide on Decompression Sickness

5.46 psia 3% CO2 Prebreathe Study (SGOR 87-004; SAM ACHE #87-8)
(SGPT approval, 9Jul87)
(Addendum; change investigators; SGPT approval, 22Apr88)
(Addendum; change exposure time; SGPT approval, 22Jul88)
(Addendum; finger stick; ACHE review, 31Aug88; SAM/CC approval, 11Oct88)
Sponsorship: This research was supported in part by USAF Contract F33615-85-C-4503 and NASA Contract T-82170.
VAX Title Code 23: 5.46 psia 3% CO2 Prebreathe Study
(Nov87-Mar89)
30 Male Subjects
4 Exposures/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: 1 h (2 of 4 exposures with 2.9-3.1% CO_2; remainder 100% O_2)
3 or 6 h/Exposure @ 5.46 psia (25,000 ft); breathing 100% O_2
Bends screening exercises (4 cycles/h)

Abstract - Audio and Visual Ultrasonic Monitoring of Altitude Decompression (Baas et al., 1988):
"Of major concern in high altitude and space flight is the development of altitude-induced decompression sickness. Bubbling occurs in a large percentage of subjects who subsequently develop decompression sickness (bends), and therefore monitoring for bubbles is an important tool in evaluating the effectiveness of specific space suit pressurization schedules. This paper details use in our laboratory of two-dimensional ultrasound with the Hewlett Packard Model Number 77020 Ultrasonic Imaging System (Sono 500). This device incorporates both visual and auditory (Doppler) real-time information for the detection of bubbles in subjects exposed to altitude. Ultrasound transducer placement is over the precordium in the acoustic window located between the fourth and sixth intercostal space, with a resulting modified short axis view of the heart. Doppler flow signals are obtained as blood passes from the right atrium through the tricuspid valve. Bubbles, when present, can be seen within the heart and heard in the flow signal. Data collected over an 18 month period of equipment operation will be presented, illustrating the suitability of an integrated auditory and visual ultrasonic system for detection of circulating bubbles."

Abstract - Effects of a Carbon Dioxide Prebreathe Gas Mixture on the Incidence of Altitude-Induced Decompression Sickness. (Baas, et al., 1989):

"Introduction. Because of the vasodilative effect of carbon dioxide in some tissues, it is hypothesized that increased perfusion from prebreathing low tensions of carbon dioxide will accelerate the nitrogen washout rate and thereby decrease the probability of bubble formation and subsequent development of decompression sickness (DCS). The purpose of this study is to determine the effect of increased carbon dioxide tension in the prebreathe gas mixture on the incidence of altitude DCS. Methods. Thirty male subjects were exposed to a simulated altitude of 25,000 ft after 1 h prebreathe of (1) 100% oxygen, i.e., control (2 exposures), or (2) 3% sea level equivalent carbon dioxide (23 torr) with the balance oxygen (2 exposures) for a total of 4 exposures. Subjects remained at 25,000 ft for 3 h or until they experienced persistent DCS symptoms. Results. To date (Sep 88), 78 altitude exposures have been conducted which resulted in 8 cases of DCS. There was no difference in incidence of DCS between the test and control groups. The carbon dioxide prebreathe test group and the control group each experienced 4 cases of DCS (10.3%). These experiments are ongoing. Conclusions. For relatively short prebreathe periods of 1 h and altitude exposures to 25,000 ft, supplementing the prebreathe mixture with 3% carbon dioxide appears to have no effect on the incidence of DCS."

Studies Planned but not Begun as of December 31, 1988

Effect of Inflight Denitrogenation on Altitude DCS

4.46 psia Inflight Denitrogenation Study (SGOR 88-003; SAM ACHE #87-30)
(SGPT approval, 9Nov87; SG approval, 9Nov87)
(Addendum, name change and add control exposure; SAM ACHE approval, 30Mar90)
Sponsorship: This research is being supported in part by USAF Contract F33615-89-C-0603.
VAX Title Code 26: 4.46 psia Inflight Denitrogenation Study
(Feb90-)
15 Subjects
8 Exposures/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: 1-2 h at ground level, 8,000', 12,000', or 16,000'.
4 h/Exposure @ 4.46 psia; breathing 100% O_2
Minimal exercise

Effect of Isometric and Isotonic Exercise on Altitude Decompression Sickness

6.07 psia Isometric/Isotonic Exercise Study (SGOR 87-007; SAM ACHE #87-15)
(SGPT approval, 17Aug87)
Sponsorship: This research is being supported in part by USAF Contract F33615-89-C-0603 and NASA Contract T-82170.
VAX Title Code 27: 6.07 psia Isometric/Isotonic Exercise Study
(May90-)
24 Subjects
9 Exposures/Subject
2 Subjects(Max)/Chamber Run
Prebreathe: 1 h
4 h/Exposure @ 6.07 psia (22,500'); 100% O_2
Moderate-heavy exercise; isometric/isotonic @ 30% max VO_2

Effect of Prebreathe with 100% Oxygen While Exercising on Incidence of Decompression Sickness (DCS)

4.3 psia Prebreathe with Exercise Study (SGOR 90-001; SAM ACHE #89-25)
(SG approval, 15May90)
Sponsorship: This research will be supported in part by USAF Contract F33615-89-C-0603.
VAX Title Code 28: 4.3 psia Prebreathe with Exercise Study
(?91-)
26 Subjects
4 Exposures/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: 1) 10 min with heavy exercise plus 5 min w/o exercise
2) 10 min w/o exercise plus 5 min w/o exercise
3) 1 h w/o exercise
4) 10 min with heavy exercise plus 50 min w/o exercise
6 h/Exposure @ 4.3 psia (30,000'); 100% O_2
EVA exercise (3 cycles/h)

Abstract from Potential for Reduction of Decompression Sickness by Prebreathing with 100% Oxygen While Exercising. (Webb, et al., 1989a): "Exercise performed for at least 30 min while prebreathing 100% oxygen prior to decompression has been reported to increase efficiency of denitrogenation by 100-500%. The incidence of decompression sickness following such a prebreathe was decreased by 50% compared to resting prebreathe. If prebreathing with exercise is to have an operational application, it must be brief, it must significantly reduce standard prebreathing times, it must not create excess fatigue, and it must use exercise equipment compatible with aerospace operations. This article provides background and recommends parameters for a test to determine the operational feasibility of prebreathing with exercise."

