FLYING AFTER DIVING

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CONTENTS

Acknowledgments v

List of Participants vi

Introduction vii

The Pressure Continuum: Need for Rational Correlation and Differentiation of the Flying and Diving Environments
C.J. Lambertsen 1

Discussion 10

NASA Requirements for Underwater Training and Surface Intervals Before Flying
D.J. Horrigan, C.K. LaPinta, and J. Conkin 11

Discussion 27

DAN 1987 Diving Accident Incidence for Flying After Diving
P.B. Bennett, J.A. Dovenbarger, B.G. Bond, and C.J. Wachholz 29

Discussion 35

Decompression Risk in Flying After Diving
R.D. Vann 37

Discussion 44

Effects of Temporary Low Ambient Pressure on Pre-Existing Gas Bubbles in the Body
H.D. Van Liew 49

Discussion 55

Experience with Altitude Provocation in Decompression Studies
E.H. Lanphier 57

Discussion 68

An Animal Model of Chokes: Comparison with Human Altitude Decompression Sickness
C.E. Lehner 71

Discussion 93

Flying After Diving: Criteria Derived from the U.S. Navy No-Decompression Limits
R.L. Bell 97

Discussion 97

Flying After Diving: Concept, Experiments and Practice in Switzerland
A.A. Buehlmann 99

Discussion 105

Review of Air Force Flying After Diving Research
R.M. Ingle 107

Discussion 119

Theoretical Considerations for Calculating Flying After Diving
R.Y. Nishi 122

Discussion 135

Flying After Diving Guidelines: A Review
P.J. Sheffield 137

Discussion 156

Workshop Discussion on the Development of Guidelines for Recreational Diving 157

CONCLUSION 163

RECOMMENDATION 164

APPENDIX A
Summary of comments on the development of flying after diving guidelines for recreational divers.
Paul J. Sheffield 165

APPENDIX B
Commercial aircraft cabin differential pressure settings and actual cabin altitudes during flights.
Michael N. Emmerman 169

APPENDIX C
Flying after Diving: A Database
Richard D. Vann 179

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The opinions, conclusions, and recommendations contained in this report are not to be construed as official or necessarily reflecting the views of the National Oceanic and Atmospheric Administration or of the Undersea and Hyperbaric Medical Society.

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INTRODUCTION

This publication summarizes the presentations and discussions of a workshop, "Flying After Diving," and recommends a guideline for recreational divers. The workshop was held 30 years after the acknowledgment that divers might be at risk if they fly after a dive.

For millions of military, commercial, scientific and recreational divers, ascent to altitude after diving has become a common practice. In 1976, a series of articles in Pressure highlighted the conflicting views on how long one should wait before flying after diving. In a membership poll, flying after diving recommendations entered a tug-of-war. On one side were conservative recommendations from the military that were intent on "zero bends." On the other side were liberal recommendations that allowed divers the maximum amount of dive time before the inevitable flight home. In 1982, the United Kingdom Diving Medical Advisory Committee Workshop formalized recommendations for commercial divers. These recommendations have been widely circulated in the open literature. However, recent patient treatment data collected by the Divers Alert Network and the United States Air Force School of Aerospace Medicine, indicates that the recommendations may not offer adequate protection for recreational divers.

The purpose of the present workshop was to review and update the fundamental issues related to decompression when flying after diving. A consensus of expert opinion was sought to establish a guideline based on current scientific knowledge. The papers are presented as they occurred at the workshop and are printed from camera-ready manuscripts provided by the authors. Discussions were transcribed from tape recordings, edited, and reviewed by the speakers. A synopsis of workshop papers is provided at the beginning of the proceedings for the convenience of the reader.

Three additional contributions have been appended as a result of taskings at the workshop. One is a summary of comments to a letter ballot used to gain a consensus of expert opinion on flying after diving guidelines for recreational divers. The second is a reprint of an article by M.N. Emmerman that discusses commercial aircraft cabin differential pressure settings and actual cabin altitudes during flight. The third is a compilation of data for human exposures to flying after diving profiles that were prepared for this workshop by R. D. Vann. All researchers known to have performed altitude ascent studies with divers were invited to provide their exposure data for this report, and we are grateful for the excellent response.

Generous support for the workshop was provided by the National Oceanic and Atmospheric Administration. We thank all who contributed interesting presentations and discussions. We appreciate the time and effort they dedicated to this workshop and hope that the reader will find these proceedings helpful.

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"THE PRESSURE CONTINUUM: NEED FOR RATIONAL CORRELATION AND DIFFERENTIATION OF THE FLYING AND DIVING ENVIRONMENTS"

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"THE PRESSURE CONTINUUM: NEED FOR RATIONAL CORRELATION AND DIFFERENTIATION OF THE FLYING AND DIVING ENVIRONMENTS"

SUMMARY

Decompression associated with various forms of underwater diving, or a separate decompression to reduced atmospheric pressures in forms of flying or aerospace activity can each produce pathophysiologic effects or death. The types and causes of decompression related events are multiple in diving and in altitude decompression sicknesses.

Present operational procedures can involve a close sequencing of underwater work and flying, compounding risks of decompression sickness in civilian industrial undersea operations, in military activity, in major aerospace development and operations, and in recreational activity.

Prevention of this compounding, and its therapeutic management, entails understanding of the physical and physiological relations involved in generation of pathologic effects in the transitions from "undersea" to "high altitude" environments.

INTRODUCTION

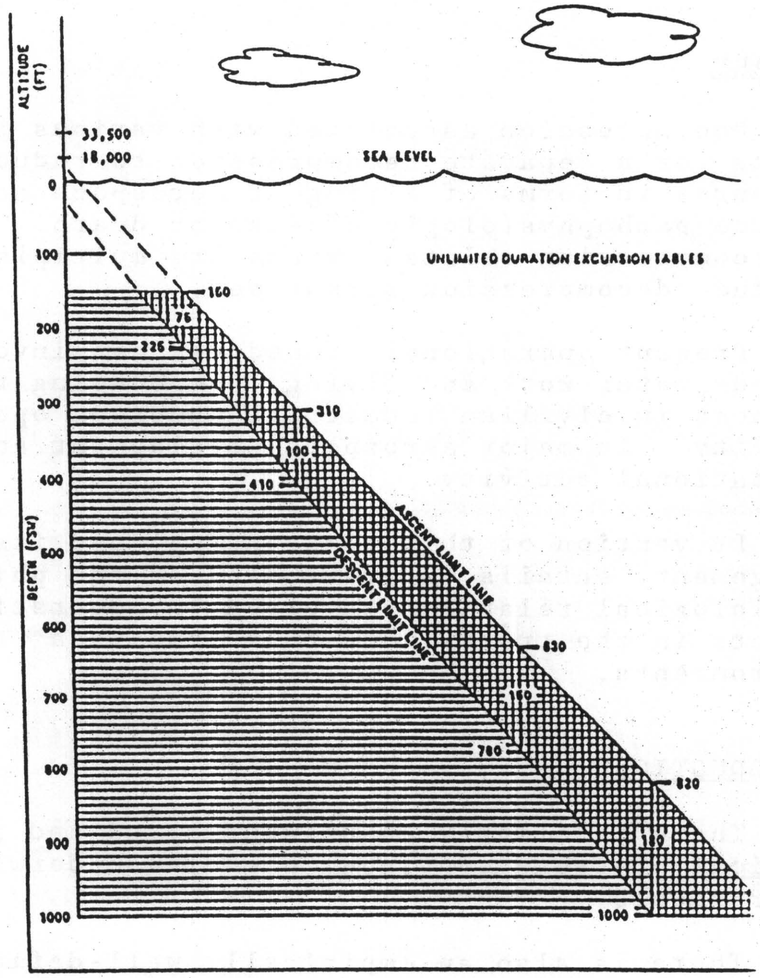
There is clearly an uninterrupted and precisely definable <u>physical pressure continuum</u> blending underwater and aerospace environments.

There is also an empirically well-defined continuum of physical and physiologic effects of human exposures over a wide range of ambient pressures.

There is undoubtedly a continuum of occurrence and mechanism for the pathophysiologic consequences of pressure reduction (decompression) along the pressure continuum.

However, defining the relationships of these decompression-related pathophysiologic events, their initiation, their scope, and their time courses is not simple, either in research or in operational practice.

FIGURE 1



THE PURE SITUATIONS OF DIVING OR FLYING

In spite of the stated physical continuum there is a hard-point of division between aerospace and underwater activity, represented by the air-water interface at the prevailing atmospheric pressure. Large differences therefore do exist between diving activity and flying or ascent to a higher altitude.

The diver leaves one ATA to do his work at higher pressure, then returns to one ATA in a controlled manner to eliminate the excess inert gas dissolved while working.

The aviator or passenger or astronaut leaves one ATA to be at a lower ambient pressure, and eliminates inert gas while working there, then re-accumulates inert gas to natural levels on return.

THE PHILOSOPHY OF THE CONTINUUM

To examine the philosophy of a continuum, in relation to combined diving and aerospace exposures, several questions will need full answers, e.g.:

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What forms of decompression sicknesses are involved?

What common features of specific decompression effect exist?

What are specific differences of decompression or effect?

What practical considerations affect safety in "flying after diving" or "diving after flying"?

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These questions will be elaborated as a function of this "Introduction To The Workshop."

WHAT ARE COMMON CHARACTERISTICS OF UNDERSEA AND AEROSPACE DECOMPRESSION SICKNESSES (GAS LESION DISEASES)?

Except for pulmonary barotrauma, decompression sickness is not a single yes or no event, in either undersea or aerospace activity. It is not a "threshold phenomenon" at a single tissue site, requiring a distinctly quantitatable physical state which overpowers physiological mechanisms and thereby produces symptoms.

Decompression sicknesses are in each case generalized systemic processes of gas phase separation and expansion, which, if severe enough in enough of the right micro-anatomical locations, will subjectively or objectively be recognized as existing in such locations. They can simultaneously go unrecognized in many different locations elsewhere (Fig. 2).

Grouping of decompression sickness effects, as for example into type I (pain only) and type II (neurologic), are not sensible descriptors of the fundamental processes involved in either diving or flying. Any decompression sickness is surely a diffuse continuum of graded degrees of pathophysiologic event and effect, in myriad scattered locations, each of which has its own local stress-effect consequences on function or structure.

FIGURE 2

PATTERNS OF DECOMPRESSION SICKNESS
(ANY COMBINATION, ANY SITE, ANY DEGREE)

ASYMPTOMATIC BUBBLE FORMATION - INTRAVASCULAR, SOFT TISSUE

CUTANEOUS - ITCHING, BUBBLE FORMATION, LESIONS ("SKIN BENDS")

LIGAMENTOUS, FIBROUS TISSUES - "BENDS". PAIN, TENDERNESS

PULMONARY - "CHOKES". SUBSTERNAL DISTRESS, COUGHING, SHALLOW RESPIRATION, PROFOUND HYPOXEMIA, SYNCOPE AND SHOCK

CARDIOVASCULAR - HYPOTENSION, LOW URINE OUTPUT, SHOCK, INCREASED VASCULAR PERMEABILITY(?)

HEMATOLOGIC - PLATELET AGGREGATION (?), COMPLEMENT ACTIVATION (?), PROTEIN LOSS, DECREASED PLASMA VOLUME.

NEUROLOGICAL - SPINAL MORE THAN CEREBRAL OR MEDULLARY. DIPLOPIA, SCOTOMATA, LABYRINTHINE DYSFUNCTION, DEAFNESS, CORD LESIONS, SENSORY LOSS, PARALYSIS

BONE - ASEPTIC NECROSIS

EYE - ASYMPTOMATIC BUBBLES IN ANY COMPARTMENT

The likelihood and the character of detectable decompression sicknesses in either diving or flying are both modified by the initial status of inert gas loading, over the full ranges of the different forms of gas-exchanging tissues involved.

Elimination of inert gas from most tissue micro-sites cannot now be practically accelerated in either diving or aerospace activity, except by reduction of inspired partial pressure of the inert gas. However, interference with inert gas elimination from slowly exchanging loci could generate prominent changes in decompression tolerance in altitude decompression, while having insignificant relation to non-saturation (excursion) diving.

The diver who thereafter flies carries with him to a lower ambient pressure whatever inert gas "loadings" remain from his dive, plus whatever finite gas lesions he retains as a consequence of his decompression from underwater activity. The latter is a pathologic adjunct to simple physiologic inert gas elimination.

WHAT ARE SOME COMMON FEATURES OF DECOMPRESSION FROM A POINT ON THE UNDERWATER-ALTITUDE PRESSURE CONTINUUM?

One common feature is the fundamental primary role of the inert gas diluent for respired oxygen.

However, inert gas uptake is not harmful in either flying or diving. Inert gas elimination is not harmful. Decompression itself is not harmful - unless it results in "gas lesions."* Gas phase development is the primary pathophysiologic event, whether microscopic or gross, in aerospace or undersea activity. It is itself caused by an elevation of tissue total gas pressure above ambient.

Another common feature is the similar inevitability of the consequences of gas lesion development, and the resulting pathophysiology of decompression sicknesses. Gas lesions do harm and detectable effects can be similar in undersea work and aviation, resulting in each case in symptoms, damaging pathology, or death.

In neither situation, diving or altitude decompression sicknesses, do gas lesions produce detectable symptoms or objective signs at all target loci.

It can be expected in each case (aerospace or undersea activity) that symptom-free decompression sickness occurs, as an un-recognized systemic disease.

In each situation it is probable that gas lesion initial development results from growth of normal, pre-existing gas nuclei, as indicated by the isobaric development of gas lesions at one ata, without prior compression or decompression.

In each case, symptoms and objective signs require time to develop, following a step in decompression.

ARE THERE DIFFERENCES BETWEEN AEROSPACE AND UNDERSEA DECOMPRESSION SICKNESSES?

Differences, at least quantitative, do exist. Some are theoretical, some physical, some physiologic, some clinical.

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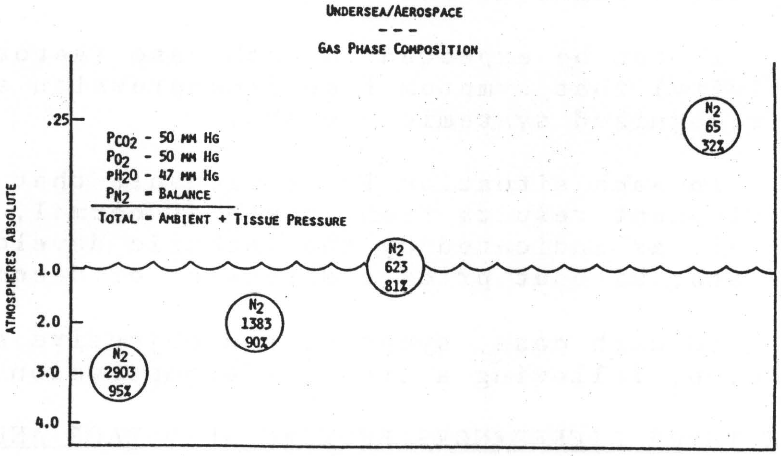
*The term "gas lesion diseases" was derived by the author to encompass decompression sicknesses, traumatic and iatrogenic arterial gas embolism, and the "superficial" and "deep tissue" forms of isobaric counterdiffusion.

A major physical difference relates to factors affecting the initial amount of dissolved inert gas in any "tissue" on beginning an altitude decompression, compared with the amount of dissolved inert gas in the same "tissues" on beginning decompression from an undersea exposure (excursion or saturation). Less inert gas is available to foster gas phase growth on ascent to altitude than is available in an undersea ascent.

Another major difference from undersea decompressions is the lower total ambient pressure at altitude. A consequence of this is the larger volume of a gas lesion at altitude in relation to the mass of gas which generated the lesion.

Still another difference is the composition of a free gas phase (gas lesion or gas embolus) (Fig. 3). At the reduced pressure of altitude the gas phase contains a lower fraction of inert gas, and a higher fraction of metabolic molecules, (including oxygen, carbon dioxide and water). Symptoms and damage can therefore conceivably be generated by evolution of smaller numbers of inert gas molecules.

FIGURE 3



ARE THERE PRACTICAL ASPECTS OF PREVENTION AND THERAPY FOR THE COMPOSITE SEQUENCES - OF "FLYING AFTER DIVING" AND "DIVING AFTER FLYING"?

These are indeed technical and common sense practical steps to both prevention and therapy in diving/flying exposures. The answers which will result from subsequent parts of this conference require blending of similarities and differences such as described above, with consideration of varied types of diving and decompression, patterns of flying, and the time courses of each. Considerable guidance can be provided by decompression analysis, by improvement in diving procedure, and by assuring guidelines relating to slowly-exchanging tissues.

In any situation, decompression to altitude resembles an "upward excursion" from saturation. It does not resemble the shallow in-water profile of a scuba diver descending briefly from the surface and returning to it.

A usual single underwater or scuba "dive" represents a superimposition of additional inert gas upon the diver's lifetime nitrogen-saturated state of all earth's inhabitants at sea level or the atmosphere of their natural altitude. Subsequent decompression to a reduced ambient pressure, as in flying, must therefore involve multiple slowly perfused tissue volumes.

One practical presumption should be that, regardless of whether symptomatic decompression sickness has occurred on ascent from diving, gas phase evolution may have occurred in multiple, diffuse tissues. Analytic methods indicate that such gas phase tends to grow in volume <u>after</u> a diver returns to one ata. The phenomenon is particularly predictable following ascent from prolonged exposure, most exemplified by decompression from saturation.

Practical aspects of monitoring must be considered. While venous gas emboli now can be monitored, gas lesions elsewhere in tissues cannot. After diving, a further decompression to ambient pressures less than one ata can be expected to enlarge the volume of any existing gas lesions by (a) expansion and (b) entry of inert and metabolic gases.

In altitude <u>recompression</u> (e.g. descent from flying) the return to one ATA tends to relieve symptoms produced by the liberated gas phase. However, in the event of either diving or altitude decompression sickness the tissue damages secondary to gas lesion development may interfere with gas phase regression during a therapy.

The prevention of development or aggravation of decompression sicknesses in flying following diving can be dependably accomplished by only three specific procedures. One is by use of oxygen-enriched inert gas-oxygen mixtures during diving and/or decompression to reduce inert gas uptake. One is by prolonged delay between diving and flying to eliminate inert gas and allow resolution of possible asymptomatic gas "bubbles." Another is by prolonged breathing of oxygen following diving, to lower the inert gas partial pressures in slowly perfused tissue sites.

When flying is the primary event, occurring before diving, it is conceivable that gas phase evolution may be initiated during flying. Subsequent diving, which may not cause full resolution of such gas phase, may predispose to diving decompression sickness on eventual ascent to one ATA. Investigation of events in such a sequence has not yet been practical, and the extreme variety of combinations of operational circumstances makes direct new experiment an unlikely general solution.

The practical solution to such interactions of diving and flying is conservative prcedure, based upon conservative analysis, and rigid discipline. Large gains can be made through integration of existing data obtained separately in undersea and aerospace research. It is necessary, for practical application to human beings, to use information obtained in human beings.

Discussion of Dr. Lambertsen's Paper

CHAIRMAN SHEFFIELD: You introduced the subject of diving after flying. How is that concept different from flying after diving?

DR. LAMBERTSEN: Since all aviators have the potential for generating bends when they are exposed to low ambient pressure, aviators can develop asymptomatic decompression sickness in flight. On return to ground level, the aviator's gas phase might not disappear immediately. Therefore, if he dives and the diving does not abolish this gas phase completely, he then enters into a diving decompression that has a potential additional factor beyond that of the person who normally dives.

MR. HORRIGAN: I have one comment on the subject. Quite often we've seen a lot of intravascular bubbles at altitude and they do not always dissolve at sea level. Consequently, the thought of cautioning people about diving after flying is well taken. There might be a physiological memory.

CHAIRMAN SHEFFIELD: At what altitude do you see bubbles?

MR. HORRIGAN: Generally the bubbles that we've seen are at less than half an atmosphere. In other words, above 18,000 feet. Usually the bubbles occur between 25,000 and 30,000 feet of altitude, but we have seen them at half an atmosphere.

DR. BENNETT: But that would not occur in commercial flying?

MR. HORRIGAN: No, unless there is a loss of cabin pressure.

DR. BUEHLMANN: The problem I think we're addressing is an acute problem, recreational diving.

MR. HORRIGAN: Yes.

DR. BENNETT: I'll get to that issue when I speak later. When flying mostly in commercial aircraft with a cabin pressure of 8,000 feet, you wouldn't expect to see the kind of bubbles that you mentioned.

MR. HORRIGAN: That's correct.

DR. BELL: The records I've read in military flying, during the Second World War, indicated that the lowest altitude where they were symptomatic apparently occurred at about 18,000 feet. Have you had cases of bends in that region?

MR. HORRIGAN: We've looked through the literature and our own experience to try to find the lowest altitude that anyone has reported symptoms. It seems that the altitude keeps getting lower. Generally speaking, half an atmosphere (18,000 ft), is considered the threshold. I would caution that there may be a range of plus or minus two thousand feet. The physiological susceptibility of the individual is also involved.

CHAIRMAN SHEFFIELD: Thank you, Dr. Lambertsen, for your excellent description of the pressure continuum of the flying and diving environments. In the next paper, Mr. David Horrigan will describe the NASA Underwater Training Program and the NASA guidelines for surface intervals before flying.

NASA REQUIREMENTS FOR UNDERWATER TRAINING AND SURFACE INTERVALS BEFORE FLYING

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Abstract

The similarity between the diver doing underwater work and the astronaut doing extravehicular activity has been exploited by NASA in the development of crew training programs in underwater facilities. The facilities used vary in depth from 9 feet to 40 feet. However, a proposed new facility is planned to be 60 feet in depth. Space suit pressures must be added to these depths to arrive at an equivalent depth physiologically. Therefore, it cannot be assumed that decompression stops would not be required.

A review of restrictions made by various Government agencies and diving organizations revealed surface time requirement while breathing air to vary between 12 and 48 hours as a function of depth and time of flying. Recommendations now being considered by NASA include a 12-hour surface time for non-decompression diving and a 24-hour duration for diving which requires decompression stops. The non-decompression diving of less than 4 hours would permit flights up to a cabin altitude of 8,000 feet.

Since the reason for the extended surface time is to eliminate from the body the excess dissolved nitrogen taken up during the dive, another approach to protection is the use of breathing mixtures containing enriched oxygen. This reduces the amount of nitrogen required and shortens the washout time on the surface. For example, a diver at 27 feet with one atmosphere oxygen in his breathing mixture would have 11.6 psi of nitrogen in the mixture. This is the same as the partial pressure of nitrogen at sea level, and would require no additional surface time. Therefore, the use of nitrox during dives of several hours in relatively shallow depths can save considerably in required surface time before flying as well as in reducing decompression time in the water.

NASA REQUIREMENTS FOR UNDERWATER TRAINING AND SURFACE INTERVALS BEFORE FLYING

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Introduction

Underwater training has been useful in preparing astronauts for extravehicular activity (EVA) in space. The training program for EVA crewmembers utilizes the Weightless Environment Training Facility (WETF) at the Johnson Space Center (JSC), in Houston, Texas (Figure 1) and comparable facilities elsewhere (Table I). A simulated EVA work station is set up underwater and the astronaut practices EVA specific techniques and use of tools that he will later be asked to use in space (Figure 2). This training has been found to be excellent preparation for EVA and it is planned to be continued in future programs. Since the crewmembers frequently fly soon after their training sessions, we have developed restrictions as to surface times after diving and before flight in training and commercial aircraft. This surface time depends on depth, time at depth, breathing gas, and intended altitudes of flight to prevent the likelihood of decompression sickness (DCS).

Current Facilities and Training

Table I lists some of the facilities used by astronauts during training or equipment evaluation. Included in the table are the depths of each tank in feet of fresh water (ffw) and the equivalent pressure depths which would be achieved when either the current space suit with a pressure of 4.3 psi or an 8.3 psi space suit, currently being evaluated, is used under water. Figure 1 is a photograph of the current facility of the National Aeronautics and Space Administration (NASA), JSC, in Houston. The depths of these facilities are such that "no decompression" diving is typical, especially for safety divers with SCUBA equipment. However, when suit pressure is added to the facility depth pressure, occasional use of decompression tables is required. Currently, the U. S. Navy Standard Air Decompression Tables are used. Figure 2 illustrates the underwater training. The EVA activity is simulated by having an underwater mock-up of the area of the space craft where the crew plan to work. Identical EVA tools are used to perform the work. As in an actual EVA, the lower extremities are used to position the body, often using foot restraints. Most of the work is done by the upper extremities, with the forearms and hands usually being the first area where fatigue occurs. The duration of the WETF training at JSC varies with requirements, but is usually two to four hours in length. However, future requirements for EVA's may dictate longer training sessions. For this reason research and analysis for appropriate decompression schedules should include pressure exposures of six to eight hours.

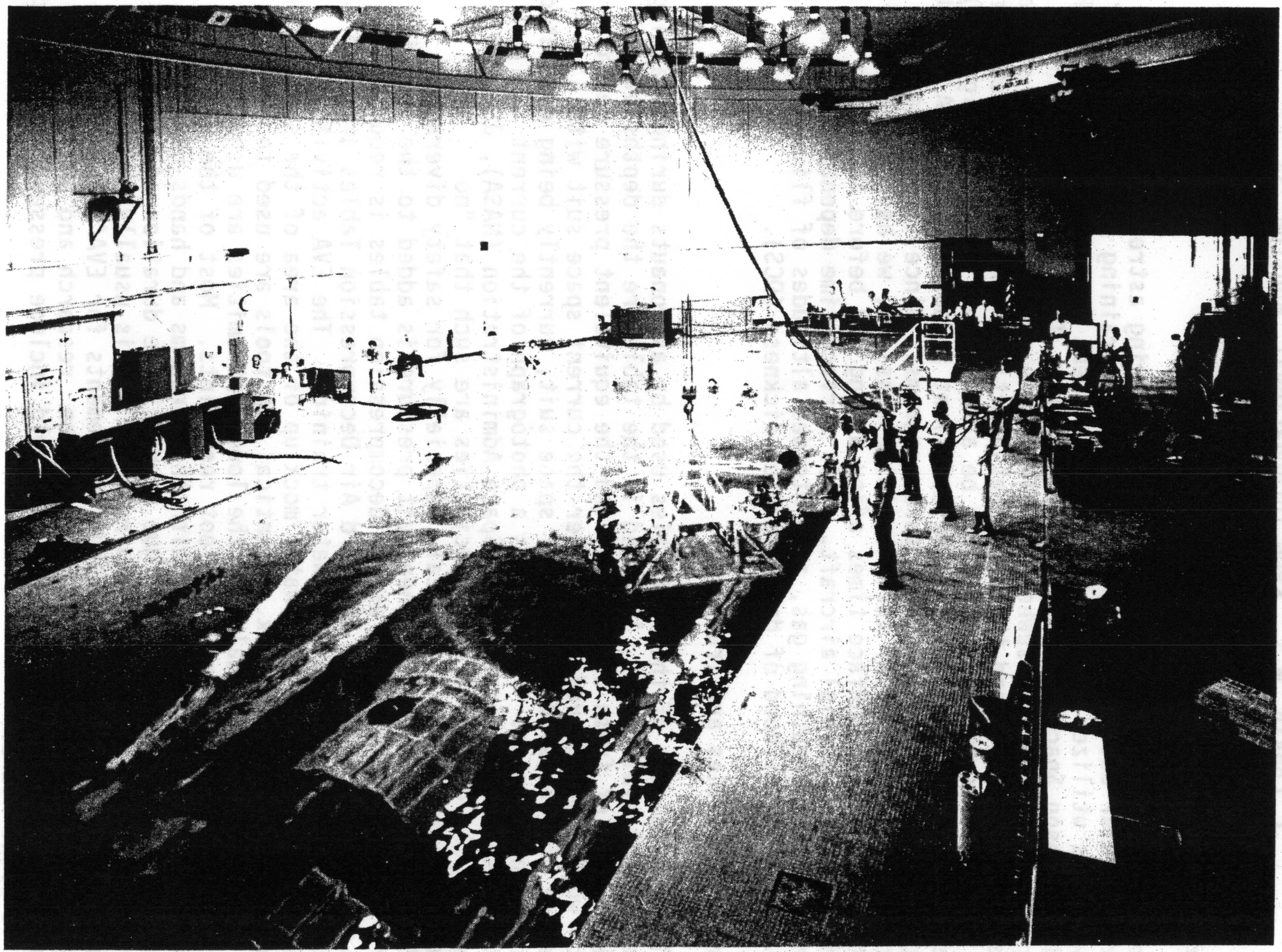


Figure 1. Current Weightless Environment Training Facility (WETF) at the Johnson Space Center

TABLE I

Underwater Training Facilities

Facility Location	Tank Depth (FFW)	Exposure Depth With	
		4.3 psi Suit or	8.3 psi Suit
JSC (Current)	25	35	44
JSC (Proposed)	60	70	79
MDSSC	35	45	54
ARC	9	19	28
MSFC	40	50	59
Brooks AFB	TBD	--	--

JSC- Johnson Space Center,
MDSSC- McDonnell Douglas Space Systems Company
ARC- Ames Research Center
MSFC- Marshall Space Flight Center
Brooks Air Force Base

Figure 2. Underwater Training for Extravehicular Activity, Johnson Space Center

FLYING AFTER DIVING AT NASA

Flying Requirements

Flying after diving may involve commercial aircraft, where the pressurization requirement is not to exceed 8,000 feet or flights in aircraft such as the T38 to much higher cabin altitudes as shown in Figure 3. A crewmember who returns to seal level after a dive to 34 feet of fresh water has undergone a reduction of ambient pressure equivalent to a ratio of 2:1. If he immediately flies to a cabin altitude of 18,000 feet, he has again decompressed by that ratio of 2:1. If non-symptomatic bubbles formed in body tissues during the ascent from the dive, they may coalesce or increase in size at altitude and cause symptoms of decompression sickness. Moreover, these bubbles are more likely to have a higher nitrogen concentration than those usually characteristic of aviators decompression sickness. Returning to sea level may not permit these bubbles to resolve, so that subsequent flights repeated within several hours may exacerbate the condition.

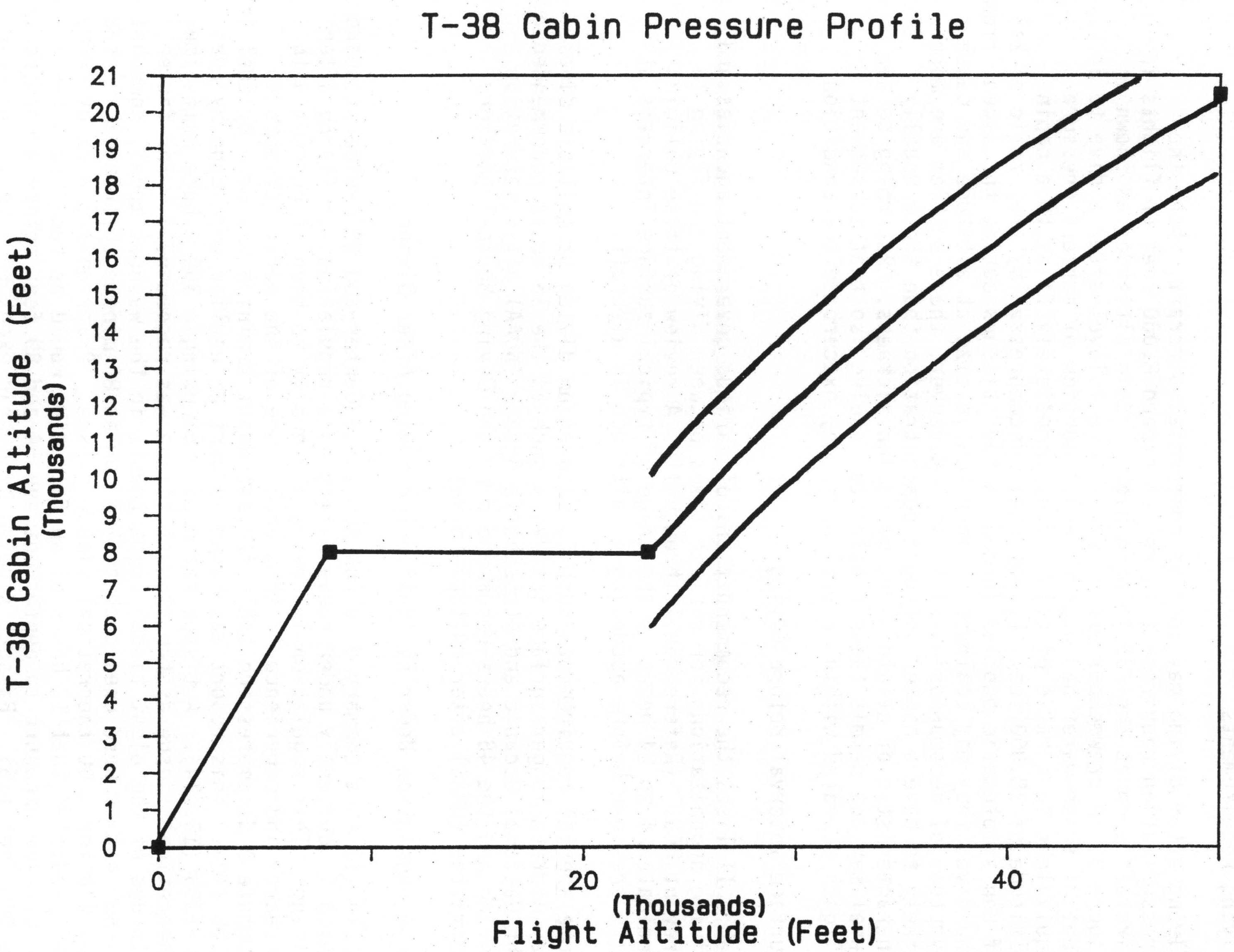
Surface Interval Before Flying

Table II lists the recommendations of various government agencies and diving organizations for surface times between diving and flying to prevent DCS. (References 1 through 11) A review of these policies indicates 4 to 24 hours is the range of typical surface intervals at site pressure before ascending to altitude in aircraft.

Some special requirements such as saturation diving or multiple dives may dictate longer surface intervals such as the 36 hours recommended by the National Oceanic and Atmospheric Agency (NOAA) after saturation diving and the 48 hours recommended by the Diving Medical Advisory Committee (DMAC) after multiple dives.

NASA Regulation Under Evaluation for Flying After Diving

Table III is a summary of a Johnson Space Center and NASA-wide standard which is currently under reevaluation as a regulation for flying after diving. This regulation is reviewed annually to keep it current with research and experience in this area. One of the early attempts to compute a decompression table for astronaut training was done by Edel in 1975 (12). This report was based in part on earlier work done by Edel in 1969 (13, 14). A tissue ratio of 1.55 using a 360 minute half-time theoretical tissue as the slowest tissue was recommended. For faster tissues of the eight tissue compartments in the washout model, somewhat higher ratios were used such as 1.8 for an 80 minute theoretical tissue and 2.0 for a 40 theoretical minute tissue. Prior animal work by Furry had predicted that 12 hours of surface time would be required after a saturation exposure to depths between 54 and 89 feet before ascending to 10,000 feet (15). Bassett studied hypobaric exposure after hyperbaric exposure and found bubbles in human subjects using a 1.5 decompression Tissue Ratio (T.R.) (16). Later work by Waligora, Horrigan, Conkin and others at JSC (17) and by several USAF investigators (18) has



Note: There is a +- 2000 foot variability in cabin pressure regulation above 23000 feet.

Figure 3. T38 Cabin Altitude as a Function of Flight Altitude

TABLE II

Recommendations for Surface Intervals (SI) Prior to Flying after Diving

Agency	No Decompression Dive (Hours of Required SI)	Decompression Dive (Hours of Required SI)	Ref
PADI	4 (< 1.0 hr dive) 12 (> 1.0 hr dive)	24	1,5
NAUI	12	24	2
DAN	24	48	3
NOAA	(Group D diver on USN tables or O2 breathing)	36*	4
USN (Diving)	(2 hours if cabin altitude more than 2300 feet)	12	6
USN (NATOPS)	24	24	7
USAF	24	24	8
NASA	12	24	9
FAA	4	24	10
DMAC	4(<1.0 hr dive before flying at 8000') 2(<1.0 hr dive before flying at 2000') 12(mult. dives < 4 hrs)	48*	11

*Flying after saturation diving

PADI- Professional Association of Diving Instructors, NAUI- National Association of Underwater Instructors, DAN- Divers Alert Network, NOAA- National Oceanic and Atmospheric Administration, USN- United States Navy, USAF- United States Air Force, NASA- National Aeronautics and Space Administration, FAA- Federal Aviation Administration, DMAC- Diving Medical Advisory Committee.

TABLE III

NASA Regulation Under Evaluation for Flying after Diving

Depth of Dive (FFW)	Type Dive	Duration (Hrs)	Surface Time (Hrs)	Flight Altitude (Feet)
< 20	No Decomp.	<4	(no restrictions)	(no restrictions)
20-62	No Decomp.	<4	12 Hrs air or 2 Hrs oxygen	>8000
20-62	Decomp. or >4 or Multi-dive	>4	24 Hrs air	Any
All Other Diving			24 Hrs air	Any

resulted in the use of a T.R. value of 1.65 for EVA's in the Space Shuttle program and 1.4 for future use in Space Station Freedom EVA's. These values are for the 360 minute tissue during saturation decompression from sea level without previous hyperbaric exposures. With altitude exposures following diving, however, the N_2 washout times of faster tissues may become more significant than in the above described EVA cases. Preexisting bubbles, which cannot be assumed to be absent in tissues after the use of standard air decompression tables, comprise a "physiological memory" which may last 12 to 24 hours, or even longer before resolution (19).

Diving after flying may also be a problem if nitrogen bubbles formed at altitude are not resolved before or during diving and are available to continue taking up nitrogen and coalescing. If sufficient data does not exist to precisely predict the probability of decompression sickness with flying after diving, almost no attention has been given to the reverse. However, JSC does have a regulation restricting diving after hypobaric chamber exposure within the previous 24 hours (Table IV). Fortunately both the descent from altitude and the initial compression of the dive are helpful in resolving bubbles formed at altitude. However, the stability of gas bubbles may permit them to remain in tissues even when an aviator has returned to sea level.

Decompression Considerations Relating to the Neutral Buoyancy Laboratory (NBL) Proposed at JSC

The NBL, proposed to be constructed and operational at JSC in 1992, is planned to be 235 feet in length, 135 feet in width on the surface, 115 feet in width on the bottom, and 60 feet in depth (Figure 4). Although the typical training will take place at about 40 feet, use of the full range of depths must be assumed. Moreover the gauge pressure equivalent to that of the space suit must be added to the pressure of the water to calculate the total pressure on the crewman. As listed in Table I, the maximum equivalent depth utilizing a proposed 8.3 psi space suit is 79 feet of fresh water. Since crew time is very important in preparation for space flight, methods to minimize decompression time and surface intervals before flying are being considered. The use of nitrox would be helpful in this regard.

Figure 5 is a guideline for the limits of oxygen use. One atmosphere of oxygen would not induce early pulmonary toxicity (2% decrement in vital capacity in 50% of the population) until nearly ten hours of breathing (20, 21). If we wish to maintain the PN2 no greater than that at sea level (11.6 psi) (Figure 6), the oxygen required at 27 ffw would be one atmosphere. Therefore, the careful use of oxygen enriched breathing gas is being studied as a valuable tool for optimum use of crew time during underwater training and in preparation for aerial flights.

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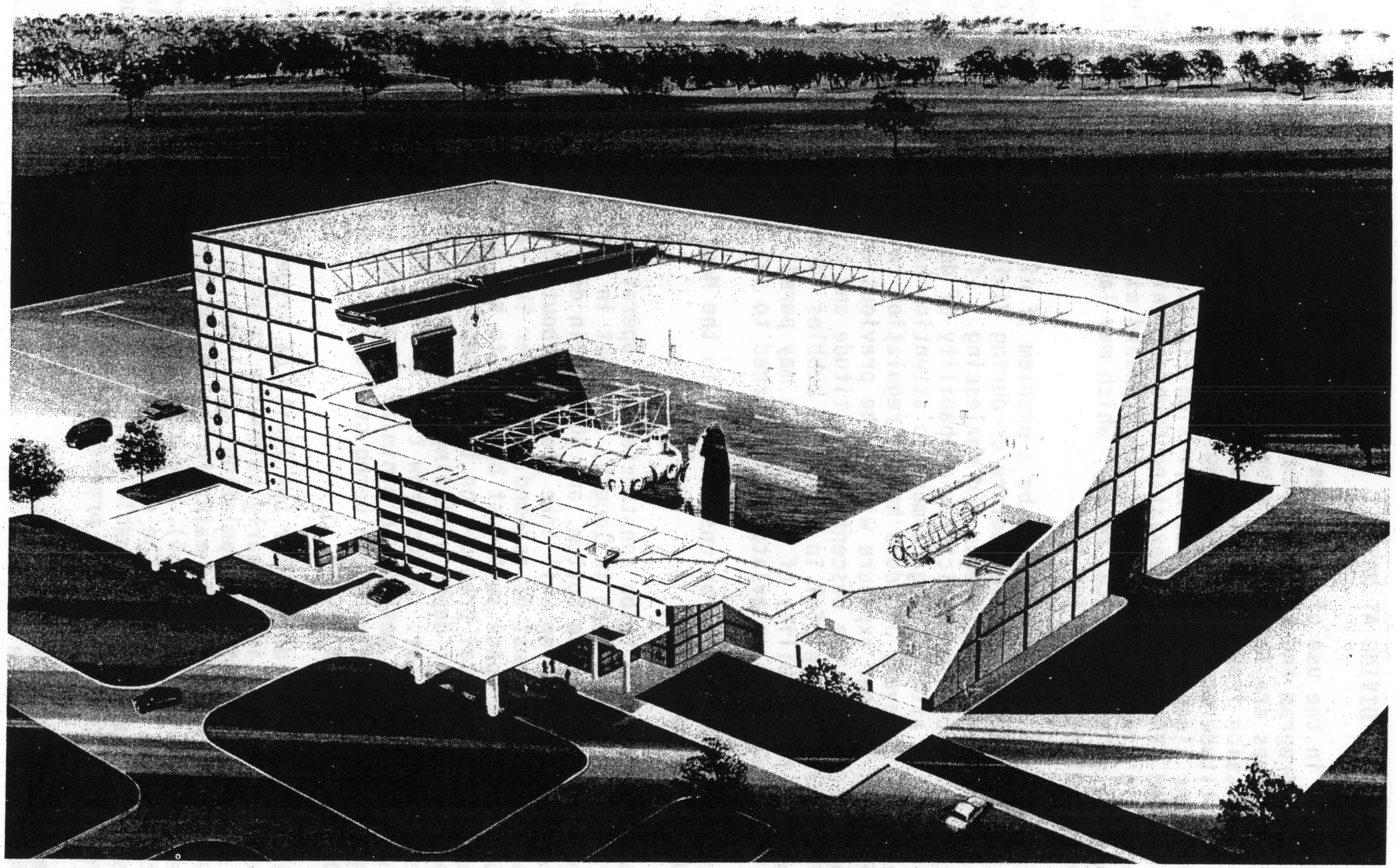

Figure 4. Proposed Neutral Buoyance Laboratory, Johnson Space Center

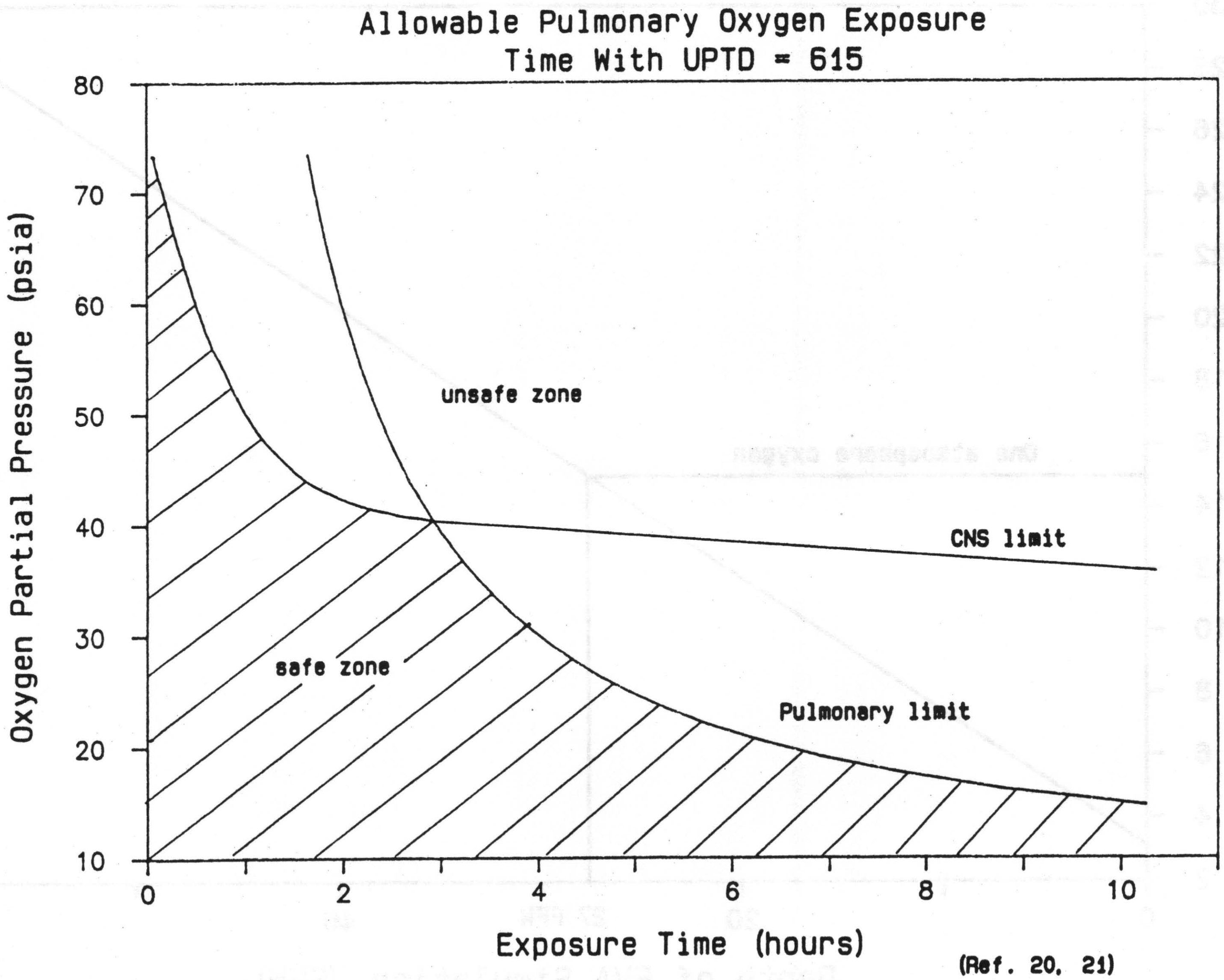

Figure 5. Guideline for Establishing Oxygen Exposure Limits, Using a Unit Pulmonary Toxicity Dose (UPTD) of 615. Data is from Clark and Lambertsen, 1971

Figure 6. pO2 Needed to Keep pN2 in the Diver's Breathing Mixture at Sea Level Equivalent

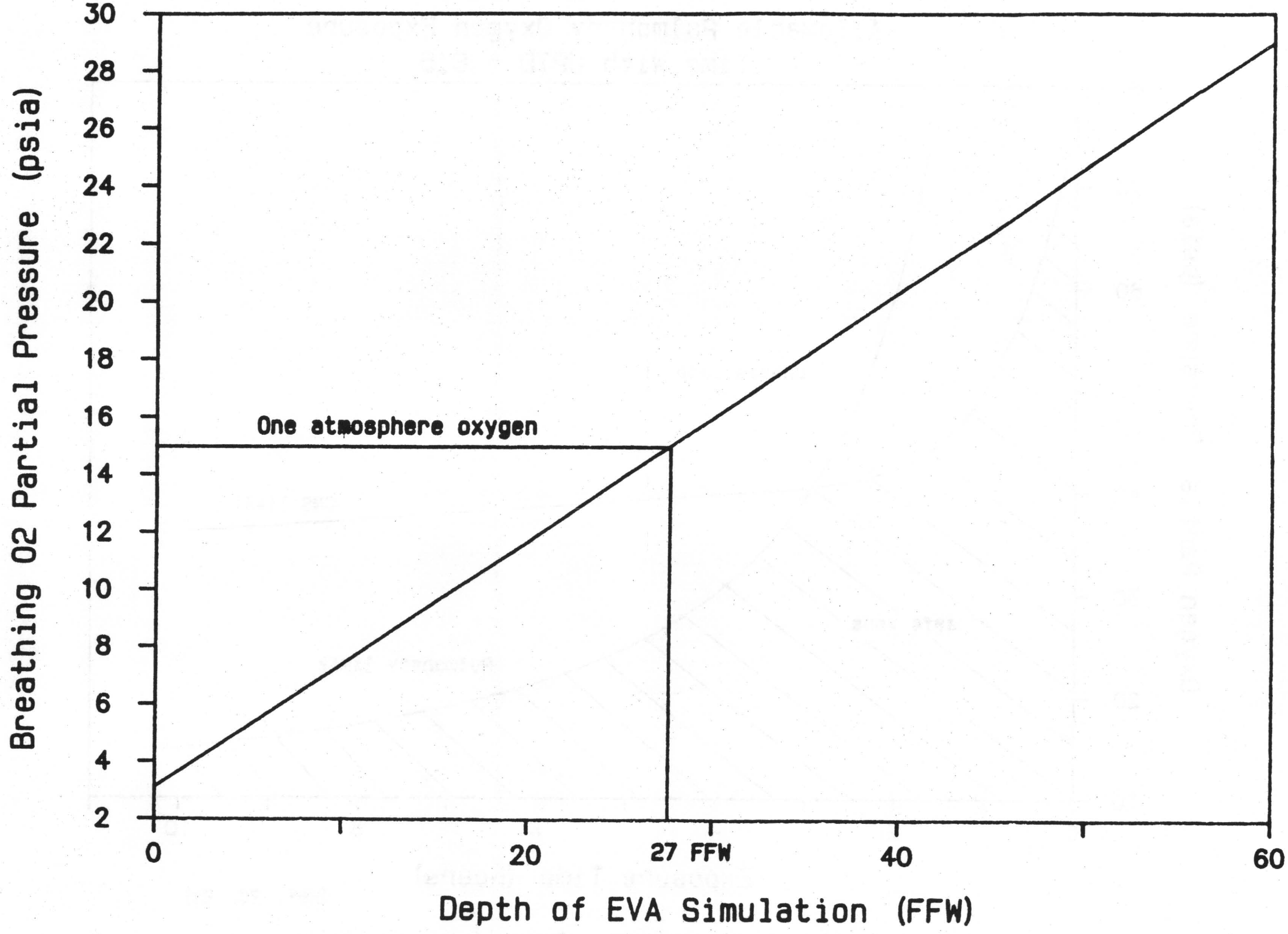

TABLE IV

JSC Requirements on Diving after Hypobaric Exposure

Exposure	Restrictions before Diving
Altitude Chamber Exposure	24 hours
Flying	none

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Discussion of Mr. Horrigan's Paper

DR. LANPHIER: I'm curious about the water temperature that you have in the 25-foot facility and what you're thinking of for the 60-foot facility. I noticed that the divers who are helping are unclad, but the person you're really interested in (the crew member) is wearing quite a formidable suit and is also working hard. How does this work out?