Decompression Sickness (DCS) Protection using a 100% Oxygen Pressure Suit Environment.

100% Oxygen Suit Environment Study (SGOR 90-; SAM ACHE #90-17)
Sponsorship: This research will be supported in part by USAF Contract F33615-89-C-0603.
VAX Title Code 29: 100% Oxygen Suit Environment Study
(?91-)
30-60 Male Subjects; 20-30 Female Subjects
1-4 Exposure/Subject
3 Subjects(Max)/Chamber Run
Prebreathe: None
6 h/Exposure @ >6.75 psia (<20,000'); 100% O_2
EVA exercise (3 cycles/h)

APPENDIXES

APPENDIX A

SUMMARY OF EXPOSURE PRESSURES AND RESULTS

PSIA	mmHg	PRESSURE ALTITUDE FEET	STUDY #	PREBREATHE TIME NOTE 1	EXPOSURE % OXYGEN NOTE 2	SUBJECTS #/GENDER	EXPOSURES #, h/SUBJ NOTE 3	EXPOSURES TOTAL #	EXERCISE TYPE NOTE 4	SUBJECTS % W/DCS 1ST EXP	SUBJECTS % W/DCS NOTE 5	EXPOSURES % W/DCS NOTE 6	MEAN MIN TO DCS NOTE 7	% W/GRADE 3-4 VGE NOTE 8	% W/GRADE 1-2 VGE NOTE 8	% W/GRADE 0 VGE NOTE 8
4.37	226	30000	1	60	100	31M	1-3, 8h	43	B	71	81	69	95	81	3	16
4.37	226	30000	1	60	100	14M	1-2, 8h	15	C	50	57	53	151	57	0	43
4.89	252	27500	1	60	100	33M	1-4, 8h	83	B	76	85	73	144	91	3	6
5.46	282	25000	8	60	100	23M	1-4, 3	77	B	26	30	12	106	96	4	0
5.46	282	25000	8	60	100	13M	1-4, 6	49	B	92	100	86	119	100	0	0
5.46	282	25000	1	60	100	27M	1-2, 8h	28	B	74	74	75	151	75	14	11
6.08	314	22500	1	60	100	19M	1-3, 8h	46	B	47	68	48	201	68	0	32
7.80	404	16500	2	0	50	32M	1-3, 6h	94	A	3	3	1	126	56	19	25
7.80	404	16500	3	0	50	32F	1-3, 6h	92	A	0	13	4	183	44	0	56
8.00	412	16000	4	0	50	25M	1, 6h	25	A	0	0	0	N/A	44	4	52
8.30	429	15000	6	0	50	20M	1, 6h	20	A	5	5	5	261	25	0	75
8.30	429	15000	6	0	50	11F	1, 6h	11	A	0	0	0	N/A	27	0	73
8.50	440	14500	4	0	50	10M	1, 6h	10	A	0	0	0	N/A	10	20	70
9.00	465	13000	4	0	50	22M	1-2, 6h	23	A	0	0	0	N/A	23	14	64
9.50	493	11500	4	0	50	6M	1, 6h	6	A	0	0	0	N/A	0	17	83
9.50	493	11500	5	0	40	20M	1, 6h	20	A	0	0	0	N/A	0	20	80
9.50	493	11500	5	0	40	12F	1, 6h	12	A	0	0	0	N/A	0	0	100
9.50	493	11500	7	0	100	12F	1-5, 8h	54	A	0	0	0	N/A	0	0	100
9.50	493	11500	7	0	100	12M	4-5, 8h	59	A	0	0	0	N/A	0	0	100
10.00	517	10250	4	0	50	9M	1, 6h	9	A	0	0	0	N/A	0	22	78
10.50	543	9000	4	0	50	2M	1, 6h	2	A	0	0	0	N/A	0	0	100

NOTE 1 -- 100% oxygen prebreathe

NOTE 2 -- If <100% oxygen, remaining gas is nitrogen

NOTE 3 -- Number of exposures per subject, maximum duration of protocol exposure

NOTE 4 -- Exercise Types: A - EVA Exercises iaw Dixon et al. (1986)
B - Bends Screening Exercise iaw Krutz & Dixon (1987)
C - Joint flexion only; no exercise

NOTE 5 -- % of subjects with Grade 2 DCS during any exposure, including the first exposure

NOTE 6 -- % of exposures with Grade 2 DCS versus % of subjects with DCS

NOTE 7 -- Mean time (min) to Grade 2 DCS for all exposures with DCS (not incl. delayed)

NOTE 8 -- % of subjects with maximum Grade of bubbles indicated on any exposure

Short Name of Each Study

Study #1: Bends Screening Index
Study #2: 7.8 psia Male Study
Study #3: 7.8 psia Female Study
Study #4: Bubble Threshold Study
Study #5: 9.5 psia Bubble Threshold Validat.
Study #6: 8.3 psia Study
Study #7: 9.5 psia Oxygen Toxicity Study
Study #8: 5.46 psia, 3% CO2 Prebreathe Study

APPENDIX B

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