MR. HORRIGAN: For the crew member, the water is heated. The temperature is maintained at 88°F. The plans are to have heating in the new facility but the temperature has not been established. This is nitrogen uptake and elimination. The way the astronaut's body heat is normally released in space is via a liquid cooling garment, worn under the suit. The astronaut also wears it in the water. There haven't been any problems with it. We rotate the scuba divers more frequently than the crew members. We replace scuba divers every 30 to 60 minutes.

CHAIRMAN SHEFFIELD: Thank you very much, Mr. Horrigan. The next two papers are companion papers. Dr. Peter Bennett will discuss the DAN diving accident incidence for flying after diving. Then Dr. Dick Vann will describe his analysis of decompression risk in flying after diving.

DAN 1987 DIVING ACCIDENT INCIDENCE FOR FLYING AFTER DIVING

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Abstract

In 1988 the National Divers Alert Network (DAN) published, for the first time, an analysis of the incidence and etiology of 270 diving accident cases out of 570 reported cases. Of these 88 involved flying after diving. Exclusion of embolism and air ambulance cases left 20 cases or 7.4% of the total cases which are discussed in relation to the time elapsed between flying and the last dive, the types of symptoms involved, and the apparent need for more caution when flying after diving.

Introduction

The U.S. National Divers Alert Network (DAN) was initiated in 1980-81 to provide quick access to transportation and treatment facilities for diving accidents through a (919) 684-8111 single access number. DAN now provides a wide range of services with a respected position in diving safety in the recreational diving industry.

It is currently divided into seven Regional Centers in the United States with its National Center at Duke University Hyperbaric Center where it operates five divisions, namely Medical, Training, Research, Marketing and Financial. In addition to its emergency telephone line is an advisory number (919) 684-2948. Among the more common questions of the over 4,000 received per year is the question of flying after diving and how long to wait.

The position of DAN in regard to flying after diving or going to elevation after diving is relatively clear. It is based in part on current recreational diver experience, including experience of decompression sickness occurring in individuals who had been diving during DAN Diving Accident and Hyperbaric Treatment courses but had had difficulty when flying home. Two examples are given below.

Divers Alert Network Experience

CASE 1

Venue: Grand Cayman

Date	1st Dive	SI	Second Dive	SI	3rd Dive
10-20-85	46' for 60 min 3 min at 10'	60 min	35' for 60 min 3 min at 10'	0	0
10-21-85	102' for 20 min 5 min at 10'	75 min	30' for 60 min 3 mins at 10'	0	0
10-22-85	80' for 23 min 7 min at 10'	57 min	30' for 60 min 10 min at 10'	0	0
10-23-88	82' for 24 min 5 min at 10'	62 min	35' for 58 min 5 min at 10'	0	0
10-24-85	30' for 60 min 3 min at 10'	0	0	0	0
10-25-85	108' for 20 min 5 min at 10'	62 min	44' for 64 min 10 min at 10'	0	0
10-26-85	105' for 18 min 5 min at 10'	53 min	40' for 55 min 3 min at 10'	2 hr 41 min	30' for 60 min 3 min at 10'
10-27-85	22 hr later flew to Miami				

Note that all dives were accurately recorded by computer and no more than 5-6 minutes was spent at the maximum depth of the deep dives. The individual describes the subsequent events as follows:

"Now in regards to the diving injury, in retrospect, my earliest symptom was approximately 24 hours after the last dive on 10-27-85, when I developed a cold and somewhat numb right foot on the airplane between Miami and Dallas. This had resolved by the time I had reached Las Vegas, and the next symptom was some minimal numbness in my right cheek and over the back of my right hand on the morning of 10-28-85. This went away in an hour or so and the next symptom was in the afternoon when I was working in the garden, exerting myself moderately, and developed diffuse numbness and tingling in my right arm and hand, and right leg from the knee down, and diffuse numbness in my right cheek and jaw. It was at that time that I activated DAN and was referred to my neurosurgeon who went over me with a fine toothed comb and found no objective neurologic findings. After discussions with a diving physician, recompression was deferred because the symptoms had shown marked regression, and at that time I only had minimal residual and numbness in my right cheek, hand and foot. 500 cc of low molecular weight dextran was given IV, and breathed 100% oxygen thru a re-breathing mask for one hour. Oral therapy with 10 grs of aspirin daily and Decadron 8 mgs qid was then instituted and continued for four days. By the next day, 10-29-85, only slight residual numbness in the cheek remained and this disappeared over the next 24 hours. I have remained asymptomatic since that time."

CASE 2

Venue: Guadalupe

03-21-83	Made 2 dives	
03-22-83	Made 2 dives	
03-23-83	No dives	
03-24-83	45 ft for 30 mins	Night dive
03-25-83	14 hrs later flew to Oregon	
03-26-83	At 10 p.m. Pacific Time he developed left chest pain, numbness, and tingling in the right leg and foot and similar but milder symptoms on left side. Evaluated at local emergency room. DAN called. Referred to recompression chamber. Treated on USN Table VI with symptom relief.	

DAN 1987 Flying After Diving Accidents

Of the 270 cases analyzed in 1987, 88 involved flying after diving, representing a surprisingly high percentage of 33%. However, many of these included air ambulance flights carrying diving accident cases to a treatment area. Including the air ambulance flights, 12 cases (13.6%) were arterial gas embolism (AGE), 5 (5.7%) were decompression sickness (DCS) Type I, and 71 (80.7%) were DCS Type II. As regards air ambulance evacuations, there were 12 AGE cases and 29 DCS.

Exclusion of the AGE and air ambulance cases resulted in 20 cases that occurred during or after flying or 7.4% of the total accidents in the report. Of these twenty cases, 16 (80%) had dived within the No Decompression Limits (NDL) of the U.S. Navy tables and 4 (20%) had exceeded the tables. Symptoms occurred at varying times post altitude. Thus 6 cases reported in the first 6 hours post flight, 2 between 7-12 hrs, 5 between 13-24 hrs, 3 between 24-36 hours and 72 hours one case and over 110 hours, one case.

Six cases additionally involved DCS due to post dive elevation by driving a car etc. to heights between 1,000 ft and 7,500 ft. Four of these cases had some symptoms beforehand which became worse between 2,500 to 7,000 ft and two were initiated by the elevation to 1,000 ft (Table 1).

Divers Alert Network Experience

Table 1. DAN 1987 Data

Onset of DCS Symptoms	Post-Dive Altitude Exposure (in hours) 0-6	7-12	13-24	24-36	72	110+
Occurred or worsened during flight	6	2	5	3	1	1
Occurred with elevation by car	4	1	1	--	--	--

DAN Recommendations

Flying in an aircraft or ascending to a higher altitude after diving can significantly increase the risk of bends. Just like ascent in the water, ascent in the air, though less drastic, decreases the surrounding pressure and allows gas bubbles to expand. A commercial airliner normally is pressurized to maintain a maximal equivalent cabin altitude of 7,500-8,000 feet. Military C-130's and Lear jets can fly at safe altitudes, maintain sea level cabin pressure and are preferred for air evacuation of injured divers. One spinal cord bends victim transported by helicopter stated he could "feel the bubble get larger in his spine" and he was said to have suffered increased pain as the helicopter rose a few hundred feet over a small mountaintop.

Several methods of calculating a safe time interval for flying after diving were devised to be more practical than the U.S. Navy guideline of 12 hours. The most widely known guideline is to wait until at least the repetitive group letter D is achieved. For example, a diver surfacing in group H at sea level would have to wait 2½ hours before group D is achieved and theoretically it would be safe to achieve an altitude up to 10,000 feet. However, it has been shown that dives made to the limits of the no-decompression schedules can result in gas bubbles in the circulation that can persist up to 4 hours or longer. Bubbles have in fact been documented in animals up to 72 hours after a dive. Therefore, all of the aforementioned guidelines have the potential of yielding a bends occurrence even when guidelines are appropriately followed. It must be remembered that dive tables and guidelines are prepared from mathematical models and that the conditions experienced by chamber volunteers are not as stressful as that experienced by divers under the variety of situations in the sea.

In 1982 the United Kingdom Diving Medicine Advisory Committee recommended the following:

Divers Alert Network Experience

Minimum Surface Intervals for Flying After Diving

Diving Exposure	Time Before Flying at Cabin Altitude 2000 ft	8000 ft
1. No-D dives air or N_2 or N_2-O_2 Bottom time 60 min or less in a 12 hour period	2 hr	4 hr
2. Air or N_2O_2 dives total time less than 4 hours under pressure	12 hr	12 hr
3. Air or N_2-O_2 greater than 4 hours under pressure	24 hr	48 hr
4. All mixed gas diving	12 hr	12 hr

Recommended restriction for successfully treated cases of decompression sickness, "bends", was the same as air or N_2O_2 exposures greater than 4 hours under pressure. Divers treated for severe decompression sickness requiring saturation hyperbaric treatment should not fly for 72 hours - 1 week depending upon the success of the treatment and the advice of the treating diving medicine physician. Recently DAN has seen three cases of recurrence of bends in flight 72 hours after successful recompression treatment. Since these guidelines have occasionally resulted in bends, a more conservative approach to flying after diving is recommended as follows:

Diving Exposure	Time Before Flying at Cabin Altitude 8000 ft
1. Single No-D dives, air, bottom time 60 minutes or less in a 12 hour exposure	4 hours*
2. No-D dives, air, bottom time 60 minutes to 4 hours in a 12 hour period total	12 hours*
3. Any repetitive dives or any with a total bottom time greater than 4 hours (air)	24 hours
4. Decompression diving	48 hours

*Keeping depth to 60 feet or less will improve the margin of safety in these recommendations. The US Navy recommends waiting a minimum of 12 hours for <u>all</u> dives.

Even these guidelines are not infallible. **Since symptoms of decompression sickness can take 24 hours or more to manifest themselves, ideally one should not fly within 24 hours after a dive.** However, no "flying after diving" guideline has ever been scientifically tested.

Flying after diving has resulted in decompression sickness as long as three days after a dive. In addition, if symptoms of decompression sickness have occurred, flying may be particularly risky. If while flying a diver should develop bends symptoms it should be quickly noted which kinds of symptoms are occurring. If a person has "limb pain only" bends, the air crew should be notified, the victim should breathe oxygen at the highest possible concentration. Upon arrival, DAN or a diving medicine physician should be consulted immediately. It should be noted here that a person with any symptom of bends limb pain should be careful to evaluate for the presence of any other symptoms as they are often subtle.

If a person has symptoms suggestive of nervous system involvement, he should also breathe oxygen but the pilot should be instructed to contact DAN or a diving medicine trained physician via radio. Depending upon the circumstances, the plane may have to fly lower or land at a nearby airport. It is also important to maintain adequate fluid intake as dehydration increases the risk of a bends injury. Gatorade, juice or water is advised. Alcoholic and caffeine containing beverages should be avoided.

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Discussion of Dr. Bennett's Paper

DR. BELL: On those cases of DCS that occurred while using the U.S. Navy tables, could there have been any adjustment to the tables to take into account other contributory factors?

DR. BENNETT: No. They say that they were diving within the safe zone of the tables. Usually the question we get is, "Why me? I was doing everything I was supposed to." In the 1987 Divers Alert Network Accident Report, there's an analysis of the various effects that could be contributory: swimming, exercise, high-level exercise, cold and so on.

MR. EDEL: Peter, is it surprising that divers get decompression sickness while diving within the Navy tables? I think everybody has pretty well concluded that if you get too close to the depth/time limit, and your biological resistance to decompression sickness happens to be on the low end of the curve, you are at greater risk.

DR. BENNETT: No, I don't think we're surprised. We're making a statement that this occurs. It's documentation of large numbers of people that dive, not as the U.S. Navy dives, (doing one dive here, one dive there), but doing the kind of diving that recreational divers do -- for which the U.S. Navy tables were not designed. Recreational divers make from two to four dives per day, six or seven times during the week or maybe more. They pack in as many dives as they can. If they are on a live-aboard boat, they may be doing four to six dives a day and they'll be diving every day that boat is out in the water. For six or seven days, they pack in an enormous number of dives and then they catch a plane and fly home. The gas loadings build up with that kind of daily dives. Our advice is that if you're diving like that, take a day off at mid week. Give your body a chance to out-gas before you can start diving again. We hope then we can reduce the numbers of decompression sickness.

CHAIRMAN SHEFFIELD: In addition to your data, in the 1988 UHMS publication edited by C.L. Waite, entitled <u>Case Histories of Diving and Hyperbaric Accidents</u>, F.S. Cramer and I reported four flying after diving cases that were treated in Air Force chambers.

DECOMPRESSION RISK IN FLYING AFTER DIVING

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ABSTRACT

The limited data from the DAN accident records suggest that most decompression sickness after sport diving could be avoided by a one day surface interval before flying. Analysis of the effects of shorter surface intervals indicates that flying after diving can increase the risk by an order of magnitude. Repetitive, multi-day diving is a particular risk factor whose effects are amplified by flying. Some divers appear to be at high risk as a result of spinal injury and previous decompression sickness.

Introduction

How long must a diver wait after his last dive before he can fly safely? Figure 1 shows the Divers Alert Network (DAN) flying-after-diving cases as a function of the pre-flight surface interval. Nine cases occurred with surface intervals of 2-10 hours and 10 cases with surface intervals of 14-26 hours. There were three other cases at pre-flight intervals of 36, 72, and 110 hours. In 10 cases which had symptoms before flight (the cross-hatched area), flying cannot be considered the initiating cause. For the 12 cases in which symptoms began during or after flight (the solid area), the longest pre-flight time was 26 hours.

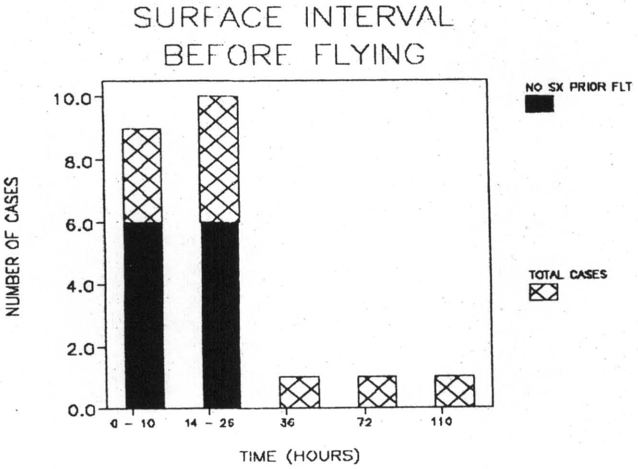

Figure 1

Figure 1 suggests that most decompression sickness caused by flying after diving could be avoided by a 24 hour pre-flight surface interval. This simple rule would permit commercial air travel only after most of the effects of diving had dissipated. The influence of shorter pre-flight surface intervals were investigated by estimating the risks of decompression sickness for several of the 1987 DAN accident reports.

Figure 2 shows Case 190 in which a 26 year old male made six dives in the Bahamas. The horizontal scale is time in minutes, and the vertical scale is percent DCS risk. The open rectangles are the dives, and the solid curves are the estimated risks.

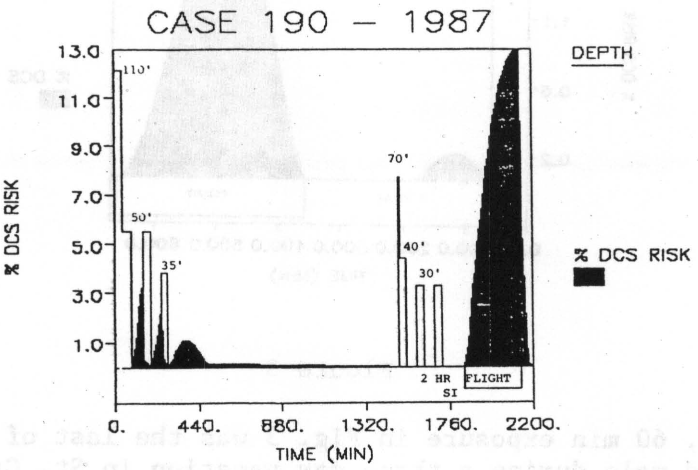

Figure 2

The first dive was multi-level with 45 min at 110 fsw and 45 min at 50 fsw. The risk was 3% at the end of a one hour surface interval. The next dives to 50 fsw for 40 min and 35 fsw for 20 min resulted in risks of 2 and 1% during the surface intervals. The 1% risk required almost 20 hrs to clear.

Three dives to 70, 40, and 30 fsw on the following day did not result in risk, but during a 2 hour surface interval prior to a commercial air flight, the diver developed headache, lower back weakness, coughing, substernal chest pain, and difficulty breathing and walking. The symptoms became progressively worse during the flight in which his risk increased to 13%.

Twenty-six hours after his last dive, the diver was treated on a Table 6 and experienced partial relief. Further HBO treatment at 33 fsw for 2 hours relieved all remaining symptoms except for muscle tightness which cleared after 3-4 days.

Figure 3 illustrates the effect of repetitive diving on DCS risk and shows the importance of complete and accurate dive profile reporting. To augment and clarify written reports submitted by treatment facilities, DAN makes follow-up phone calls to treatment personnel and injured divers. Despite these efforts, complete dive profile information often cannot be obtained.

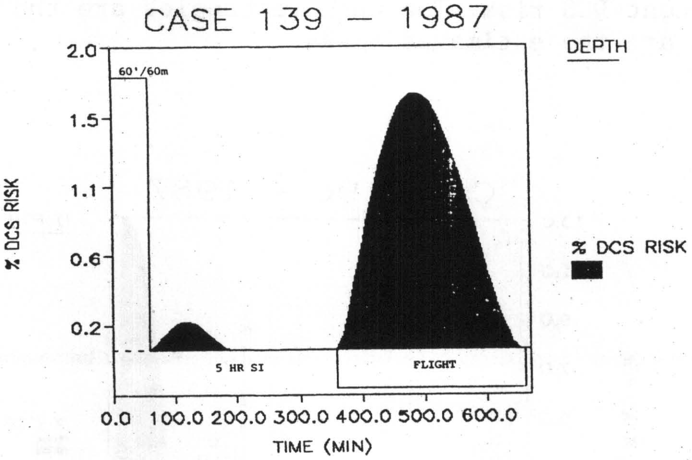

Figure 3

The 60 fsw, 60 min exposure in Fig. 3 was the last of 5 dives made by a 28 year old male during a three day vacation in St. Croix. The diver was hung-over and fatigued when he made this 7 AM dive five hours before he was to fly home. His post-dive risk reached 0.2% but cleared well before flight-time. During the flight, assumed for lack of complete information to be 5 hours long, his maximum risk was 1.7%.

The complete dive profile which was found in a supplemental report appears in Fig. 4. The first day's dives to 120 fsw for 45 min and to 75 fsw for 75 min had risks of 3 and 6%. These were multi-level dives, but as only maximum depths and total bottom times were recorded, the risks shown in Fig. 4 are overestimated. The second day's dives of 45 min at 100 fsw and 90 min at 70 fsw had risks of 2 and 5%. Twenty hours later, the diver made his final 60 fsw dive followed after 5 hours by air travel in which his risk increased to 25%. When only the final dive was considered in Fig. 3, the risk was 1.7%.

Upon landing, the diver developed extreme fatigue, headache, and arm and knee pain. He was treated 36 hours post-dive on a Table 6 and had partial relief. An HBO retreatment at 45 fsw for two hours produced additional relief although some residual pain remained.

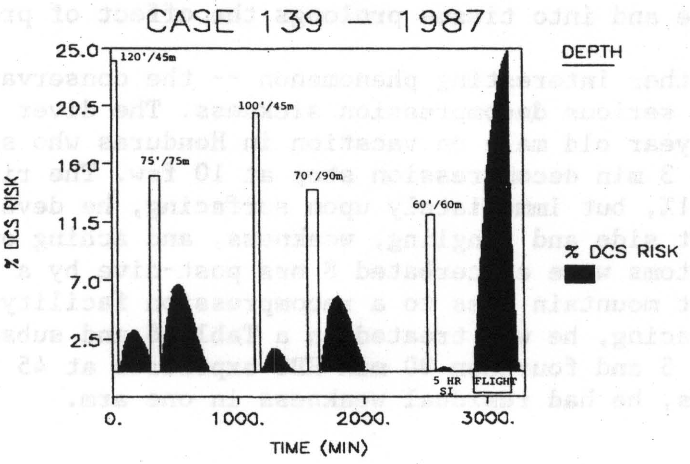

Figure 4

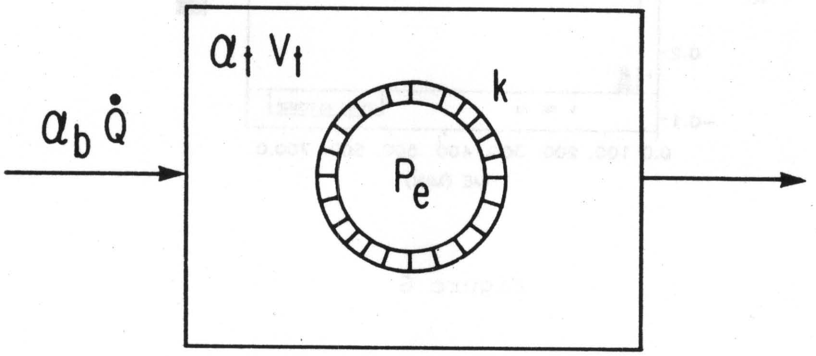

Figure 5

The foregoing risks were estimated using a decompression model with three parallel tissues of the kind shown in Fig. 5. The circle is a bubble surrounded by a diffusion barrier which simulates the diffusion-limited inert gas exchange around bubbles in tissue. Tissue around the bubble is assumed to be perfusion-limited. The largest of the three bubbles determines the risk. Risk becomes zero when all bubbles are ab sorbed, but nitrogen dissolved in each tissue does not begin to dissipate until its corresponding bubble is gone. The slow diffusion of gas out of the bubble and into tissue prolongs the effect of previous dives.

Now consider another interesting phenomenon -- the conservative dive which results in serious decompression sickness. The diver in Case 49 of Fig. 6 was a 41 year old male on vacation in Honduras who spent 35 min at 80 fsw with a 3 min decompression stop at 10 fsw. The risk after this dive was only 0.1%, but immediately upon surfacing, he developed tingling on his left side and tingling, weakness, and aching on his right side. These symptoms were exacerbated 8 hrs post-dive by a taxi ride over a 2,500 foot mountain pass to a recompression facility. Twelve hours after surfacing, he was treated on a Table 6 and subsequently received a Table 5 and fourteen 90 min HBO exposures at 45 fsw. In spite of these measures, he had residual weakness in one arm.

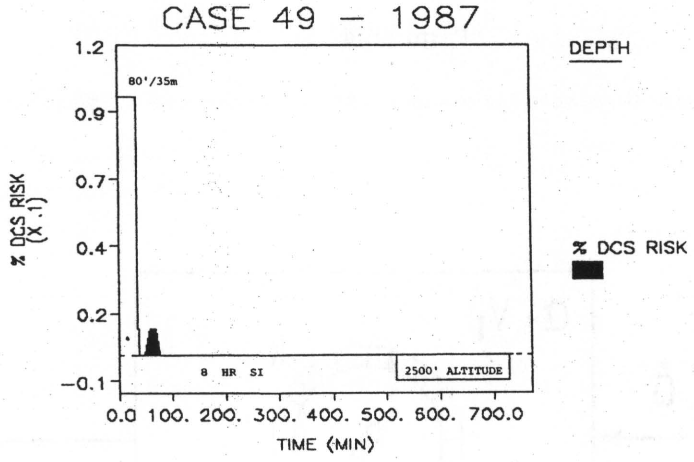

Figure 6

A search of the DAN accident records revealed that this diver had developed decompression sickness while diving in Jamaica in 1985 on the profile in Fig. 7. Four hours after his last dive to a maximum depth of 153 fsw with a risk of 0.8%, he developed numbness, tingling, and pain in his back and legs. These symptoms became worse and generalized weakness ensued during a flight 16 hrs post-dive where his risk increased to 3%. He was treated 24 hrs post-dive on a Table 5 with one extension and subsequently received additional low pressure HBO therapy. Nevertheless, over the next two years, he had coordination problems, a right arm which tired easily, and occasional tingling and weakness on his right side. When he made his 80 fsw, 35 min dive in 1987, he was still suffering from these residual symptoms.

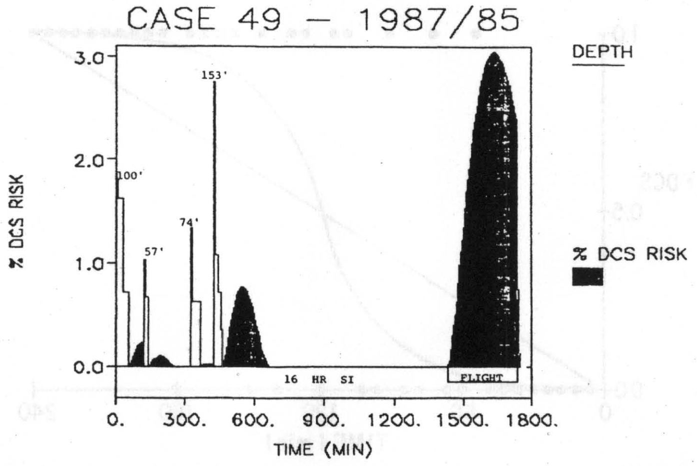

Figure 7

This diver's medical history was remarkable for an accident in 1982 which fractured two lumbar vertebrae and required surgery. Back injuries and surgery of this nature are associated with gas bubbles in the spine known as vacuum phenomena (1,2). Such accumulations of gas can find their way into the spinal canal (3,4) with potentially disasterous consequences for divers.

Case 49 demonstrates a challenge facing the development of decompression standards be they for flying after diving or repetitive no-stop diving. Individual differences in susceptibility due to spinal injury, residual symptoms from previous accident, patent foramen ovalae, or other pathology may place some individuals at high risk. These are the divers for whom standards should apply.

The standards issue can be approached statistically by relating decompression stress to the fraction of the diving population which develops decompression sickness. Figure 8 is a conceptual illustration in which a sigmoidal dose-response curve defines the relationship between no-stop time at 60 fsw and the fractional population incidence. A large fraction of the population can dive safely to 60 fsw for 60 min, but a small fraction will develop decompression sickness. This fraction can be made as small as is desired by setting standards which reduce the allowable bottom time. In Case 49 (Fig. 6), for example, the 0.1% estimated DCS risk means that 99.9% of the population can dive safely to 80 fsw for 35 min. Decompression standards for the remaining 0.1% should limit the bottom time to less than 35 min.

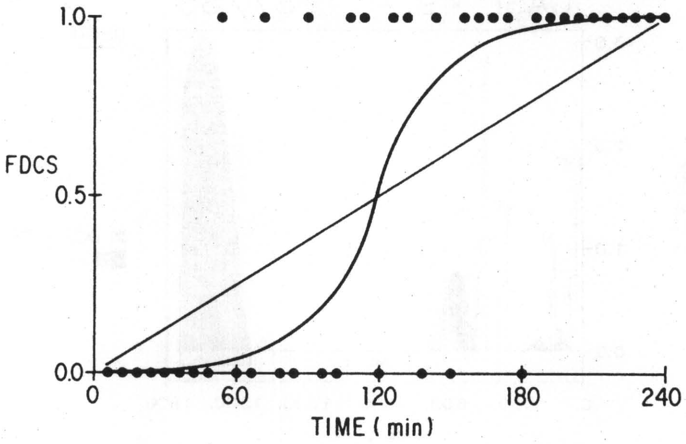

Figure 8

The foregoing risks were based on the test dives of the 1957 trials of the Navy's Standard Air Decompression Table (5). They are, therefore, extrapolations when applied to recreational divers and to repetitive, multi-day, no-stop diving followed by flying. Such extrapolations soon will be unnecessary with the advent of dive computers which record depth and time. Statistical analysis of data acquired by these computers will result in the establishment of standards for diving and flying which significantly improve both safety and efficiency.

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Discussion of Dr. Vann's Paper

CHAIRMAN SHEFFIELD: Thank you very much Dr. Bennett and Dr. Vann for these companion papers.

DR. BENNETT: Dick, I didn't quite understand the test dives on the 1957 table. Are you referring to the dives that were made by the Navy?

DR. VANN: Yes, they were the tests of the Standard Air Tables reported by Workmain in NEDU -57.

DR. BENNETT: Are you aware how those tests were done?

DR. VANN: I certainly am. They were done in warm water. The tests were working dives and I think there were no more than six tests on any one schedule.

DR. BENNETT: What was the frequency of the divers' exposure? As I understand it, they were diving almost every day, two or three times a week.

DR. VANN: That information is not provided. You can't find the surface intervals.

DR. BENNETT: This was before Hempleman's paper on acclimatization in divers. Hempleman had not come out with this until 1959 I believe. So, they weren't aware of it. They were in effect acclimatizing divers during the process and that is why on the extreme exposure tables you have experimental data that says that the exceptional exposure table at 300 feet is valid. But I wouldn't advise trying it without being acclimatized first.

DR. VANN: Unfortunately, it seems to be a little more complicated than this. The notion of adaptation or acclimatization appears to be at odds with the multi-day diving that we see occurring in the DAN cases. For example, you would be tempted to say that divers who dove every day would become acclimatized, yet they have higher risks under those conditions.

DR. BENNETT: No, that's not true. Look at the acclimatization of tunnel workers.

DR. VANN: Very different.

DR. BENNETT: If you do not expose the diver to extreme risks on day one, but are very conservative on day one, and then increase the exposure as you go, this is proper acclimatization.

DR. VANN: There's a difference in the way it's done and I think that's the key.

DR. BENNETT: I would support the evidence that we have from our data. I had a strong suspicion just from our diving courses. The divers get decompression sickness in the latter part of the week. They were diving every day. You see a lot of sensitization. But we're not seeing the acclimatization of divers.

DR. VANN: That's because they aren't concerned about the initial dive.

DR. BENNETT: That's not true. Recreational divers make their deepest dives early on, just because that's what they want to do. If we take groups to the Cayman's, the first dives on Monday, Tuesday, and Wednesday will be deep dives (that means a hundred feet or more). Later on, as they get tired and have other interests, they dive to 80 feet or 40 feet and yet they're still getting hurt on Thursday and Friday because of the accumulation of nitrogen. I'm sorry, I used to believe in adaptation too. After all, I worked with Hempleman many years. I came to learn that in recreational diving, acclimatization is not the thing; in fact, it's the other way around.

MR. EDEL: I think it was well demonstrated to you. Take a look at their data on the exceptional exposure table. How can you explain that in any way other than acclimatization? Can you make those dives and get those figures on an initial dive without any pre-exposure?

DR. VANN: Exceptional exposure tables have a tremendously high DCS incidence.

DR. LAMBERTSEN: The talk of acclimatization assumes that there are mechanisms going on that are not pathological or physiological. In diving, there's no conceivable way to acclimatize to the pathological events. You're talking about two separate things as though there was only one; there has to be two.

DR. VANN: Certainly.

MR. HORRIGAN: We looked at repetitive extravehicular activity exposures and we had subjects in a chamber at 10,000 feet for several days. We then took the subjects repetitively down to spacesuit pressure each day for about three days and determined whether they were more or less susceptible to altitude decompression sickness. With the amount of denitrogenation we had done, we did not see an increase in susceptibility. We attributed this to the fact that we went to a lot of trouble to avoid forming sub-symptomatic bubbles on their first exposure. Therefore, I don't believe there was any pathophysiological mechanism involved. Because of that, our repetition allowed them to off-gas more completely. I think if we had not had such a conservative denitrogenation schedule, we might have begun a series of events that would have caused the susceptibility for DCS to worsen each day.

CHAIRMAN SHEFFIELD: For the record, what was your suit pressure?

MR. HORRIGAN: 4.3 psi.

DR. BENNETT: That's a good point, I think the feature of the dives was that they made their deep dives first--when they were more fit and felt more like diving. That's probably the time when they generate silent bubbles and change the entire gas loading and off-loading system.

DR. BELL: We looked into the acclimatization problem. Dr. Lambertsen has suggested that there is a difference between a physiological and a pathological problem, or a physical problem and a pathological problem. The physical problem simply deals with bubble limits. If you're going to acclimatize a diver you have to get them to a pressure initially that will reduce the bubble size to a point where surface tension effects will resolve it. We have to get them down to threshold, otherwise there has been no acclimatization from that viewpoint.

DR. LANPHIER: Please clarify the utility of your DCS risk. You have four cases where your calculated DCS risks are at 0.2 to 25 percent and yet everybody had the bends. What use is that estimate to you as it relates to DCS?

DR. VANN: DCS risk is probably best viewed as a population risk. Thus, for a relatively conservative pressure profile, 0.2% of the reference population would develop DCS while a more provocative profile would result in 25% DCS. The reference population refers to those divers and the DCS incidence they experienced during a particular series of pressure profiles. Through the magic of maximum likelihood, this exposure database is used to determine the parameter values of whatever decompression model is being applied to the database. In effect, the parameter values are a representation of the database via the transforation imposed by the decompression model. We presume that of two models applied to the same database, the one with the largest likelihood (i.e., the best fit to the data) will give the truest predictions of DCS risk. In making such predictions, however, it must be recognized that the population to which the predictions apply is different from the reference population. The pressure profiles also may be different. This introduces uncertainty into risk prediction. The larger the reference population and pressure profile database, the smaller the uncertainty becomes. The limitation of such predicted population risks is that individual divers seem to differ in their susceptibility to DCS. Thus, the predicted population risk will underestimate the risk of a sensitive diver and overestimate the risk of a resistant diver. Risk estimation, therefore, is not perfect, but it is a better description of reality than the traditional threshold approach where a given pressure profile is either safe or unsafe.

DR. BELL: I think the problem is, when you report something like a tenth of a percent, for that particular individual it doesn't matter, because it's a hundred percent for him.

DR. VANN: But this is the only way that you can handle the data.

DR. BELL: But don't you have to balance that against what the DCS risks were in the population as a whole? In other words, you're looking at a single case, a tenth of a percent, at a hundred percent probability of decompression sickness. Unless you know what the risks are in the rest of the population, it's hard to evaluate what the probability is.

DR. VANN: You're asking a question which is impossible to answer because risk is determined, to a large degree, by the individual susceptibility of the diver. If we could identify those divers who are more susceptible for one reason or another and if we can convince them not to dive, then we're going to reduce the incidence. That's not going to be an easy task.

DR. BELL: If you go below a tenth of a percent for a hundred percent probability, basically you're going to get to where nobody goes in the water.

DR. LEHNER Thinking from the standpoint of the DCS risk estimates that you've generated, there are two questions. Namely, how many tissues were you modeling?

DR. VANN: In this case, three.

DR. LEHNER What were those tissues?

DR. VANN: They were tissue compartments each of which contained a bubble. Perfusion controlled the blood-tissue exchange of inert gas and diffusion controlled the bubble-tissue gas exchange. This represents an on-going program where we go one small step at a time. I think the work that you have done, Charlie, shows that Type II bends appear to occur. In our introduction, Chris Lambertsen reminded us that there are different mechanisms. You're going to do much better on correlating your data if you look at different tissues that are assigned to the various symptoms: neurological, pulmonary, or pain. In this case, they are all lumped together. If one goes back to Val Hempleman's postulate, one can avoid marginal symptoms. I think we can now say this is not the case. We have to look at it in a little more sophisticated fashion.

DR. LANPHIER: I'd like to follow that up with a comment you made on susceptible risks. Obviously, given the pathophysiological conditions introduced by Chris Lambertsen, from the standpoint of various forms of decompression, I think it's an acceptable risk.

DR. BENNETT: You've got to understand that you're dealing with 500,000 to about 3 million divers a year and you've got maybe 500 injuries. You're dealing with 0.017 percent incidence. Many people are running around with much bigger numbers in their head, including lawyers, that are just not true. The actual diving incidence risk is low. As we've said, if you happen to be that case, it becomes one hundred percent for you. If it's a very dramatic case which is paralyzed with a partial recovery, that creates a lot of interest by a lot of people. Nevertheless, the risk is much safer than skiing, for example. Skiing has an accident figure much higher than that (0.29 percent).

CHAIRMAN SHEFFIELD: Part of that risk is the altitude of the flight to which the individual is exposed after the dive. One person who has collected a lot of information from commercial airlines is Mr. Michael N. Emmerman. Mike, would you like to comment?

MR. EMMERMAN: For the last five years I've monitored aircraft cabin altitudes using an altimeter and verified the data with the flight personnel when possible. During my flights, I have recorded a number of environmental problems within the aircraft cabin. Others have been verified from seven years of U.S. Senate subcommittee documentation. [There is a report in JAMA this month on passive smoking in commercial aircraft that I found fascinating.] I don't believe we have any idea what the data really are on incidence of DCS either in the aircraft or afterwards. I work with hundreds, if not thousands, of divers every year. The one thing that is missing in the data are their denial. I see it on boats, I see it in the aircraft, I see it on the ground. I do not believe the numbers. I work with Dick Vann, I know the people. I believe that the DCS number is much larger because of denial.

I use the Edge diving computer in aircraft as a tissue simulator and I have no idea if this worked. However, it took the Edge two and a half hours to off-gas to its maximum, no matter how long the flight was. I had two 14-hour flights. After landing, it also took up to 48 hours to on-gas to its original readings at sea level. I found this fascinating. I checked with Karl Huggins and others. They think it should have worked properly, but it's not scientific. When discussing pressure related problems, we must consider the diver's predisposition. For instance, I don't know if they're drinking alcohol in the aircraft and I don't know how dehydrated they really get. I don't know how much smoke is in the cabin. I don't know their diet, the ozone concentration, or their fatigue level. I think all those things have an influence when trying to set up guidelines.

I want to suggest a questionnaire for divers who fly in commercial aircraft. The questionnaire might identify specific aircraft or specific profiles that help to identify a risk. In my opinion, there's one aircraft you may have to worry about when flying after a dive, and that's a DC-9. A DC-9 will take you to an 8,000-foot cabin shortly after takeoff. This occurred every time I was on a DC-9. In all other aircraft I've flown in, the average altitude was between 4,500 and 5,500-foot cabin pressure, no matter what the aircraft altitude was.

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CHAIRMAN SHEFFIELD: Thank you, Mr. Emmerman. Any questions or comments?

MR. HORRIGAN: Paul, one of the assumptions that we made is that commercial aircraft attain cabin pressures of 8,000 feet. What I am concerned about is how many times cabin pressures exceed 8,000 feet. Is there any experience or information on that?

MR. EMMERMAN: Using data from 150 flights, the only time we went above 8,000 feet was on landing in Quito, Ecuador, because that landing strip is at 9,200 elevation. My concern relates to those divers present in an aircraft that only went to 4,500 or 5,000 feet and never got to 8,000. If the cabin pressure didn't get to 8,000 feet, and the diver got bends, then the risks that we're looking at are very different.

CHAIRMAN SHEFFIELD: If those data are correct, one might conclude the flying following diving guidelines used by those divers were too liberal. We've now explored the environment, reviewed cases, and discussed the risk of flying after diving. The next series of presentations will be physiology. In the next paper, Dr. Hugh Van Liew will describe the response of pre-existing gas bubbles in the body during ascent to altitude.

EFFECTS OF TEMPORARY LOW AMBIENT PRESSURE ON PRE-EXISTING GAS BUBBLES IN THE BODY

H. D. Van Liew, Department of Physiology, University at Buffalo, SUNY

Bubbles in the body, such as decompression sickness bubbles which develop in blood or tissues of a diver, may be associated with symptoms or they may be "silent". In either case, the bubbles can be expected to enlarge if the person decompresses to altitude, as in flying in an aircraft. The pre-existing bubbles will grow for two reasons -- because Boyle's law decrees that a given number of molecules occupy more volume when total pressure is less, and because the inert gas in the breathing mixture (nitrogen in an air-breathing person) will diffuse into the bubble from the surrounding tissues.

In an air-breathing person, most of the molecules in a bubble are nitrogen but all other gases which are in the tissue or blood will permeate into the bubble -- oxygen, CO2, water vapor, alcohol, anesthetic gas, and so on. As each of these gases tends toward its own diffusion equilibrium between inside and outside of the bubble, it helps to set the stage for nitrogen diffusion by contributing to the difference in PN2, between the bubble and the tissue, which is known as the "oxygen window" or "inherent unsaturation".

Method

Using a computer program (BASIC and Apple MacIntosh), I simulated bubble size before, during, and after a decompression. The basis of the simulations was a modification of differential equations which predict diffusion of nitrogen into or out of a spherical bubble (1, 2):

$$dR/dt = - [\ \text{alpha}\ D\ Ps\ ][\ 1 - Pa/Pg\ ][1/R + \sqrt{Q/D}\ ] \qquad (1)$$

where R is bubble radius, t is time, alpha is solubility of nitrogen in tissue, D is diffusivity of N2, Ps is a standard atmosphere, Pa is partial pressure of N2 in the venous blood and tissue, Pg is partial pressure of N2 in the gas bubble, and Q is blood perfusion in the tissue near the bubble. Values for Pa and Pg were calculated from barometric pressures using representative values for alveolar and tissue gases (3).

The first pair of brackets in Eq. 1 contains constants. It may be helpful to look upon the items in the first bracket pair as serving to attenuate or amplify the rate of growth or decay of the bubble, dR/dt. The items in the second pair determines whether the bubble will grow or shrink and the rate of growth or shrinkage, and the items in the third pair modifies the actions of the other two pairs. The equation accounts for major variables that affect diffusion of gas into or out of bubbles and the results calculated by the equation correspond well with experimental data from bubbles which could be observed.

It was assumed that the effect of surface tension was to increase the total pressure inside the bubble and thereby to increase the nitrogen partial pressure:

$$P_g = F_{N2}\ (P_B + 2\ T/R) \qquad (2)$$

where F_{N2} is fraction of N_2 in the bubble, P_B is barometric pressure in the decompressed state, and T is surface tension.

Results and Discussion

Figure1 illustrates the N_2 partial pressures that govern diffusion exchange between a bubble and its surroundings when a person decompresses from 1 ATA to 0.636 ATA (12,000 ft altitude). Partial pressure of nitrogen inside the bubble is essentially parallel to the barometric pressure because the bubble contains O_2, CO_2, and water vapor, which are all relatively independent of pressure. The partial pressure of N_2 in the tissue (or venous blood) is lower than Pbub at the left and right sides of the diagram, but does not follow the P_B trace; nitrogen takes time to wash out of the tissue. The figure shows time without units; the behavior of bubbles depends on time it takes to decompress relative to the washout rate of nitrogen in the tissue.

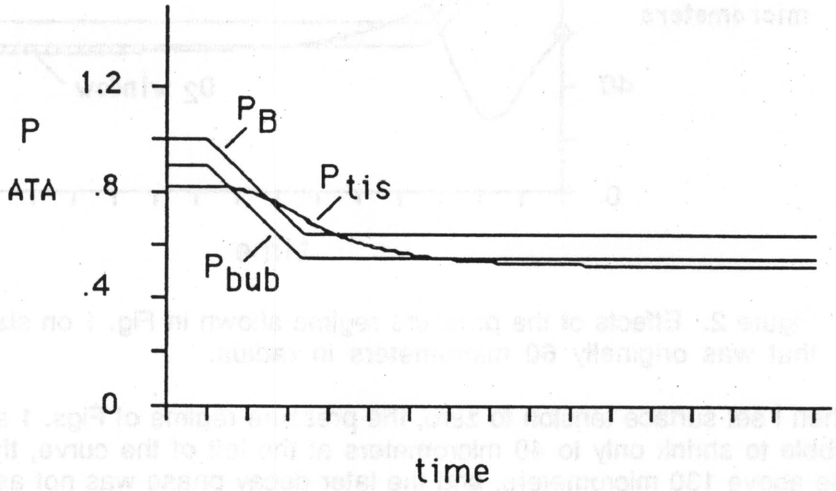

Figure 1. Barometric pressure (P_B) and nitrogen partial pressures in a pre-existing bubble (P_{bub}) and in tissue (P_{tis}) when a person is decompressed from sea level to an altitude of 12,000 feet.

Before the decompression, the partial pressure of nitrogen in the person's tissue and venous blood is approximately equal to that in air at 1 ATA, or more if the person's tissue is still carrying excess nitrogen that was taken up during a dive, whereas the partial pressure of nitrogen in the bubble is low because the bubble is at the low barometric pressure of the decompressed state. Except during washin or washout, nitrogen in the tissues is set by nitrogen in the lungs, and nitrogen in the lungs is relatively low because oxygen in the lungs is relatively high. Carbon dioxide is close to being the same in lung and tissues, so the nitrogen difference between tissue and bubble is set mainly by oxygen.

At the right-hand side of Fig. 1, nitrogen in tissue is again below nitrogen in the bubble, but not as much below as at 1 ATA at the left. The oxygen window is less at 12,000 feet than at sea level because lung oxygen is less due to the rarified air, but physiological mechanisms operate to keep tissue oxygen about the same as at sea level.

Figure 2 shows the results of the pressure pattern illustrated in Fig. 1; the radius of a pre-existing bubble decreases in size, then grows, and finally, when bubble nitrogen is again below tissue nitrogen, shrinks again. The Boyle's law effect of decompression on bubble size would have increased the radius from 60 only to 70 micrometers, so we conclude that the addition of gas by diffusion is a major effect. The pressures shown in Fig. 1 are repeated in Fig. 2, except that the oxygen window for causing bubble absorption is dramatized by hatching.

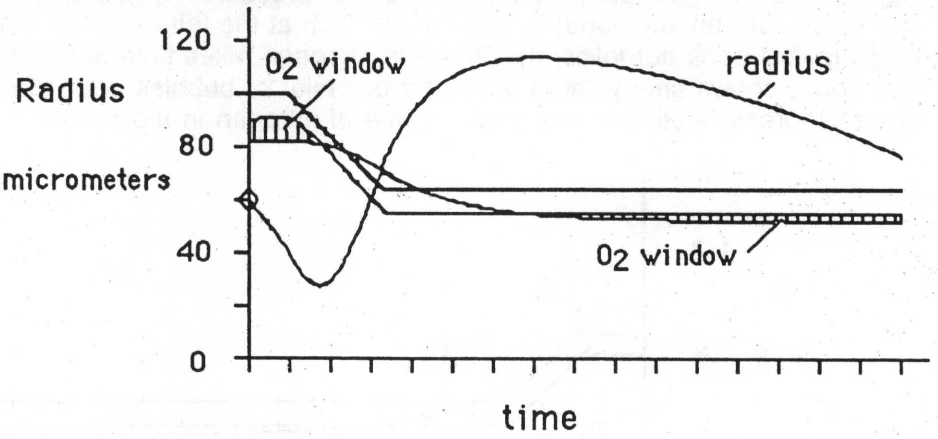

Figure 2. Effects of the pressure regime shown in Fig. 1 on size of a bubble that was originally 60 micrometers in radius.

When I set surface tension to zero, the pressure regime of Figs. 1 and 2 caused the bubble to shrink only to 40 micrometers at the left of the curve, the peak radius was a little above 130 micrometers, and the later decay phase was not as steep as in Fig. 2. Similarly, when I simulated the effect of some "other gas" which exerted a partial pressure of 76 mmHg, the bubble grew a little larger than without the added gas and the magnitude of the effect was about the same as the effect of setting surface tension to zero; for this simulation, it was assumed that the other gas, such as a gaseous anesthetic, was in alveolar air and in tissues. Fortunately alcohol will not cause appreciable enhancement of bubble growth; even at toxic levels in a person's blood and tissues, alcohol will exert a partial pressure of less than one mm Hg.

GROWTH AND DECAY OF BUBBLES AT ALTITUDE

If there is a switch of breathing gas, say from air to heliox or from heliox to air, there are four main determinants of bubble growth or shrinkage -- rates of washin or washout from the tissues for the two inert gases, and rates of permeation in or out from the bubbles for the two gases; the bubble's career is determined by a more complex set of variables than is dealt with here.

Because of the oxygen window, bubbles in the body can be expected to shrink unless there is a decompression. Figure 3 shows what would have happened to the bubble under the same regime as in Figs. 1 and 2 if the person were given just enough supplemental oxygen to keep the alveolar oxygen at the sea level value. Bubble absorption is markedly faster because of a larger oxygen window.

The rapid demise of bubbles, which can be seen for the O2-supplement case in Fig. 3, is caused by two factors: When a bubble is small, its rate of change, either absorption or growth, is large because the surface-to-volume ratio is large -- diffusion is facilitated by a large surface area. In addition, the rapid shrinkage is aided by surface tension, which adds to the total pressure inside the bubble in inverse proportion to the radius, and thereby adds to the nitrogen partial pressure inside the bubble.

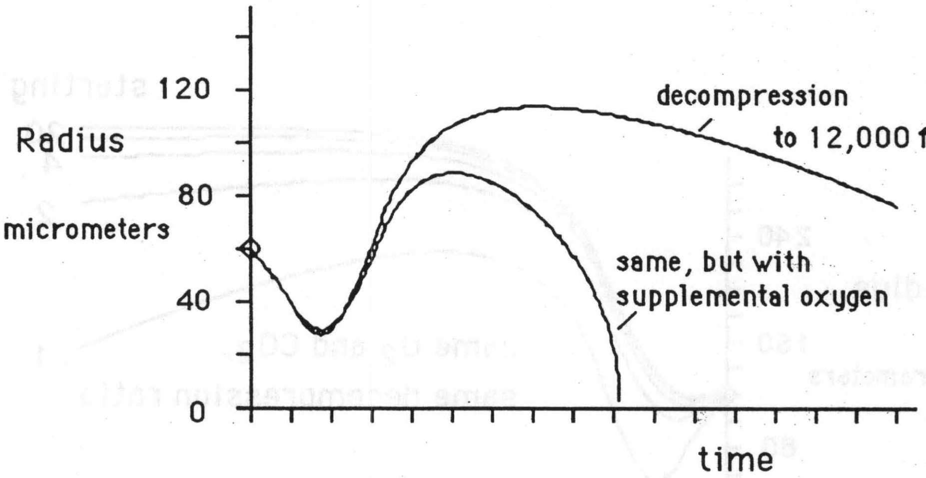

Figure 3. Effect of supplemental oxygen on bubble size. The upper curve is the same as in Fig. 2.

Note that the absolute pressure does not appear in Eq. 1; a way of understanding this is to remember that more gas molecules diffuse when partial pressures are high, as at depth, but it takes more gas molecules to change the radius when the bubble is pressurized -- the two effects cancel each other.

The Pa/Pg ratio in Eq. 1 is reminiscent of the decompression ratio, the ratio of barometric pressures before and after decompression. In fact, the barometric pressures do not directly determine diffusion of the inert gas -- the governing variables are the inert gas pressures themselves, which appear in the equation as the

Pa/Pg ratio. The two inert gas pressures differ from the barometric pressures by what we can call "modifying pressures" that are relatively constant in the face of changes of barometric pressure -- partial pressures of oxygen and CO2, water vapor, other gases, and pressure caused by surface tension when radius is small. When barometric pressure is low, as at altitude, these relatively-stable modifying pressures are a large fraction of the barometric pressure, so they have relatively large effects on bubble growth. When barometric pressure is high, the modifying pressures shrink in importance. This gives perspective on the oxygen window -- oxygen changes the nitrogen in tissue and bubble, but if total nitrogen is very large, as at 20 ATA, the effect of oxygen is small.

Figure 4 shows the effect of differing decompressions, all of which have the same decompression ratio. For example, the lowest curve is decompression from 1 to 0.636 ATA, a "normal" decompression to 12,000 feet similar to that in Fig. 2; the highest curve is decompression from 20 ATA to 20 multiplied by 0.636, or 12.7 ATA. All the curves have the same oxygen window. The curves appear to be approaching a limiting curve which grows to a radius that is about 40% larger than the normal curve, and has much longer duration and slower decay.

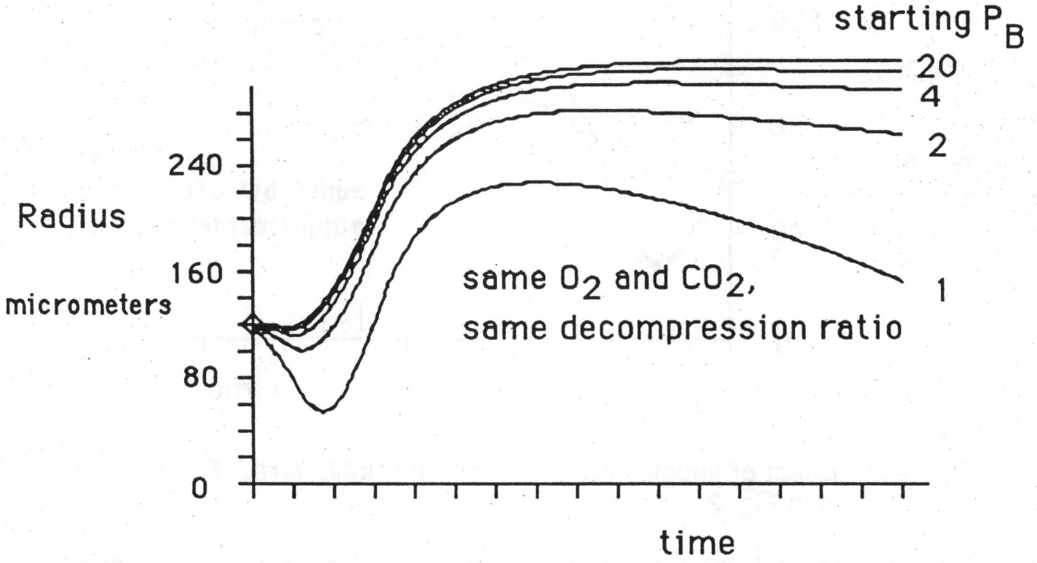

Figure 4. Bubble size when oxygen window and decompression ratio are constant, but decompression starts from 1, 2, 4, 8 and 20 ATA.

Conclusions

The simulations demonstrate the effects of several variables that concern decompression bubbles. One general statement about decompressions from sea level to altitude, in contrast to decompressions from depth to sea level, is that altitude bubbles have a smaller oxygen window because of the rarified air at altitude, so bubbles tend to grow bigger and shrink less rapidly than if the person were breathing normal sea-level oxygen. A second general statement is that there is a tendency for altitude bubbles to be more affected by "modifying effects" (alveolar and tissue oxygen and CO_2, water vapor, other gases and surface tension).

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Discussion of Dr. Van Liew's Paper

MR. HORRIGAN: I have one question I would like to ask you about the carbon dioxide. We've been very interested in the relationship of metabolic rate to susceptibility to bends at altitude. What are your feelings about the generation of carbon dioxide during exercise and its possibility of enhancing bubble size?

DR. VAN LIEW: I've been looking into that. When the CO_2 is high and the oxygen is low, they tend to balance each other. The sum of O_2 plus CO_2 is about the same, no matter how metabolic rate changes, until bloodflow ceases. If there is a region that has no bloodflow, then the carbon dioxide can build up to very high levels, not only because of elevated carbon dioxide, but also because of local acid production that can liberate more carbon dioxide from bicarbonate.

DR. VANN: In 1945, Thomas and Williams reported that the best correlation between pain and the bubbles that they observed in x-ray at altitude were the bubbles that were seen along fascial planes or tendons. This suggests that spherical bubbles may not be the ones that we should be concentrating on. The important ones may be flat sheets of gas. These would reduce the effects of surface tension. How important would this be if you applied your analysis to a sheet of gas as opposed to a sphere? What effect do you think that would have on the kinetics?

DR. VAN LIEW: Probably gas in a sheet would presist longer than the same volume of gas in a spherical bubble. In the body, even spherical bubbles break up into a bunch of other bubbles when they get to a certain size.

DR. BENNETT: You had high altitude pressures. Would you like to comment on the more typical pressures we've been hearing about, such as 4,500 to 8,000 foot altitude and the likelihood of how much greater the effects would be for divers today?

DR. VAN LIEW: I can simulate any situation you want to give me. As a quick answer, you would probably see less of an increase in bubble size at lower altitudes. Interestingly, if I didn't start with a big enough radius, the simulated bubble would disappear. There was a minimum bubble radius in order to avoid having the bubble disappear before it grew.

CHAIRMAN SHEFFIELD: What bubble size was required?

DR. VAN LIEW: Eighty microns. Of course the size depends on the washout rate that you set for the tissue and how intense the growth tendency was.

DR. BELL: One factor that ameliorates that is stabilization of the bubble in a little vesicle or cleft. For example, a bubble trapped in some geometric physical space where the radius of curvature is defined by the angles of that space rather than by the sphere of the bubble. Such a bubble can be stabilized.

DR. VAN LIEW: I suppose so. I think that tissues tend to be watery and that bubbles tend to be round. Although other investigators tell me that there are clefts, and they even point out places in bone cells where clefts exist, I'm not convinced yet.

DR. LAMBERTSEN: What you have in the computer is an electronic situation, no cleft, no pathological event when that bubble does or does not form. You're looking at an arithmetic analogy. You're using that computer to do arithmetic. If you could make your computer develop a lesion, and let that lesion stay there, then you could go ahead and do the arithmetic. With the residual bubble and the altered circulation, the arithmetic is no longer relevant to that region. You could still get the same results you are getting now. In other words, you are calculating an ideal circumstance, disregarding entirely the conditions at the lesion site.

DR. VAN LIEW: My model attempts to include as many variables as possible. A more complex model might simulate even more complex situation.

DR. BENNETT: At DAN we have taken out Dopplers on the dive boats to look for bubbles in the divers, over the course of a week. We've found remarkably few bubbles. It doesn't mean that those divers will not present with decompression sickness. You have to be very careful about making the jump when you think of Doppler detected bubbles and their relationship to decompression sickness. What is the relationship of Doppler bubbles to decompression sickness? Are they really related? In my experience and readings you can draw any conclusion. We have to be cautious in making quantum jumps from bubble analysis in spherical bubbles and trying to relate them directly to the 570 cases of DCS that I presented earlier in the workshop.

MR. EDEL: The Doppler is only looking at one specific area and I think its relevance may be limited to that area. There are other events that occur in other areas that it can't detect.

MR. NISHI: We've listened to some Doppler tapes that were done by sports divers and they're very poor quality. It's very difficult to see how they could detect bubbles in those signals. It depends quite a lot on the user of the Doppler.

CHAIRMAN SHEFFIELD: Hugh, your model is fascinating. In the Air Force we put a lot of emphasis on transporting bends patients while breathing 100 percent oxygen. We emphasize the need for tightly fitted aviators' masks to deliver 100 percent oxygen. Occasionally, we'll see a patient who received oxygen by a Venturi mask system in which he only got 30 percent oxygen. With your model, would there be any difference in bubble resorption with 100 percent oxygen versus 30 percent oxygen delivery?

DR. VAN LIEW: A big difference. When a person breathes 100 percent oxygen, the rate is maximal. Anytime you give pure oxygen you speed up bubble resorption.

DR. LAMBERTSEN: Paul, could we elaborate on that? Practically speaking, you don't see a visible fast change because the problem is not susceptible to fast recovery, but the effect is large and important. Your time points are measured in hours, since you're dealing with decompression largely in swollen tissues. Therefore, it takes a long time for even pure oxygen to do anything, but while it's slow, it's doing something. I think pure oxygen is inevitably the only method for reducing the bubble size and the amount of nitrogen. There's no other way in existence.

DR. VAN LIEW: Even in a tissue that gets very little bloodflow, giving oxygen will eventually help to denitrogenate that tissue and cause the bubble to go away, whereas, if you don't denitrogenate, you leave the nitrogen in that unperfused tissue.

CHAIRMAN SHEFFIELD: Thank you Dr. Van Liew. In the next paper, Dr. Ed Lanphier will describe his experience with altitude provocation in decompression studies of sheep.

EXPERIENCE WITH ALTITUDE PROVOCATION IN DECOMPRESSION STUDIES

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When we first began studies in decompression at the University of Wisconsin (1), we wanted to explore the suitability of sheep and pygmy goats for that purpose. Spencer (2) had used sheep in the development of his ultrasonic Doppler bubble detection system, but we found essentially no published information on the susceptibility and responses of sheep. We found nothing at all about *pygmy* goats, but we had a report containing extensive Royal Navy data for ordinary domestic goats (3). That was presented in terms of ***threshold***: the least exposure pressure that would produce a definite sign of decompression sickness (DCS) upon decompression in a particular animal.

The Royal Navy study was based upon no-stop decompression from presumed saturation. We assumed that saturation would be essentially complete after 24 h in sheep and pygmy goats; so in order to produce comparable data, we used the threshold approach with no-stop decompression from 24-h exposures.

This involved an all-or-none sort of end point; and when an animal showed nothing, we would have no idea how close it might be to its particular threshold. We did not have Doppler monitoring equipment at the time and in fact were concerned about the possibility that ultrasound would *promote* bubble formation. We adopted a procedure that we called "altitude provocation." The basic idea was not original with us. Kiessling and Duffner (4) and Kiessling and Wood (5) had reported a similar approach in the early 1960's.

METHODS

Fig. 1 illustrates the profile used in the initial study. We exposed 6-8 animals at a time in the large chamber in the University of Wisconsin Biotron. After they had been at simulated depth for 24 h, they were brought to surface at about 60 ft/min and were observed at surface for 20 min. Those that showed no definite sign of DCS were then taken to 570 mmHg (equivalent to about 8,000 ft of altitude) for 15 min. Those that showed no definite sign at 570 mmHg were then taken to 420 mmHg (equivalent to about 16,000 ft).

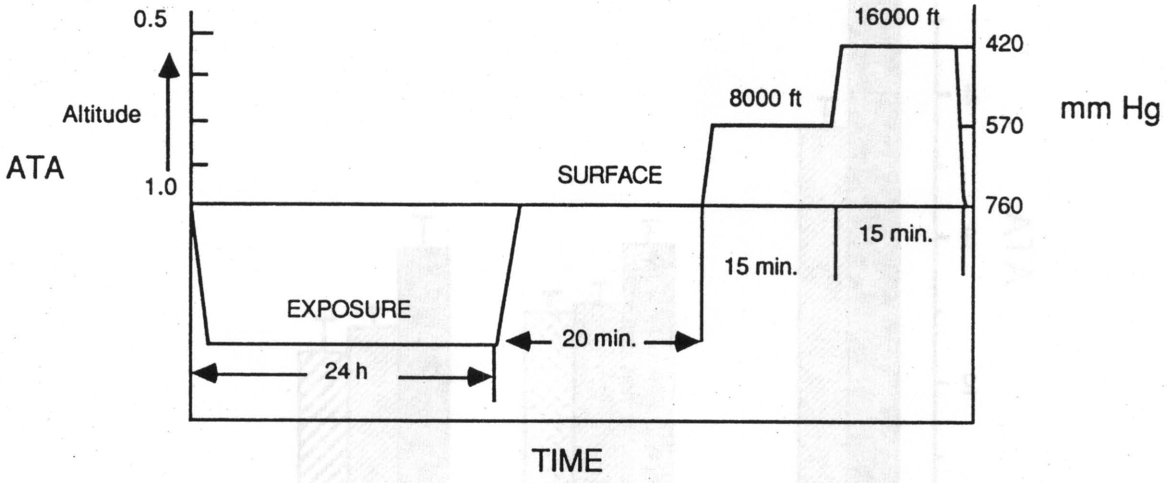

Fig. 1. Pressure profile of simulated 24-h dives with altitude provocation.

We repeated this process at approximately 1-week intervals with increasing exposure pressures until every animal had shown some distinct sign of DCS. The vast majority of the signs were the typical sort of limb-lifting shown in the classic photograph published by Boycott, Damant, and Haldane (6) in 1908. If unwillingness to bear weight on a limb was definite, we counted it as DCS even though the limb was not held up consistently.

Altitude provocation provided us with additional information from each experiment. An animal that had DCS at 570 mm was probably within a pound or two of its surface "threshold." If it showed nothing even at 420 mm, we would dare to take a larger step-up in pressure for its next test exposure. In this process, we also determined thresholds for the two altitudes.

RESULTS AND DISCUSSION

Thresholds: surface vs altitude

The bars at the right of Fig. 2 illustrate the thresholds determined in 24-h exposures in 11 sheep of various breeds for ascents to surface, 570 mmHg, and 420 mmHg. Clearly, less exposure pressure was required to produce DCS at altitude than at surface. Thresholds were somewhat lower in the goats, but the pattern was very similar.

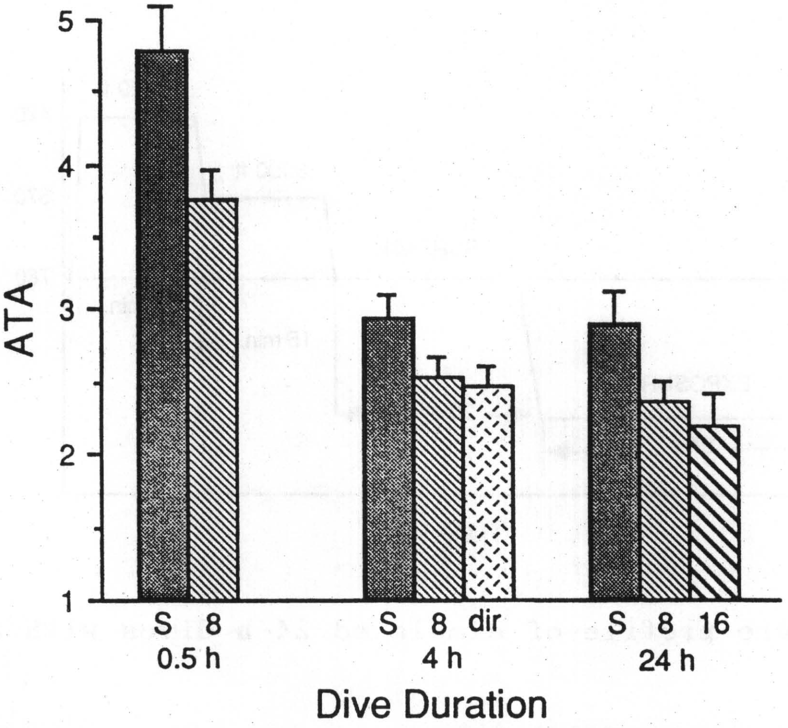

Fig. 2. Thresholds for simulated dives of 0.5 h, 4 h, and 24 h duration with ascent to surface [S], to 8,000 ft (570 mmHg) [8], or 16,000 ft (420 mmHg) [16]. All ascents to altitude followed 20 min of observation at surface except those represented by the lightly-shaded bar [dir] (direct ascent).

Influence of the "surface stop"

We wondered whether the 20-min stop at surface made a significant difference in the response at altitude. The middle set of bars in Fig. 2 represents a similar set of experiments but with exposures of only 4 h. Here, we eliminated the 420 mm - 16,000 ft - excursion and instead determined thresholds for surface, for 570 mm with the usual 20 min stop at surface, and for going directly to 570 mmHg.

There are two interesting points to notice here: First, there is very little difference between 24-h and 4-h dives in either surface or 570-mm thresholds. Second - looking at the "direct" ascents represented by the third bar in the second group - we see that skipping the 20-min surface stop also made very little difference.

Finally, we investigated 30-min simulated dives. The findings in three sheep are shown in the first set of columns. As would be expected, we had to go to higher pressures to elicit any form of DCS with such a short exposure. The difference between "surface" and "altitude" thresholds is quite large despite the fact that with such short exposures, the 20-min observation at surface might have been expected to reduce the difference. In 8 goats tested in the same way but not shown here, the mean "surface" threshold was very similar; but the difference between surface and altitude was about half as great -- nearly the same as the surface vs altitude difference in the longer dives.

The really surprising finding of these 30-min dives was the very high proportion of *spinal cord* DCS in both sheep and goats. This was the first indication we'd had of the important influence of *dive profile* on the type of DCS (7).

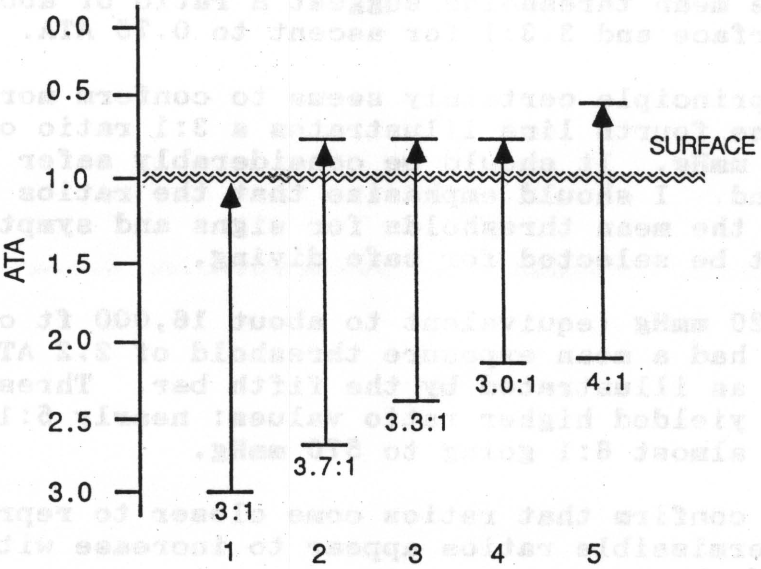

Fig. 3. Pressure differences and decompression ratios in ascents from threshold exposure pressure to 1.0, 0.75, and 0.55 ATA.

"Delta P" vs Decompression Ratios

From the standpoint of "flying after diving," the most interesting aspect of these findings is the difference in exposure pressures required to produce DCS at surface vs altitude. If a given exposure were "just barely safe" for ascent to surface, how much "safer" - shallower - would it have to be, for example, if the diver were to fly home in a commercial aircraft shortly after surfacing?

The simplest theory would focus on the pressure-difference (or "delta P") between exposure pressure and the ambient pressure to which the diver can be decompressed.

The first vertical line in Fig. 3 indicates decompression from a pressure of 3 ATA to surface, with about 3 ATA representing the mean threshold in our longer exposures. The second line indicates an ascent to 570 mmHg (0.75 ATA), just 0.25 atm less than the pressure at surface. We might assume tentatively that a safe exposure pressure would be 0.25 atm less than that for ascent to surface, indicated by the fact that the second line is the same length as the first. The third line indicates what we actually found: in terms of mean thresholds, exposure for ascent to 0.75 ATA had to be ***0.5 atm*** less than for ascent to surface.

So the difference in pressure - the "delta P" theory - does not fit our findings. That shouldn't be surprising since we've all been brought up on Haldane's "2:1 ratio" (6) and variations thereon. The mean thresholds suggest a ratio of about 3:1 for ascent to surface and 3.3:1 for ascent to 0.75 ATA.

The ratio principle certainly seems to conform more closely to the data. The fourth line illustrates a 3:1 ratio of pressures going to 570 mmHg. It should be considerably safer than what we actually found. I should emphasize that the ratios discussed here reflect the mean thresholds for signs and symptoms of DCS and would not be selected for safe diving.

Going to 420 mmHg (equivalent to about 16,000 ft or 0.55 ATA) in our study had a mean exposure threshold of 2.2 ATA, yielding a ratio of 4:1 as illustrated by the fifth bar. Thresholds in our 30-min dives yielded higher ratio values: nearly 5:1 going to surface, and almost 6:1 going to 570 mmHg.

In sum, we confirm that ratios come closer to representing the truth; but permissible ratios appear to increase with both higher altitudes and short exposures.

The variability of "thresholds" between animals and in the same animal from time to time led us, later, to adopt approaches other than determining thresholds. We do not wish to press conclusions too far, but we believe that threshold values were instructive in this context.

Relevant tissues

When we were doing the work with thresholds, we hoped that our various maneuvers would shed some light on which "tissues" - in terms of half-times of saturation or desaturation - were actually responsible for the DCS that we saw. I've done some simple Haldane-type calculations in a range of half-time "tissues."

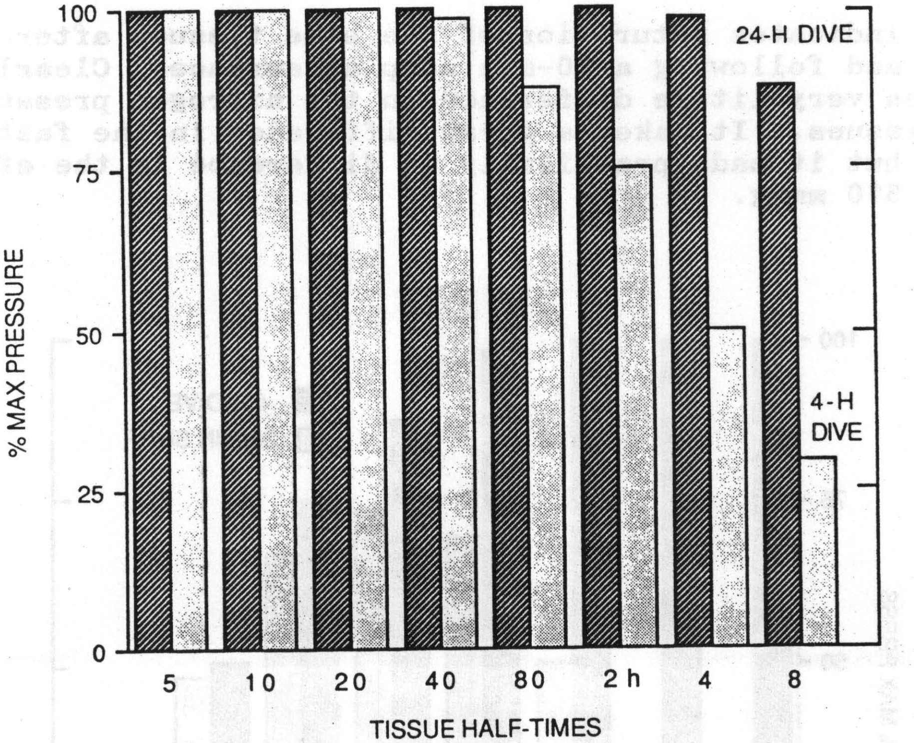

Fig. 4. Nitrogen saturation in percent of maximum (exposure) pressure in hypothetical tissues with half-times from 5 to 480 min after simulated dives of 24 h (heavy shading) and 4 h (light shading).

Fig. 4 illustrates the degree of saturation in a range of tissues after exposure to increased pressure. The bars represent half-times from 5 min to 80 min and from 2 h to 8 h. The ordinate represents the tissue N2 pressure in terms of percent of the maximum (exposure) pressure. Note that 24 h is long enough to bring all of these to near-100% saturation.

Four-hour exposure, also shown, falls considerably short of saturating slower tissues, yet there was little difference in outcome. This suggests that the very slow tissues either do not exist in sheep and goats - or that, if they do exist, they are not "relevant" in the sense of producing obvious DCS. (I think it was Brian Hills who first used the term "relevant tissues," and that suggests a useful concept.) Here, tissues with half-times of 80 min or less might be relevant, having nearly the same saturation for both 4- and 24-h exposures.

Effect of "surface stop"

Fig. 5 indicates saturation of the same tissues after 4 h of exposure and following a 20-min stop at surface. Clearly, the stop makes very little difference in the nitrogen pressure in slower tissues. It makes a great difference in the faster tissues, but it made practically no difference in the effect of going to 570 mmHg.

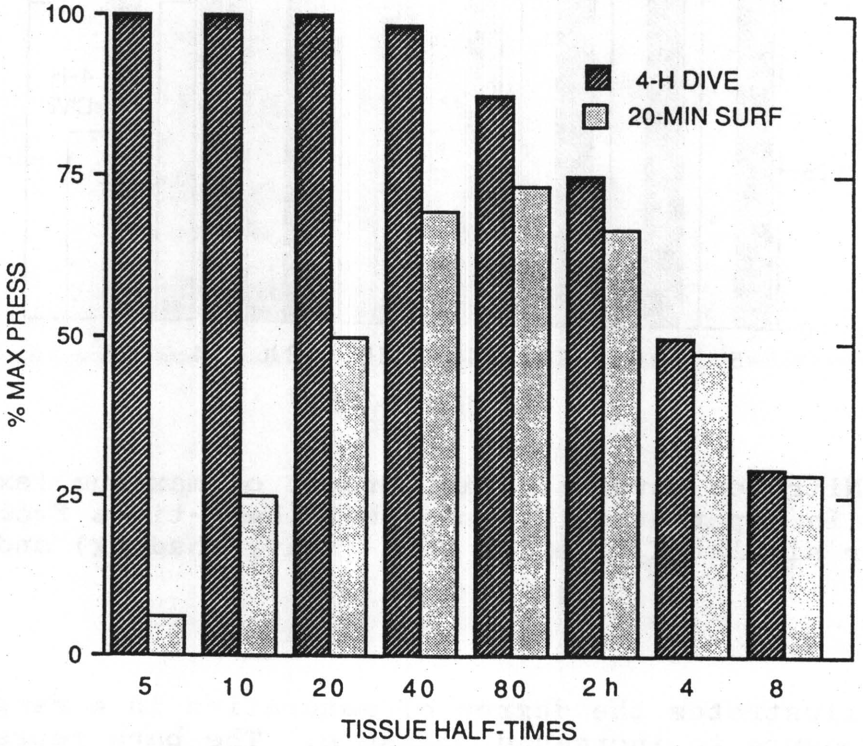

Fig. 5. Nitrogen saturation (in percent of maximum) in tissues with various half-times following a 4-h simulated dive and after a subsequent 20-min stop at surface.

The fact that neither 4-h vs 24-h nor a 20-min stop on the way to altitude made any significant difference makes it plausible to look for a tissue that had high nitrogen presssure in either 4- or 24-h exposure and that showed little change with 20 min at surface. In those terms, the 40- and 80-minute tissues seem most likely to be relevant in relatively long exposures in sheep and goats and thus responsible for most of the symptomatology. However, Captain Thalmann (8) would remind us that supersaturation and bubble formation during the surface stop could cause gas elimination to be much slower in crucial tissues than I have indicated.

Findings in 30-min dives

As shown in Fig. 6, a 30-min dive brings only the fastest tissues close to saturation. It is surprising to see how little a 20-min stop at surface accomplishes. The values point a finger at the 40-min tissue as one with substantial nitrogen pressure and little change in 20 min at surface.

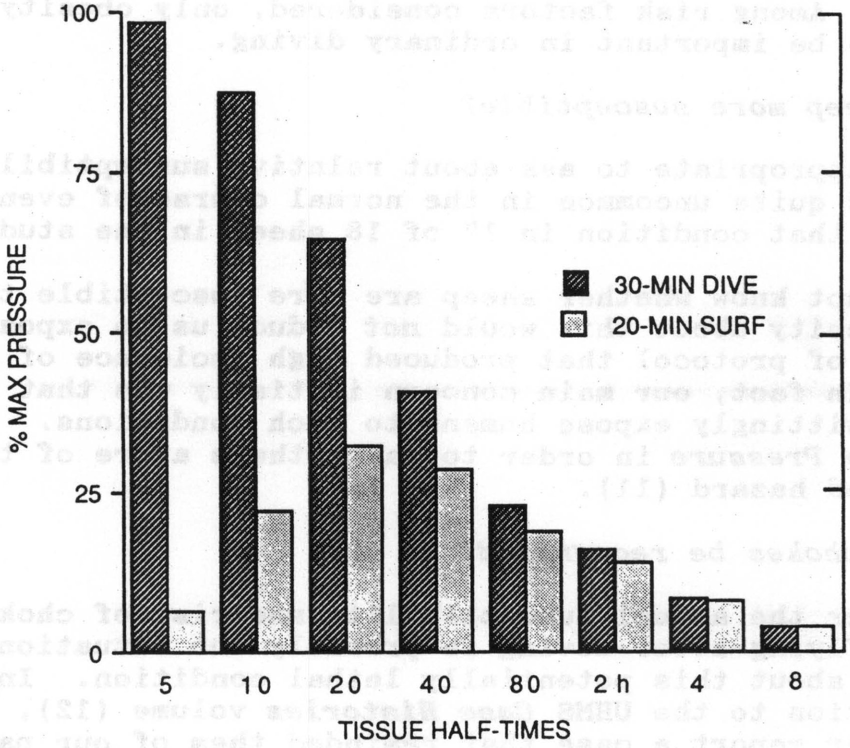

Fig. 6. Nitrogen pressure (percent of maximum) following a 30-min simulated dive and a subsequent 20-min stop at surface.

This line of reasoning certainly has faults, but more extensive observations of this sort might well be illuminating. Especially in the case of short/deep dives, it would be helpful if we could focus upon a particular "relevant tissue" in trying to construct safer tables both for ordinary surfacing and for flying-after-diving. The fact that a 20-min stop at surface makes so little difference here casts doubt upon the probable value of a short "safety stop" on the way to the surface or before going to altitude.

Reflections on Respiratory DCS - Chokes

Observations at the University of Wisconsin concerning chokes (9, 10) focus attention on the risk of developing that condition in flying-after-diving. The "Wisconsin Chokes Model" involves a long exposure to increased pressure, ascent to 8,000 ft (an accepted cabin altitude in commercial aircraft), and more than 15 min at altitude. The protocol included an observation period of approximately 40 min at surface.

Long exposure seems an essential part of the picture, but the period of observation at surface probably is not. A relatively long period at altitude seems necessary although one animal out of 18 developed serious chokes at the surface. In other experiments, we have seen chokes at surface, especially in obese animals. Among risk factors considered, only obesity seems likely to be important in ordinary diving.

Are sheep more susceptible?

It is appropriate to ask about relative susceptibility since chokes is quite uncommon in the normal course of events while we produced that condition in 17 of 18 sheep in one study (9).

We do not know whether sheep are more susceptible than divers, but curiosity about this would ***not*** induce us to expose humans to the sort of protocol that produced high incidence of chokes in sheep. In fact, our main concern initially was that someone might unwittingly expose humans to such conditions. We wrote a letter to ***Pressure*** in order to make others aware of this unexpected hazard (11).

Would chokes be recognized?

Whatever the actual susceptibility and risk of chokes in humans, flying-after-diving is probably the situation most likely to bring about this potentially lethal condition. In their contribution to the UHMS ***Case Histories*** volume (12), Sheffield and Cramer report a case that reminded them of our paper on the subject at the Eighth Symposium on Underwater Physiology in 1983 (13).

How many cases of chokes would be diagnosed correctly by physicians without training in diving medicine? The situation most likely to be confused with chokes is probably acute pulmonary edema following myocardial infarction. The character of associated pain would usually be different, but it can vary considerably in both conditions. Unproductive cough could be present in both although aggravation by deep inspiration (Behnke's Sign) (14) might not be present in pulmonary edema from causes other than chokes.

How many missed cases?

One can only wonder how many cases of chokes have been misdiagnosed even at autopsy, or how many victims recover spontaneously and escape from medical surveillance and reporting. How many "heart attacks" occur on flights returning from prime diving areas? The number is probably not very large, but I strongly suspect that it includes some chokes cases. It may be some time before we can be sure whether flying after diving produces a significant number of chokes cases in divers.

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Discussion of Dr. Lanphier's Paper

DR. VANN: Ed, can you elaborate on the relationship between chokes and spinal decompression sickness in your animals?

DR. LANPHIER: Absolutely no connection as far as I could see. We didn't see a single sign of spinal cord or cerebral injury in those animals that had the chokes. Charlie Lehner will discuss that some more.

DR. BELL: You show that there's about a 3 to 1 ratio in going to the surface and about 3.3 to 1 ratio in going to 8,000 feet. Do you think that there is statistical significance given the end point that you were able to use?

DR. LANPHIER: Well, I really don't know. Originally, we weren't thinking about this application. By the time I got the old data dug out and put together, I didn't have time to do some of the statistics. But if you look at the standard deviations indicated on the bar graphs, especially the differences between altitude and surface, they look significant. The differences between the other events probably aren't. Charlie, do you have any thoughts?

DR. LEHNER Basically, we didn't have enough sample points to test the relationship.

DR. LANPHIER: Does that answer your question?

DR. BELL: Yes.

DR. LANPHIER: I want to make it very, very clear that when I say a 3 to 1 ratio, that is going to be the average for sheep having the bends; not anything that might be safe.

MR. HORRIGAN: You mentioned a concern that the ultrasonic instrumentation might be provocative to bubbles. Could you elaborate on that?

DR. LANPHIER: Well, we worried about it back then. Nobody else seems to worry about it at all. I wonder if it isn't still a valid concern. We were delighted to find all this in chokes because we now have something for Doppler detected bubbles to do. We talked to Brian d'Aoust and others about this and we were just brushed off by everyone: How could you even ask such a question? I still don't believe that, but I don't think it makes a lot of difference.

DR. INGLE: As for the physical acoustic cavitation theory, I talked to Dr. Larry Crum, a leading researcher in the physics of ultrasound at the University of Mississippi Acoustics Research Lab, and he says the energies we're using in ultrasound are not likely to produce physiological effects.

DR. LANPHIER: Well, I hope they are not, because a lot of people have been wasting their time with this problem.

DR. BENNETT: In general, we don't see a lot of divers, even on the altitude side, with the chokes-type symptomatology. I noticed that case number 23 (Sheffield and Cramer, 1988) is a chokes case. A 44 year-old female made a six-day SCUBA diving trip. She made a dive at 45 feet and then flew in an unpressurized aircraft at 6,500 feet for 1.5 hours to Miami and then flew on to Atlanta where she had substernal chest pain, numbness of fingers, and headache. She was eventually treated on a Table 6. She was diagnosed as chokes secondary to flying after diving.

In terms of your cardiac situation, there are fatalities in the diving accident data from "heart disease." Where the bubbles were in relationship to those fatalities, I don't know. I was recently in Palau and talked to one of the dive operators. I asked if he had any diving accidents and he said, "No, we had two cardiac cases." I didn't press him, but I think those could well have been decompression sickness with chokes.

DR. LANPHIER: The case that you just quoted, is that the same one where you said that it reminded you of my presentation in Grand Rocks on this subject?

DR. BENNETT: Yes.

DR. LANPHIER: I appreciate that very, very much.

CHAIRMAN SHEFFIELD: In the 1940's and 1950's, there were 17 fatalities among aviators, primarily due to chokes and shock. In 1959, the first Air Force aviator was treated at Little Creek Navy Amphibious Base with a diagnosis of chokes, secondary to altitude chamber exposure. As a result of that successful treatment, the Air Force Surgeon General purchased hyperbaric chambers and implemented the hyperbaric medicine program. During the period Jan 1965 - Jan 1989 Air Force hyperbaric facilities treated 766 cases of altitude decompression sickness, and there were only 10 cases of chokes among them. There were no fatalities among those treated. In March 1987, the first altitude decompression sickness fatality occurred since the implementation of hyperbaric medicine to treat this disorder. In this case, the aviator lost pressurization in flight to around 30,000 feet, experienced chest pain, landed, was eventually diagnosed with decompression sickness (chokes) and transferred to a civilian hyperbaric facility where he expired during hyperbaric treatment. I have to clarify this for the workshop: of the 766 cases of altitude decompression sickness that the Air Force has treated to date, only four involved ascent to altitude after diving. The rest were single exposures or multiple exposures to altitude.

DR. BENNETT: It reminds me of my time at RNPL at Seafield Park Air Base, where they were doing a lot of high altitude work. They had some severe cases coming back down from high altitude, with post-altitude decompression shock, which is extremely hard to treat. That's why we ended up with pressure chambers to treat those cases. I don't think we see very much decompression shock, and I don't know why. At that time if you had any kind of altitude decompression sickness, we regarded it as far more serious than any other kind of decompression sickness cases we were getting at RNPL.

CHAIRMAN SHEFFIELD: Thank you, Dr. Lanphier. In the next paper, Dr. Charles Lehner will discuss respiratory decompression sickness, or chokes, and other DCS manifestations in sheep as compared to humans.

AN ANIMAL MODEL OF CHOKES: COMPARISON WITH HUMAN ALTITUDE DECOMPRESSION SICKNESS

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Abstract

Flying after diving can provoke decompression sickness (DCS) manifestations that vary with the site of tissue injury. One manifestation, respiratory decompression sickness (RDCS), known as the chokes, is caused by pulmonary microembolism. In sheep, massive numbers of precordial bubbles detected by ultrasound, elevated pulmonary artery pressures (>25 Torr), and pulmonary edema indicated that RDCS is a form of obstructive pulmonary hypertension caused by bubbles in the venous circulation. Total body fat or obesity was found to be a risk factor in RDCS. DCS manifestations at altitude appear comparable to those provoked by decompression from near-saturation air dives to surface pressure. Since altitude decompression typically begins with a condition of tissue saturation at surface, diving within a day before flying will add more inert gas to tissues susceptible to decompression injury and will increase the risk of DCS when flying.

Introduction

Flying after diving and diving after flying subject people to pressure changes that can provoke decompression sickness (DCS) from altitude (17,21–23,26) and hyperbaric (16) decompression. The problem of DCS caused by flying after diving has been investigated by Edel and colleagues (15) and more recently by Balldin (2,3) and Bassett (5) in laboratory simulations with human subjects. Decompression sickness occurs in the diver or aviator and passenger, with manifestations distinguished by tissue sites of decompression injury. Clinically, the most important DCS manifestations include limb bends, indicated by pain in joint regions, and more serious, potentially-fatal manifestations. Serious manifestations include central nervous system DCS, with cerebral and spinal cord injury, and the chokes or respiratory DCS (RDCS), with lung injury.

This paper focuses on: 1) a sheep model of human RDCS, and 2) comparisons between the DCS manifestations provoked in sheep and humans by decompression to altitude. Animal decompression studies at the University of Wisconsin-Madison investigated the pressure conditions needed to produce RDCS and described the pathogenesis of RDCS. Other studies compared surface and altitude DCS in sheep with human altitude DCS. These animal studies and a literature review raise concerns about the safety of the diver flying after diving.

Altitude Decompression Sickness

Various tissues are affected differently by the bubble formation that accompanies decompression. Some tissues are relatively tolerant to decompression and to the presence of bubbles. Others, because of their tissue composition, architecture, or blood flow rates are predisposed to decompression injury resulting either from bubble formation or bubble microembolization.

Two examples of decompression injury after different pressure profiles illustrate the importance of tissue site in DCS. The eyes can be a site of decompression injury. A rat, in one of William Fenn's studies at the University of Buffalo, was observed to have bubbles in its eyes after explosive decompression from a short, high pressure exposure. This observation recalls Robert Boyle's observation in the 17th century when he observed a bubble in the eye of a decompressed viper (27). Bubbles are also sometimes found on the decompressed human eye when it is covered by a hard contact lens (53), and ocular fundus lesions have been observed in divers (43). Long bone lesions in dysbaric osteonecrosis of caisson workers present another tissue site of decompression injury. Injury to the long bones, often in the shafts of the femur and humerus (11), typically occurs after relatively shallow but lengthy hyperbaric exposures. In sheep, lesions are prominent foci of marrow necrosis associated with reactive bone formation manifested as endosteal thickening in the bone shafts. In both the eye and long bones, compartmentalization may play a significant pathogenic role in tissue injury caused by bubble formation.

A principle illustrated in tissue decompression injury is that different pressure profiles can target different tissues susceptible to decompression injury (32). Differences in the site of tissue injury appear primarily due to tissue perfusion rates which largely control the washin and washout rates of inert gases in susceptible tissues. We observed a high incidence of spinal cord DCS in short, deep no-stop dives, but fewer cases of spinal cord DCS occurred with long shallow dives that provoked mostly limb bends. We reasoned that tissues responsible for spinal cord DCS signs and symptoms consist of relatively fast washin and washout tissues. Presumably only those tissues with relatively high perfusion rates and characterized by rapid gas washin rates would have sufficient gas loading in a short dive to promote bubble formation upon ascent. In contrast, tissues responsible for limb bends symptoms appear to represent slower washin and washout tissues. Therefore, tissues responsible for the various DCS manifestations may be characterized by their different tissue half-times and tolerance to inert gas pressures, a principle earlier recognized by Buhlmann (9).

Animal and Human Responses to Decompression

Sheep in the decompression studies at the University of Wisconsin-Madison are comparable to humans in body mass, with sheep usually weighing > 50 kg, and are presumably similar in their tissue perfusion rates and tissue composition. Sheep have been subjects for a series of decompression experiments that involved hyperbaric and hypobaric provocation of DCS (31).

Sheep Model and Human RDCS

RDCS studies in sheep illustrate how precipitous and hazardous RDCS might be in humans after comparable decompressions to altitude. In a protocol originally designed to provoke dysbaric osteonecrosis, a sheep suddenly and unexpectedly died at 8000 ft simulated altitude 43 min following a 24-h exposure at 19 psig, equivalent to 43 FSW and 2.3 ATA. Another sheep in the same experiment also died during recompression treatment with US Navy Table 1A. Sheep fatalities after such a seemingly moderate decompression compelled us to communicate our findings in a letter to Pressure (30). We thought that a similar outcome could occur in humans under comparable pressure profile conditions. This protocol resulted in the RDCS collapse and deaths of 4 out of 14 animals, for a 29% mortality (33).

Fatal RDCS in the sheep raised questions about the pathogenesis of RDCS, thought to be a form of obstructive pulmonary hypertension induced by bubbles carried in the venous circulation through the right heart and into the lungs. We investigated RDCS in a later study (1) that used essentially the same pressure profile as before (33). Sheep were monitored for their physiological responses to a simulated dive followed by altitude provocation. The protocol included a 22-h air dive at 43 FSW (2.27 ATA) followed by a surface stop of approximately 40 min and altitude ascent to 8000 ft (570 Torr), a typical cabin pressure in commercial aircraft (Fig. 1). Nine of the 18 sheep (73 kg mean weight) were instrumented with indwelling vascular catheters, 3 sheep with aortic catheters and 6 fully-catheterized sheep with pulmonary artery, left ventricle, and aortic catheters; the other 9 sheep remained free of any invasive procedures (1).

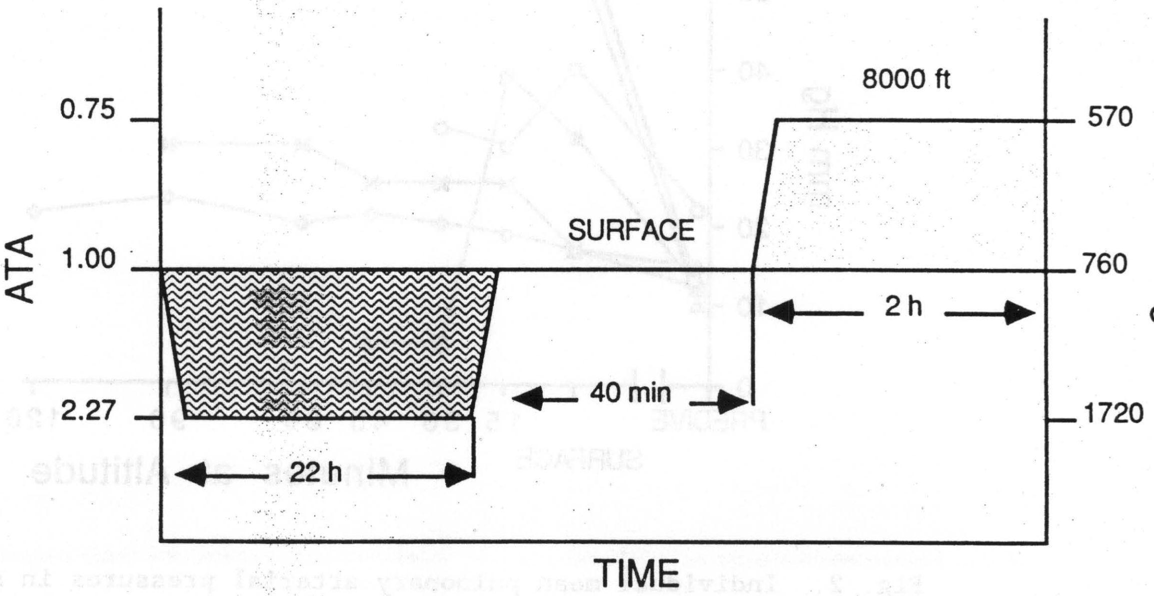

Fig. 1. Hyperbaric and altitude exposure protocol used to provoke respiratory decompression sickness (RDCS) in sheep.

Pulmonary artery pressures in the 6 fully-catheterized sheep rose significantly above pre-dive control values during the surface stop and with altitude provocation (Fig. 2). At surface, pulmonary artery pressures exceeded 35 Torr in three sheep and were above 50 in two. Among the 6 fully-catherized catheterized sheep, only 1 was judged as a "survivor" after 120 min at 8000 ft altitude. Its pulmonary artery pressure never exceeded 25 Torr. Clinical RDCS signs, coincident with pulmonary bubble loading, generally became more pronounced in these sheep with altitude exposure. These findings point to the development of fatal obstructive pulmonary hypertension in RDCS.

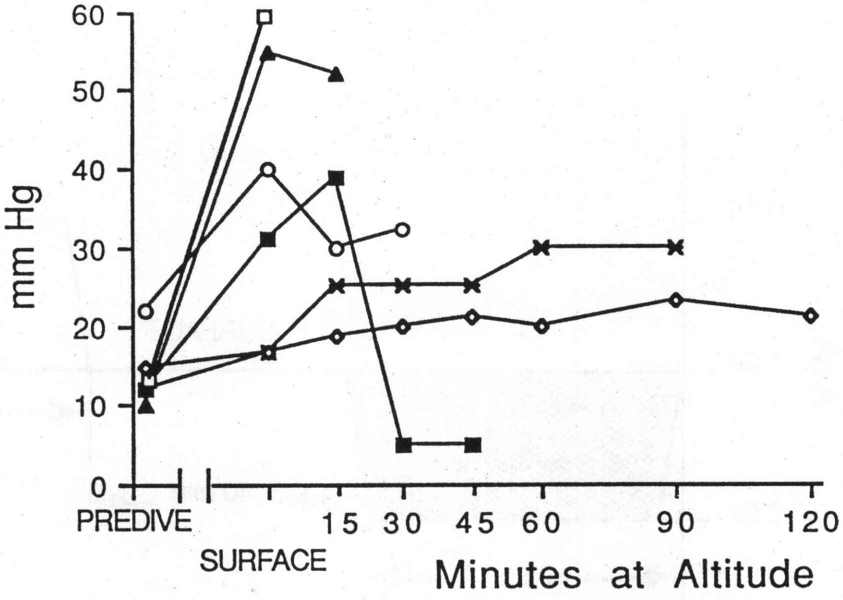

Fig. 2. Individual mean pulmonary arterial pressures in six sheep.

Clear evidence of pulmonary bubble loading came from precordial Doppler monitoring of intravascular bubbles (40-42,49). High bubble grades, as mean Spencer grades (DOP), reached 3 or above in most sheep soon after surfacing (Fig. 3). Doppler-detected bubble signals increased with altitude and bubble grades predicted the course of clinical signs in RDCS. Mean pulmonary artery pressures (PAP) rose with elevated Doppler bubble grades. A trend of decreasing mean systemic pressure (PAO), and decreasing arterial P_{02} values (PO2) matched the progressive clinical development of RDCS in sheep. Moreover, bubble grades and decreased numbers of circulating platelets and neutrophils (1) point to the possible roles that pulmonary bubble loading and bubble-blood interactions (28), particularly those involving neutrophils (35,45), have in the pathogenesis of RDCS.

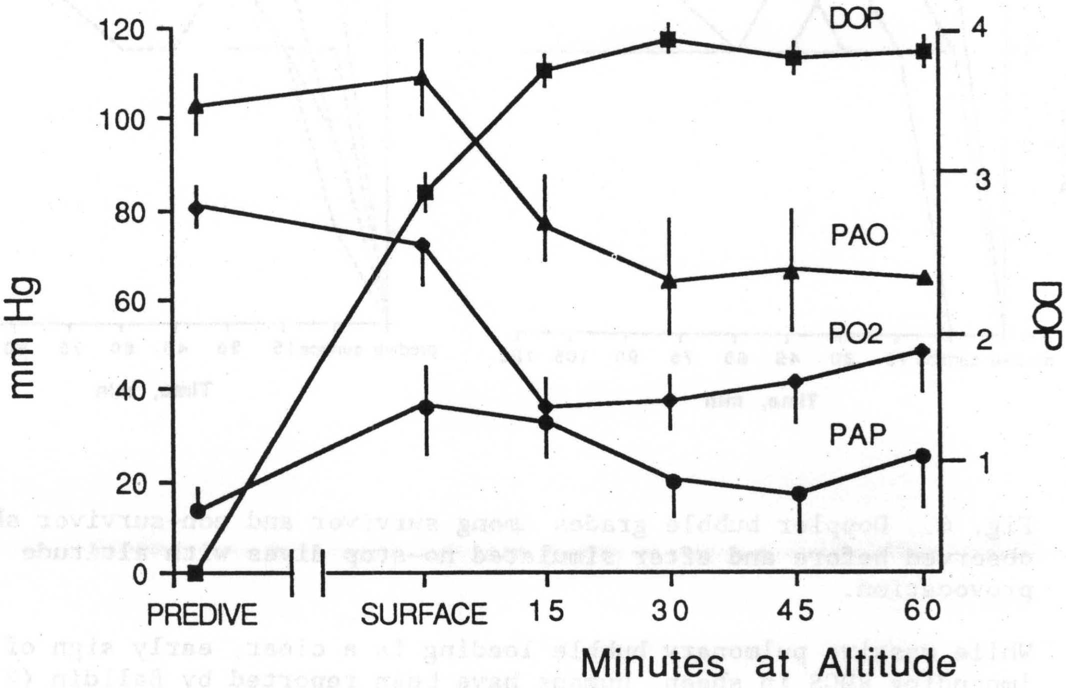

Fig. 3. Decompression responses in sheep to simulated no-stop air dive and altitude provocation. Symbols represent Doppler bubble grades (DOP), aortic blood pressure (PAO), arterial P_{02} (PO2), and pulmonary artery pressure (PAP).

Sheep were compared for Doppler bubble grades and their clinical outcome as either survivors, with clinical improvement at 90 min, or non-survivors that were moribund and euthanized within 90 min at altitude (Fig. 4). All sheep attained bubble grades of at least 3 during the postdecompression observations, and all but one sheep presented with clinical signs of RDCS. Observations in other sheep studies in our laboratory support the pathogenic relationship between pulmonary bubble loading and clinical signs of RDCS.

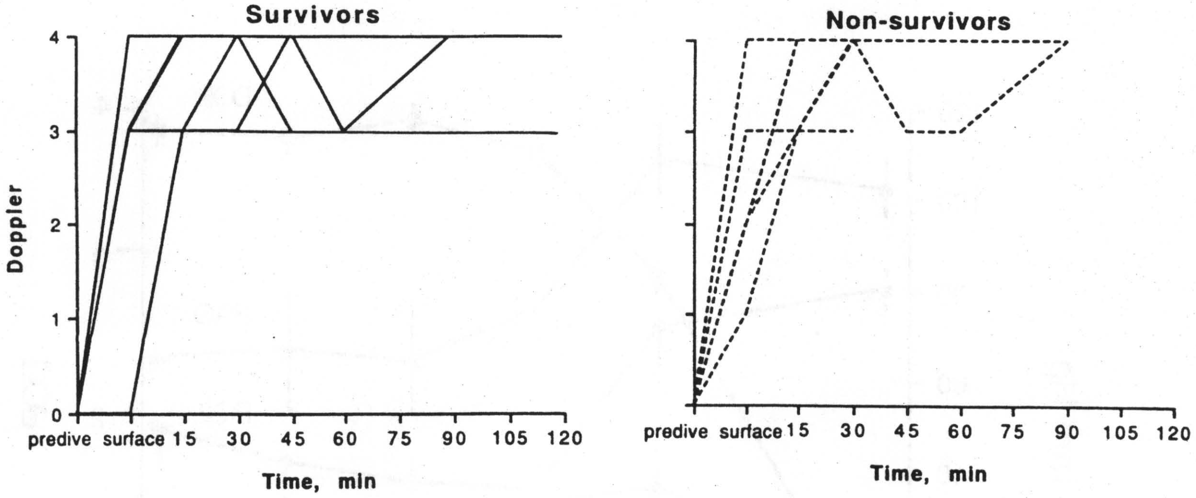

Fig. 4. Doppler bubble grades among survivor and non-survivor sheep observed before and after simulated no-stop dives with altitude provocation.

While massive pulmonary bubble loading is a clear, early sign of impending RDCS in sheep, humans have been reported by Balldin (2) and by others to have high bubble grades often without frank RDCS. Oxygen is often breathed during such altitude decompression experiments (5) and during experiments that simulate extravehicular activities in space (13,14,51). Under such conditions, O_2 is thought to have an important protective effect that blunts the development of RDCS. This is consistent with our experience that one of the most alarming aspects of RDCS is its refractory response to recompression treatment with only air. The use of O_2 in recompression might significantly improve treatment outcomes. However, unfavorable outcomes in the recompression treatment of sheep with RDCS may be due also to pulmonary edema.

Pulmonary changes associated with pulmonary edema and pleural effusion in RDCS are illustrated in lung radiographs of RDCS-affected sheep (1). A pre-dive radiograph shows the normal lung appearance in sheep #10 (Fig. 5). After a simulated dive and altitude, the affected lung (Fig. 6) had widespread patchy infiltrates consistent with a radiographic diagnosis of pulmonary edema, with evidence of pleural effusion indicated by arrows. Such pleural effusion was often delayed, so that more acutely stricken animals died before pleural effusion could presumably develop.

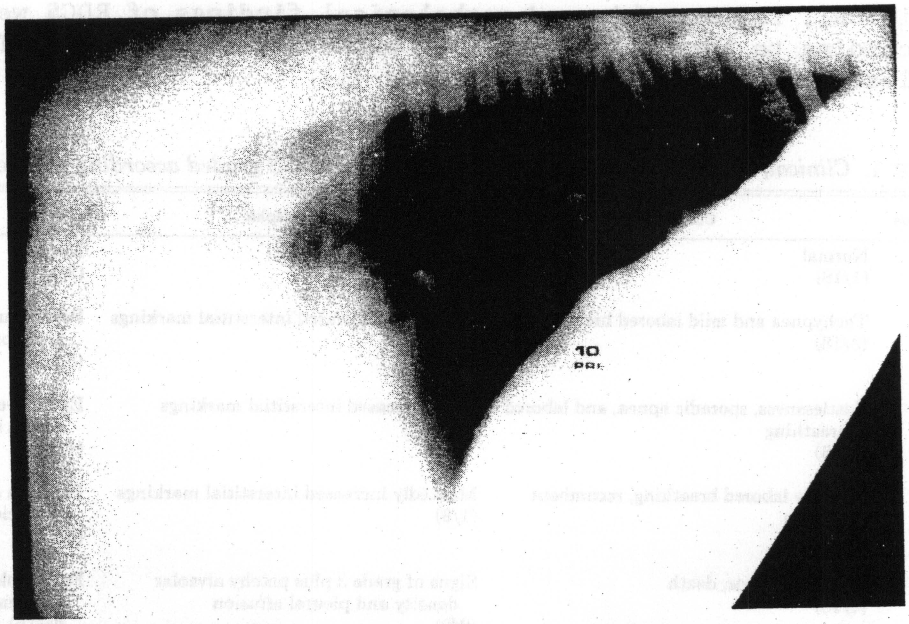

Fig. 5. Lateral thoracic radiographic appearance of predive normal lungs in sheep #10 (1).

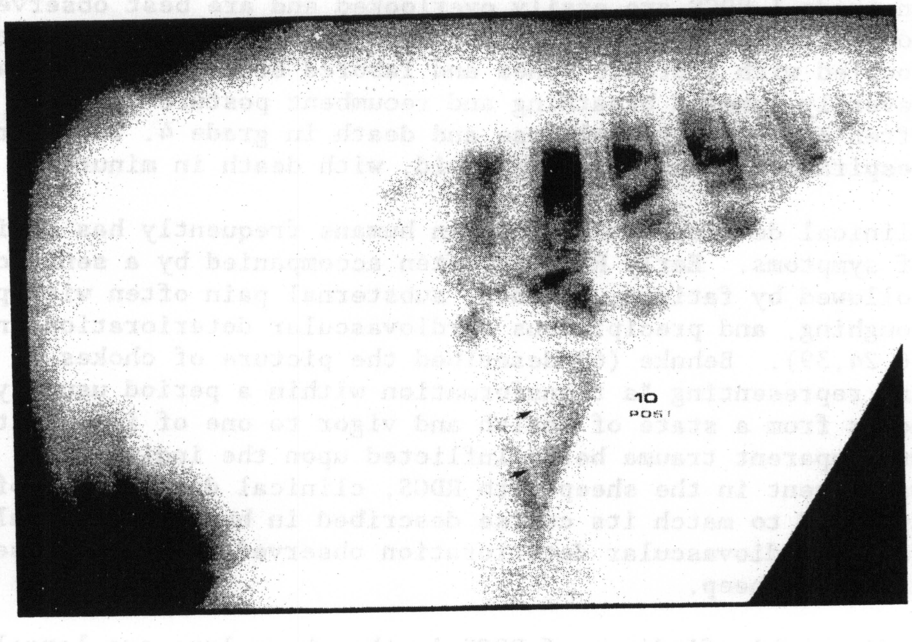

Fig. 6. Postdive appearance of patchy pulmonary infiltrates consistent with pulmonary edema and pleural effusion (see arrows) in sheep #10 with frank signs of RDCS (1).

Clinical, radiographic and pathological findings of RDCS were graded according to increasing severity, with a scale of 0 to 4 (Table 1), illustrated in our RDCS sheep study (1).

TABLE 1. *Clinical, radiographic, and pathological signs of RDCS graded according to severity from 0 to 4*

Grade	Clinical	Radiographic	Pathological
0	Normal (1/18)	Normal (2/9)	Normal (3/17)
1	Tachypnea and mild labored breathing (3/18)	Minimally increased interstitial markings (1/9)	Perivascular interstitial edema in anterior and ventral lung only (5/17)
2	Restlessness, sporadic apnea, and labored breathing (5/18)	Mild increased interstitial markings (3/9)	Extensive perivascular and interstitial edema in lungs (4/17)
3	Severely labored breathing, recumbent posture (5/18)	Markedly increased interstitial markings (1/9)	Previous signs in grades 1 and 2 plus thoracic fluid (3/17)
4	Collapse, stupor, death (4/18)	Signs of grade 3 plus patchy alveolar density and pleural effusion (2/9)	Frothy blood in right ventricle (previous signs may not develop because of rapid death) (2/17)

RDCS, respiratory decompression sickness. Nos. in parentheses represent fraction of sheep.

Clinical signs of RDCS in sheep initially present with tachypnea and mild labored breathing (1). These incipient and typically subtle signs in grade 1 RDCS are easily overlooked and are best observed under controlled conditions. Restlessness and agitation in grade 2 RDCS, coupled with sporadic apnea and labored breathing, are readily apparent. Severely labored breathing and recumbent posture in grade 3 RDCS are often a prelude to collapse and death in grade 4. The course of this respiratory disease may be rapid, with death in minutes.

Clinical development of RDCS in humans frequently has an insidious onset of symptoms. Early RDCS is often accompanied by a sense of well-being followed by fatigue, dyspnea, substernal pain often with paroxysmal coughing, and precipitous cardiovascular deterioration in the patient (6,24,39). Behnke (6) described the picture of chokes as that of shock and representing "a transformation within a period usually of several hours from a state of health and vigor to one of incapacitation without any apparent trauma being inflicted upon the individual." Although cough was absent in the sheep with RDCS, clinical development of RDCS in sheep appeared to match its course described in humans, especially with a rapid cardiovascular deterioration observed in the most severely affected sheep.

Radiographic findings of RDCS in the sheep lung are largely characterized by increased interstitial markings. In grade 4 RDCS, patchy alveolar density and pleural effusion are present as previously seen in the sheep radiograph (Fig. 6).

Pathological grades in sheep reflected the radiographic and clinical findings (1). Increasing perivascular edema characterized RDCS grades in sheep lungs. Thoracic fluid and frothy blood in the right ventricle are also sometimes present in fatal cases in sheep. Correlations of maximum individual grades in RDCS were significant ($P < 0.05$), because clinical, radiographic and pathological grades closely matched each other.

RDCS risk factors identified in sheep were body weight and instrumentation (the presence or absence of vascular catheters), illustrated by survival in Fig. 7. Survivors generally weighed less and usually carried no catheters; non-survivors generally weighed more and were catheterized.

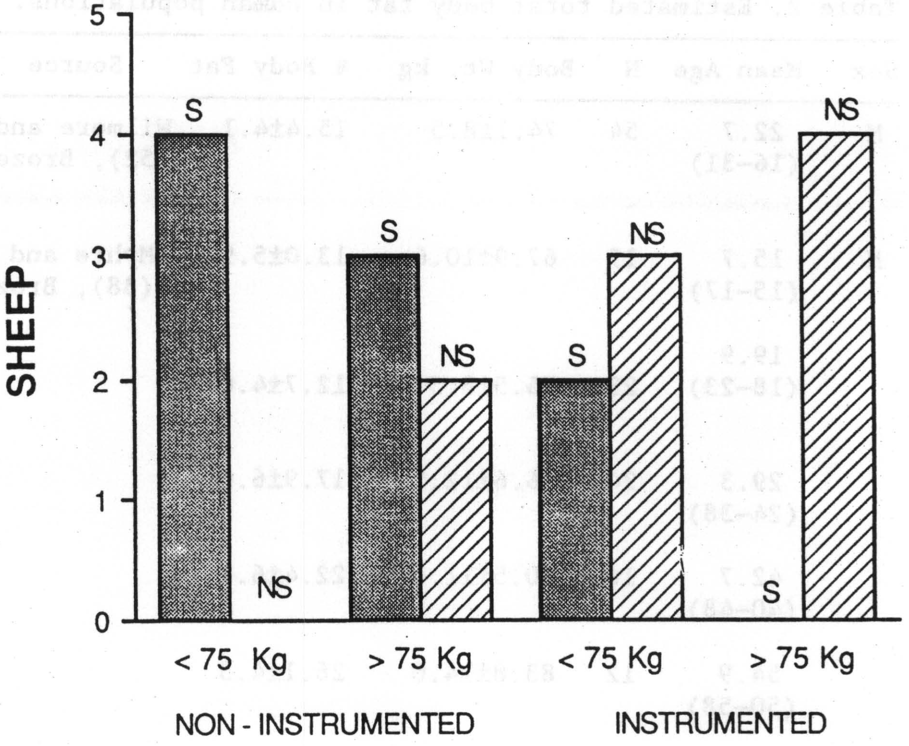

Fig. 7. Body weight (>75 kg) and instrumentation (vascular catheterization) risk factors predicted survival (S) and non-survival (NS) outcomes in RDCS sheep (1).

Body weight in sheep correlated with our qualitative assessment of body fat in the sheep (1,33). Body fat serves as a reservoir for dissolved N_2 that can form bubbles upon decompression. Because N_2 is about 5 times more soluble in fat than in H_2O, additional body fat can dramatically increase the body's storage capacity for dissolved N_2. In a classic study, Boycott and Damant found an increased susceptibility to fatal DCS among fat animals (7); their study foreshadowed body weight as risk factor of RDCS in decompressed sheep (1). Sheep generally have fat percentages (10) that equal or exceed total body fat percentages reported in humans.

In humans, total body fat shows wide variations among individuals (Table 2.). For example, 54 young college men examined by Wilmore and Behnke (52) had an estimated body fat of 15% by weight. Eighty-three young women in the Pollock et al. study (44) had an estimated 24.8% fat, and sixty middle-aged women had an estimated 29.8% fat. Body fat percentage in males doubled when age increased from 15-17 to 50-58 years as reported by Myhre and Kessler (38). We view an individual's percentage body fat as an important risk factor that can predict susceptibility in human RDCS.

Table 2. Estimated total body fat in human populations.

Sex	Mean Age	N	Body Wt, kg	% Body Fat	Source
M	22.7 (16-31)	54	74.1±8.5	15.4±4.1	Wilmore and Behnke (52), Brozek et al.
M	15.7 (15-17)	17	67.9±10.6	13.0±5.9	Myhre and Kessler (38), Brozek et al.
	19.9 (18-23)	23	75.5±8.5	12.7±4.0	
	29.3 (24-38)	24	76.6±12.5	17.9±6.6	
	42.7 (40-48)	16	80.5±11.4	22.4±6.1	
	54.9 (50-58)	12	83.8±14.0	26.1±4.3	
	71.1 (60-87)	8	66.1±8.4	23.4±8.0	
F	20.2 (18-22)	83	57.5±7.4	24.8±6.4	Pollock et al. (44), Siri.
	44.7 (33-50)	60	61.2±8.4	29.8±6.7	

Values are means ± standard deviations, with ranges in parentheses. Body density measurements were used to estimate total body fat by either Brozek et al.(8) or Siri (48) density-specific gravity equations.

Altitude Decompression Sickness

In DCS case reports of 16 men and 5 women described by Sheffield and Cramer (47), all 3 diagnosed RDCS cases presented in females. Balldin in his study of bubble formation in flying after diving suggested that more venous bubbles might occur in the elderly and fat persons and possibly in women when decompressed (3). However, individual susceptibility to RDCS would appear to be better predicted by an individual's body fat as a risk factor than by being female or older. Case records of human RDCS typically contain descriptions of an overweight condition and thus support the view that obesity increases an individual's susceptibility to RDCS (20,24,39).

In experimental RDCS (1), indwelling vascular catheters (instrumentation), by their presence or absence, predicted survival in decompressed sheep. Although the exact mechanisms are unclear, catheters may promote bubble formation and thromboembolization. Also, catheter flushing can introduce additional bubbles.

RDCS pathogenesis appears governed by intravascular bubbles transported in the venous circulation to the lungs to cause pulmonary bubble loading. Moreover, decompression to altitude after diving can promote or exacerbate the bubble formation and pulmonary microembolism that drives the development of RDCS.

Animal and Human Altitude DCS

Proportions of the major DCS manifestations at surface and altitude appear similar in sheep, especially from decompression in near-saturation air dives. Similar responses to decompression would be expected from closely-spaced repetitive dives if we assume Haldanian gas loading in DCS-susceptible tissues. Percentages of DCS manifestations at altitude in humans most closely match sheep responses after 24-h air dives. Therefore, sheep responses to surface (1 ATA) and altitude decompression offer a model for predicting DCS manifestations in humans at altitude.

Decompression experiments with sheep taken to altitude after simulated no-stop air dives permit the comparison of animal and human altitude DCS. Intact, mature sheep were decompressed after 1/2, 4 and 24 h simulated air dives to surface for a 20 min observation and then decompressed to altitude at 8000 ft (570 Torr) and 16,000 ft (420 Torr) for successive 15-min observations (31). The 16,000 ft observation stage was omitted in later 1/2 and 4 h dives. Threshold decompression responses in sheep to no-stop air dives, also reported by Dr. Edward Lanphier in this Workshop, demonstrated little difference ($P > 0.05$, Kruskal-Wallis) in percentages of DCS manifestations between altitude and surface observations (Table 3). With pooled surface and altitude

Table 3. DCS manifestations observed in each sheep at surface and altitude after simulated no-stop air dives.

Duration, hours	1/2	4	24
DCS manifestation[1]			
Limb bends			
Surface	4/11	12/14	19/20
Altitude	3/3	14/14	17/20
CNS-DCS			
Surface	9/11	3/14	6/20
Altitude	3/3	3/14	3/20
RDCS			
Surface	5/11	1/14	7/20
Altitude	1/3	0/14	12/20
Animal dives, N	58	308	238
Pressure[2], ATA	3.2-5.2	2.1-3.2	2.0-3.3

[1] Fractions (a/b) represent a, the number of sheep with at least one case of the DCS manifestation, and b, the total number of sheep tested for dive duration and observation stage.

[2] Pressures equivalent to 33-138 ft sea water.

DCS cases in sheep, there is a significant difference ($P< 0.05$) between percentages of limb bends, CNS-DCS with mostly spinal cord manifestations, and RDCS at dive durations (Fig. 8). For example, decompression provoked a higher percentage of CNS-DCS signs in DCS-affected sheep after 1/2-h dives than after 4-h and 24-h dives.

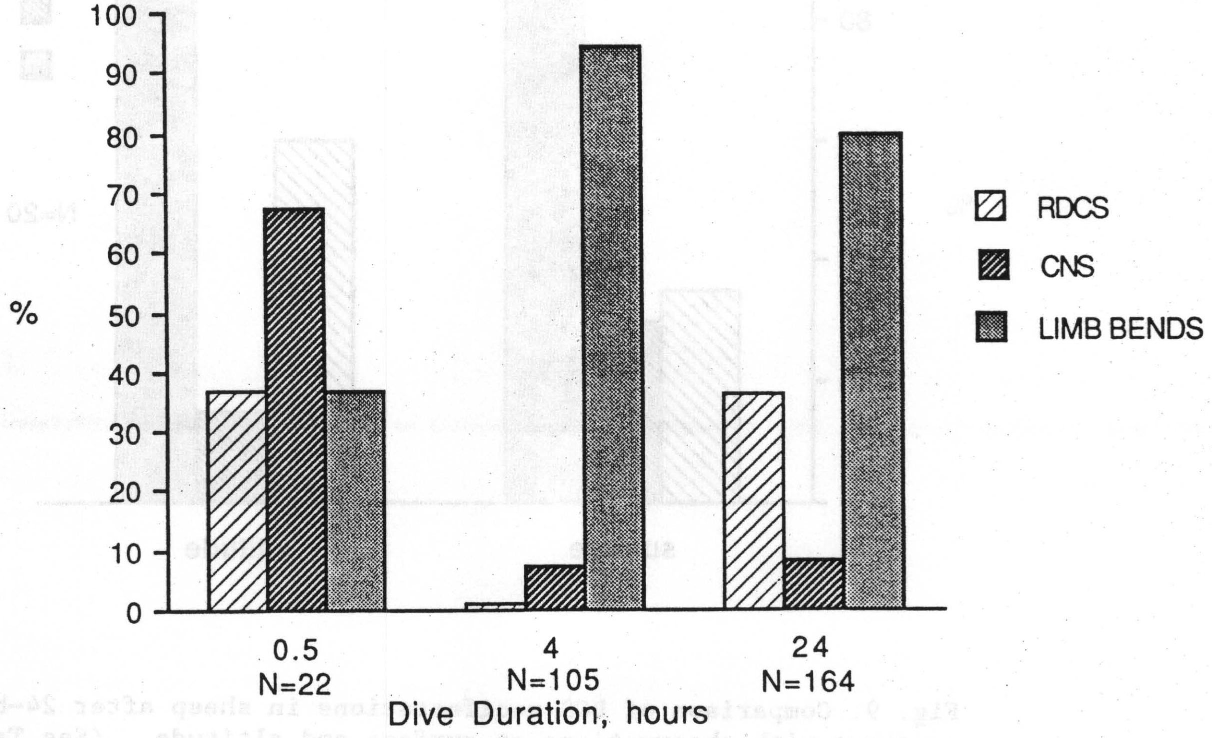

Fig. 8. Percentage DCS manifestations in sheep after no-stop air dives and altitude provocation.

As previously mentioned, decompression from 24-h air dives with altitude ascent provokes DCS manifestations in sheep with percentages that correspond to reported DCS manifestations in human altitude DCS. In 24-h sheep dives, there is a relatively high prevalence RDCS coincident with a low prevalence of CNS-DCS (Fig. 9). In addition, there is a trend for higher RDCS incidence at altitude than at surface ($0.2 > P > 0.1$), based on a Mann-Whitney test for differences.

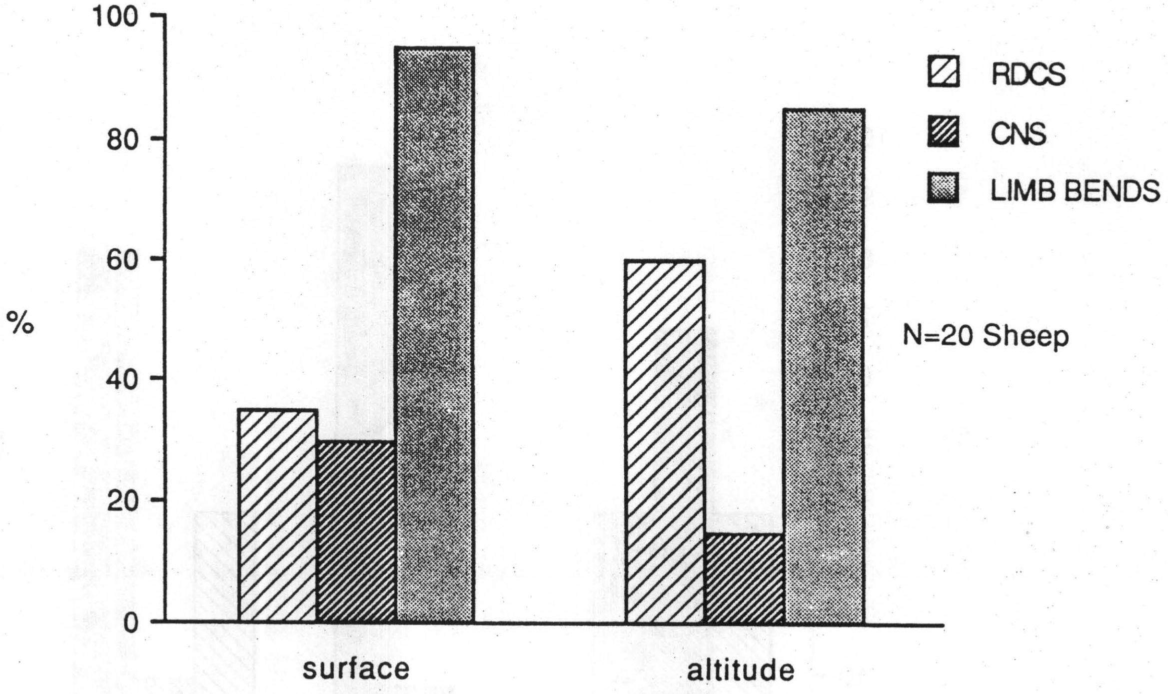

Fig. 9. Comparison of DCS manifestations in sheep after 24-h hyperbaric exposure with observations at surface and altitude. (See Table 3.)

An increased RDCS incidence at altitude suggests an altitude effect in potentiating RDCS by hypoxic vasoconstriction (36). Mountain sickness that develops in climbers and trekkers during chronic decompression to altitude has been reviewed by Heath and Williams (25). Mountain sickness shares a number of interesting similarities with RDCS. Hypoxic vasoconstriction is also thought to play a key role in the pulmonary hypertension in high-altitude pulmonary edema (50). Heath and Williams (25) state that O_2 treatment dramatically lowers pulmonary hypertension in mountain sickness. This observation points to similar therapeutic benefits that O_2 may have for pulmonary hypertension and hypoxemia in RDCS. Microthrombi often found in the pulmonary capillaries of individuals dying of high altitude pulmonary edema (25) and pulmonary bubble loading in RDCS suggest the pathogenic importance of pulmonary microembolism in mountain sickness and RDCS. Pulmonary edema (46) may be responsible for the breathlessness sensation in mountain sickness attributed to J receptor stimulation caused by interstitial fluid accumulation within the alveolar walls (25). This mechanism may also account for the dyspnea frequently reported in human RDCS.

RDCS is one of the major forms of DCS, along with limb bends and CNS-DCS with cerebral manifestations, that occur at altitude. Studies of human altitude DCS provoked in decompression from surface to altitude provide an extensive source of information about the potential effects of flying after diving.

Humans decompressed to high altitude to simulate flight conditions sometimes presented with DCS, commonly with RDCS manifestations, and such test flights were aborted. During World War II, approximately 20% of the DCS cases produced in human decompressions with O_2 (21,19) were RDCS cases (Fig. 10). Human DCS cases under these conditions are

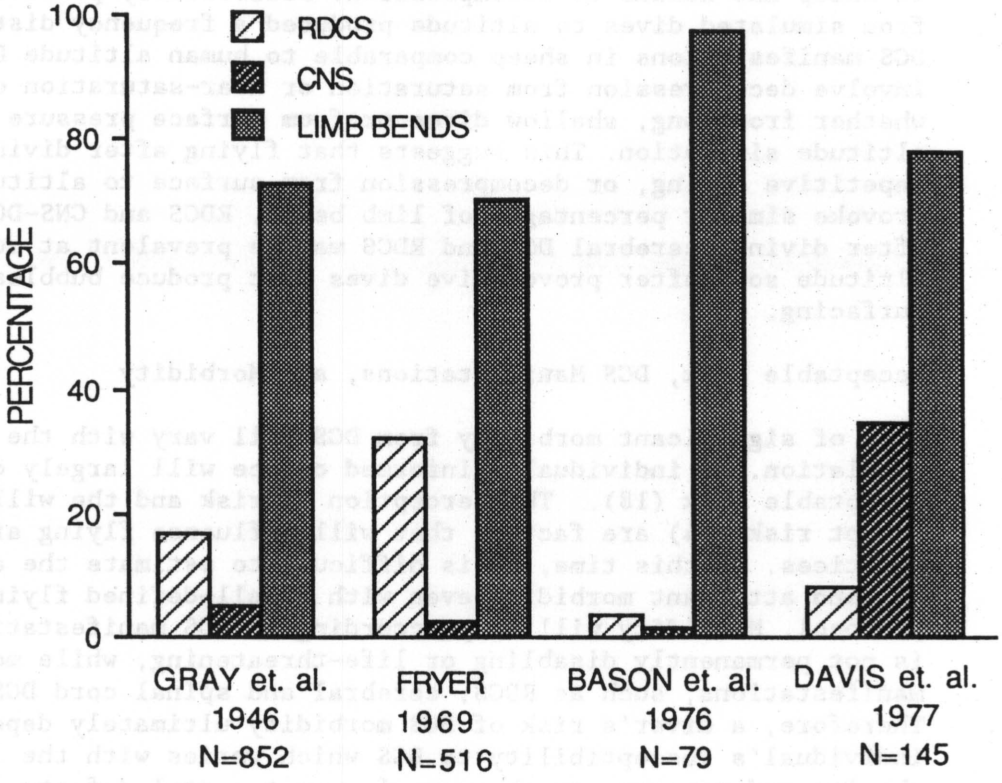

Fig. 10. Human DCS manifestations with altitude decompression from surface pressure.

similar to the sheep responses to 24-h dives with altitude provocation to 16,000 ft (420 Torr). In later human reports, the RDCS incidence appears much lower. A lower RDCS incidence may be due to less provocative exposures or to a greater awareness of potential CNS-DCS. Most increases in DCS were reported as cerebral DCS cases (4,12). CNS-DCS in many of these cases may be due to patent septal defects that permit the passage of venous bubbles into the systemic circulation (29,37). Substantial precordial bubble loading will promote both RDCS and cerebral CNS-DCS among those individuals with septal defects. Prolonged 0_2 denitrogenation (23,51), now commonly used, appears to have an important protective effect against RDCS development in altitude decompression. Early "flight" trials, without prolonged denitrogenation, demonstrated a significant RDCS risk associated with provocative altitude decompression in humans.

Similar DCS Manifestations After Long Air Dives or Altitude.

The frequency distributions of limb bends, RDCS and CNS-DCS in sheep studies and simulated high altitude exposures indicate similar responses in sheep and humans to decompression. Deliberately provocative ascents from simulated dives to altitude produced a frequency distribution of DCS manifestations in sheep comparable to human altitude DCS. Both involve decompression from saturation or near-saturation conditions, whether from long, shallow dives or from surface pressure before altitude simulation. This suggests that flying after diving, especially repetitive diving, or decompression from surface to altitude will provoke similar percentages of limb bends, RDCS and CNS-DCS. In flying after diving, cerebral DCS and RDCS may be prevalent at moderate altitude soon after provocative dives that produce bubbles upon surfacing.

Acceptable Risk, DCS Manifestations, and Morbidity

Risk of significant morbidity from DCS will vary with the diver population. An individual's informed choice will largely determine acceptable risk (18). The perception of risk and the willingness to accept risk (34) are factors that will influence flying after diving practices. At this time, it is difficult to estimate the actual risk of DCS and attendant morbidity even with a well-defined flying after diving protocol. Morbidity will vary according to DCS manifestation: limb bends is not permanently disabling or life-threatening, while more serious manifestations, such as RDCS, cerebral and spinal cord DCS, often are. Therefore, a diver's risk of DCS morbidity ultimately depends on 1) an individual's susceptibility to DCS which varies with the individual's obesity and presence or absence of patent septal defects, and 2) the diver's pressure profile.

Conclusions

Several implications drawn from these findings can improve our understanding of DCS at altitude and reduce the risk of flying after diving.

1. RDCS represents a significant hazard to the diver if venous bubble formation is massive, especially when initiated by flying too soon after diving.

2. Obesity appears to be an important risk factor in RDCS based on both animal findings and human case reports.
3. Doppler ultrasound bubble detection is useful for monitoring potential RDCS.
4. Altitude decompression provokes DCS similar to decompression from near-saturation and closely-spaced repetitive dives.

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Discussion of Dr. Lehner's Paper

CHAIRMAN SHEFFIELD: Could you expand on obesity being a risk factor?

DR. LEHNER: It became obvious by looking at the case reports, that humans exposed to altitude oftentimes were obese and, frankly, quite grossly obese. In this case, the individual may be carrying 25 to 30 percent of his body mass in fat. I looked at a series of reports, one done by Wilmore and Behnke (1969), in <u>J.A.P.</u> In their population of college men at Berkeley, they estimated total body fat composition at about 15 percent. More recent studies were done with middle-aged women and, I think, people like myself. (I'm probably carrying 20 to 25 percent of my body mass in body fat.) Given the fact that nitrogen is five times more soluble in fat than aqueous tissues, or at least water, presumably the increased fat composition in an individual who is mildly obese or very obese is an important risk factor from the standpoint of development of bubbles on decompression. That is to say, there's simply just going to be more bubble formation associated with obesity.

DR. LAMBERTSEN: What did you have in mind, Paul?

CHAIRMAN SHEFFIELD: I wonder if we've really had that experience. Is there really a need to recommend restrictions on overweight individuals who dive or fly? Should there be a weight restriction? I've always taken the position that there should not be a weight restriction because we've been unable to find the literature that supports it. There are several reports that indicate that a person who bent was also obese, but I was not aware of a report that directly correlated bends with obesity.

DR. VANN: Yes, there is one. It's a report by Mark Denbert in UBR. He analyzed Navy decompression sickness cases and found that weight (fat) was one of the best correlations for risk. Philp has also shown this very nicely in rats, but, obviously, rats are not humans.

DR. LEHNER: Boycott and Damant, in 1908, had a paper on obesity associated with decompression sickness. It's a very early study that indicated that obesity was a factor in decompression sickness.

MR. HORRIGAN: There's also some work by Tom Allen, at the U.S. Air Force School of Aerospace Medicine, back around 1969/70 in which he had categories of obesity related to altitude decompression sickness. Within the population we've tested at the Johnson Space Center, we tried to match the astronauts' population so that everyone was in relatively good condition. Within that population, we didn't see any change in degrees of obesity, but we didn't have any truly obese subjects.

DR. LEHNER: What percentage of body fat did they have?

MR. HORRIGAN: The percentages of body fat in our subject populations usually were between 15 and 22 percent.

DR. LAMBERTSEN: Paul, the reason I asked what you had in mind, there obviously is something you weren't getting an answer to. It seems as if you're going to be concerned with regulations and you may feel that it shouldn't be treated as a simple question, subject to simple regulation. From a philosophical standpoint, picture body fat as having several roles in decompression sickness. One is to get bends themselves, and nobody cares. Another is the dissolving gas which, during a severe decompression, you can picture off-loading gas and getting large amounts of venous gas emboli. That's a separate matter from having the symptomatic event, which probably never occurs. The third element of this is a chronic situation, such as bone. There are other vital structures where fat is present but it's not the material that's involved in the symptoms. The spinal cord is an example of that. The spinal cord isn't a fatty organ, but it has a lot of fat deposits around it. The neurological event in a spinal cord hit doesn't have to relate to the fat necessarily, even if there is a lot of fat around the spinal cord. In your role as a policy maker in medical aviation, you have to avoid letting someone cause you to make a regulation without weighing the gravity of the situation.

CHAIRMAN SHEFFIELD: We fly and dive a lot of very heavy people who never get the bends.

DR. LAMBERTSEN: Well, I think there were some studies made in World War II on very large populations. They related obesity and age in the course of decompression risk with a statistical correlation. But when you look at individuals you could find people at the extreme edge of the table, in terms of obesity and risk, who had a higher resistance then some of the individuals at the other end. Maybe it suggests that there are other factors, but I don't think they're very significant factors. There are some overlying factors that are much more important.

DR. LEHNER: I would like to address that issue very briefly. The study you're talking about is in Fryer's book, Subatmospheric Decompression Sickness. He had a section dealing with body weight as compared with susceptibility to decompression sickness. He showed a positive relationship.

Getting back to the point that Chris Lambertsen made about spinal cord decompression sickness. I saw no obvious relationship between the weight of an animal, presumably that is in some way correlated with obesity, and the susceptibility to decompression sickness in our half hour series. In animals with respiratory decompression sickness there seems to be a very strong obesity factor (at least body weight) effect on whether an animal survived or did not survive its respiratory decompression sickness. So I think for some forms of decompression sickness it is important. But, as Paul Sheffield was saying, there are individuals who are heavy who don't succumb to decompression sickness. In future studies, we'll be using ultrasound to assist us in fat composition determinations in our animals.

DR. BELL: You went through a decompression sickness end point. I'm wondering if an ultimate conclusion can be drawn from that? Is it possible that a person's body fat exacerbates, rather than being the cause of respiratory decompression sickness?

DR. LEHNER: On the basis of what mechanism?

DR. BELL: I'm not suggesting any mechanism. I'm looking at what your data suggest to you, that you went to an end point where you had decompression sickness.

DR. LEHNER: No. Seventeen out of the 18 animals had respiratory decompression sickness.

DR. BELL: You got them to that end point?

DR. LEHNER: Yes.

DR. BELL: Then I guess the real question is whether or not obesity was the complication, once you got your end point, or whether it was the cause.

DR. LEHNER: Well, they were fat to begin with before they stepped into the chamber. Therefore, they had greater fat stores and presumably a greater reservoir of dissolved nitrogen available for bubble formation when the sheep were decompressed 24 hr later.

DR. BELL: That could exacerbate the problem rather than be the cause. That's what I'm saying.

DR. VANN: Two comments, Charlie. One, it struck me, how many more precordial bubbles there are at altitude than in diving, and yet we don't have serious problems. If we had the same amount of bubbles in diving, we would really expect some spinal DCS. Just doing a simple calculation based on Fick's first law, you can see that a bubble will be absorbed twice as fast, at 18,000 feet, as compared to one atmosphere. That may be part of the explanation. The other comment concerns the refractory nature of respiratory decompression sickness to recompression on oxygen. There is good evidence that shows complement in the lung can produce pulmonary edema and also increase pulmonary artery pressure. There is evidence from Ward that bubbles stimulate the formation of complement. That might be a potential mechanism.

DR. LEHNER: Well, first of all, we were recompressing the animals on air. We weren't using oxygen.

DR. VANN: I believe that it does tend to be refractory with air recompression.

DR. LEHNER: It is extremely refractory. In fact, we've had animals that appeared to have recovered and then a couple of hours after apparent signs had diminished, with perhaps only mild labored breathing, a precipitous event occurred within 30 minutes or so and the animal expired.

DR. LANPHIER: I don't think you have to go much further than the fact that they must have substantial pulmonary edema by the time you try to treat them. You can squeeze bubbles all you want, but recompression isn't going to make pulmonary edema disappear very fast.

MR. HORRIGAN: I add one more dimension to this story. The physiological changes in null gravity have us concerned, too, because of the redistribution of fluid to the trunk and head area. Choke-like symptoms of altitude decompression sickness might be more prevalent in that environment.

CHAIRMAN SHEFFIELD: Thank you, Dr. Lehner. In the next four papers we will concentrate on specific decompression schedules developed for diving at altitude and extended to flying after diving. In the next paper, Dr. Richard Bell will discuss his diving at altitude table using flying after diving criteria derived from U.S. Navy No-decompression limits.

FLYING AFTER DIVING: CRITERIA DERIVED FROM THE U.S. NAVY NO-DECOMPRESSION LIMITS. Richard L. Bell, Ph.D., Dept. of Chemical Engineering, University of California at Davis, Davis, CA.

EDITOR'S NOTE: The author did not provide a formal paper. The court recorder transcription was impossible to follow for lack of the figures presented during the workshop.

> ***SYNOPSIS:*** *Dr. Bell discussed the criteria he used to develop diving at altitude tables for fresh water. The U.S. Navy critical pressure rules were generalized and extrapolated to altitude. This extrapolation was used to predict surface intervals required before flying. Surface intervals depended on the dive profile and the aircraft cabin pressure. Then extrapolation was tested on dive profiles at 6,000 ft. altitude.*

DISCUSSION OF DR. BELL'S PAPER

MR. HORRIGAN: When you were diving your subjects in a mountain lake, did you equilibrate them to the PN_2 of that altitude prior to diving or were they equilibrated to sea level?

DR. BELL: The way that we did it was that we trained everybody to be a diving tender, a chamber operator, and an Emergency Medical Technician. One team would come up to the lake and equilibrate and start through its sequence. The other team would be there to run the chamber and the surface supply diving operation. During that time they would equilibrate. They were there for about five days before we allowed them to dive. No alcohol, no drugs, nothing except water skiing.

MR. HORRIGAN: Are you extrapolating that information to a person who would be at sea level, dive, and then fly to those altitudes?

DR. BELL: No. What I'm saying is that we tested the calculation technique. We tested the parameters that were put in; they worked for that specific case. The fact that we could also predict Peter Edel's results gave us some additional confidence. So I'm presenting that an evidence that perhaps we can make this next step to the altitude problem.

DR. INGLE: How far can you comfortably extrapolate these data at altitude? At what point do you say they can't be extrapolated further?

DR. BELL: Well, I ran into a practical problem with this when I was asked to calculate some dives at a 19,000-foot Peruvian lake. I just simply said there was evidence that people who had been equilibrated at sea level going to 19,000 feet in B-17 bombers would experience bends. I mean, it breaks down right there. I will not try to extrapolate it any further. I've shown the 15,000-foot extrapolation and so far we've never tested anything else.

DR. VANN: My model is wrong. Your model is wrong, and all models are wrong. Nevertheless, they all work to some extent. The difficulty is in distinguishing which model works a little better than another. You do 168 dives and you say it worked. Dr. Buehlmann does 168 dives and his model works. What this workshop could do very profitably would be to collate all the actual test dives that are done and print them in the same format, in the same publication so that anybody could analyze dives. It's irrelevant which model generated them if we know exactly the dive profile that was used and all the conditions. With such a database, perhaps other people can determine how flying after diving correlates with each model and perhaps we can start to distinguish subtle differences between models. Without using all the data, however, it becomes a statistical nightmare. You can't draw any conclusions when you get down to such small bends incidences of a tenth of a percent or a hundredth of a percent unless you have many dives. So if you could, Paul, encourage the participants who have actual data to submit them for joint publication.

CHAIRMAN SHEFFIELD: I think that's a good idea. As a matter of fact, during the summary session, we will seek out what tasks need to be done and what kind of effort we need to put into it. Perhaps this should be a follow-up project. Our next paper is another approach to decompression. Professor Buehlmann was kind enough to travel from Switzerland to share his concept for the diving at altitude and flying after diving tables that he developed.

FLYING AFTER DIVING

Concept, Experiments and Practice in Switzerland

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Abstract

The relation between the maximal tolerated nitrogen oversaturation and the ambient pressure is practically linear. Tissues with short half-value times have a higher tolerance than tissues with long half-value times. The human body can be regarded to consist of 16 compartments with half-value times for nitrogen from 4 up to 635 minutes. The coefficients to calculate the minimal tolerated ambient pressure for a given nitrogen partial pressure in the tissue can be derived mathematically from the half-value times of nitrogen. These values represent the "theoretical limits" of tolerance according the concept ZH-L16A.

The experimental results of 332 simulated air dives at normal ambient pressure and 190 decompressions to altitude after a surface-interval show a good accordance with the "theoretical limits" of tolerance.

The elimination of nitrogen by the lung during the surface-interval is diminished. This fact - important for repetitive diving and flying after diving - is considered in the ZH-86 air decompression-tables and in the advanced electronic decompression-computers developed in Switzerland.

The concept ZH-L16 to calculate the tolerated ambient pressure

The linear relationship between the maximal tolerated nitrogen partial pressure in the tissue (PN_2 t.) and the ambient pressure (P amb.) can be formulated:

$$(PN_2\ \text{t.} - a) \times b = \text{P amb. tolerated}$$

$$\text{or} \quad \text{P amb.}/b + a = PN_2\ \text{t. tolerated}$$

The coefficients a and b can be derived directly from the half-value time of nitrogen (N_2-½ t in minutes):

$$a = 2\ \text{bar} \times \left[\frac{N_2\text{-}\tfrac{1}{2}\ t}{\text{min}}\right]^{-1/3}$$

$$b = 1.005 - 1 \times \left[\frac{N_2\text{-}\tfrac{1}{2}\ t}{\text{min}}\right]^{-1/2}$$

Example: N_2-½ t 27 min:

$a = 0.6667$ bar

$b = 0.8126$

These directly derived coefficients give the "theoretical limits" according the concept ZH-L16 and are called ZH-L16A. The empirical values of a tolerated or nontolerated PN_2 t. can be expressed in percents of the "theoretical limits" according the coefficients of ZH-L16A.

Table 1 shows the tolerated PN_2 t. at the end of decompression after simulated air dives in percent of the limits of ZH-L16A. In 16 different series of trials without symptoms of DCS, the percentage is between 93 and 100 for the half-value times of 18.5 up to 635 minutes. In 8 additional series using the same decompression profiles, the stop-time on the last step has been shortened. If the PN_2 t. is 103 - 104 percent of the "theoretical limits" for the N_2-half-value times 54.3 up to 635 minutes, symptoms of DCS of the skin, muscles or the joints but not of the CNS can be observed. The coefficients of ZH-L16A represent the upper limit of a tolerated PN_2 t. at a normal ambient pressure.

Flying after saturation diving

At Zurich (400 m above sea level) the PN_2 t. in all tissues is 0.715 - 0.720 bar. The coefficient for a tissue with a N_2-half-value time of 635 minutes are: a = 0.2327 and b = 0.9653.

$$(0.715 - 0.2327) \times 0.9653 = 0.4656 \text{ bar}$$

The tolerated P ambient is 0.4656 bar. 16 subjects were decompressed in 15 minutes to an ambient pressure of 0.460 bar (6200 m above sea level). The subjects - 15 men and 1 woman - remained in this altitude for 180 minutes breathing air and working every hour for 10 minutes 150 - 180 Watt on a bicycle-ergometer. Mild symptoms of hypoxia but no bends occured. This experiment proves the practical linear relationship between the tolerated nitrogen oversaturation and the reduced ambient pressure at altitude for the longest half-value times.

At sea level (P amb. = 1.0 bar) the tolerated PN_2 t. using the same coefficients is: 1.2686 bar. Ascending to 4000 m above sea level (P amb. = 0.610 bar) for flying, the tolerated PN_2 t. will be: 0.8646 bar. Breathing air at an ambient pressure of 1.0 bar, the PIN_2 is 0.740 bar. 23 hours are necessary to reduce the PN_2 t. from 1.2686 to 0.860 bar. Breathing 100 % oxygen, the same desaturation needs 6 hours.

Flying after scuba-diving

Table 2 shows the results of simulated air-diving at normal ambient pressure and decompression to altitude after a surface-interval. 14 series of dives in depths of 30 m - 42 m with bottom times between 15 and 120 minutes and interval-times at surface of 20 up to 200 minutes are analyzed.

For the group A the PN_2 t. at the end of the surface-interval reached only 90 - 95 percent of the "theoretical limits" for an ambient pressure 0.687 bar (3000 m above sea level) regarding the N_2-half-value times of 109 minutes up to 635 minutes. The 59 subjects had during a stay of 120 - 180 minutes at altitude no symptoms of DCS.

For the group B the PN_2 t. for one or more N_2-half-value time has been higher than 95 percent of the "theoretical limits". The incidence of DCS in this group is 12.2 percent. We never observed disturbances of the CNS. In all cases the mild symptoms of DCS disappeared during the stop lasting 120 - 180 minutes at altitude (1400 m - 4000 m above sea level).

The number of only 59 divers in the group A might be perhaps too small. But the group B gives a clear statement, if we compare with the results given in table 1. After a first dive a PN_2 t. of 95 percent of the "theoretical limit" according the coefficients ZH-L16A is tolerated. The same value is a little to high for a repeated dive or for a decompression to altitude after a surface-interval lasting not longer than 3 - 4 hours. The explanation is in our opinion a reduced elimination of nitrogen by the lung during the surface-interval, caused by a right to left shunt as a result of microbubbles in the capillaries of the lung. The PaN_2 in the blood reaching the tissues is considerably higher after a dive during 2 up to 4 hours than the PIN_2 of the breathing gas.

Air decompression-tables and PDC

We accept in our new tables (ZH-86) for the first dive and for the N_2-half-value times 4.0 - 18.5 minutes 100 - 101 percent of the "theoretical limits". For the N_2-half-value times 27.0 up to 635 minutes, the tolerated PN_2 t. is 92 - 98 percent of the "theoretical limits" according the coefficients of ZH-L16A.

For repeated dives and for flying after diving the tolerated PN_2 t. is not higher than 90 - 91 percent of the "theoretical limit". The waiting time in the tables is combined with the repetitive groups (table 3). There are only 7 designations for 72 different dive-profiles, and we have to considerate the worst condition. The PDC can give more flexibility. The PDC ALADIN PRO using only 6 and not 16 half-value times calculates the waiting time before flying for an altitude of 4800 m above sea level. The examples in table 3 show a good correlation between the ZH-86 decompression-table and the PDC ALADIN PRO.

The decompression-table ZH-86 has been introduced at the beginning of 1987. Up to day we had no problems with flying after real diving.

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Table 1

Simulated Diving At Normal Ambient Pressure

Calculated PN_2 in the tissue (PN_2 t.) at the end of decompression in % of the limits ZH-L16A.

A. 16 series without symptoms of DCS (PN_2 t. $\geq$ 90 %) 0/252
B. 8 series with symptoms of DCS* (PN_2 t. $>$ 100 %) 34/80**

N_2-½ t min	8.0	12.5	18.5	27.0	38.3	54.4	77.0	109.0	146.0	187.0	239.0	305.0	390.0	498.0	635.0
A.	103.0	101.0	99.0	94.1	92.9	95.2	94.7	93.6	99.0	99.7	98.1	93.7	94.4	95.6	100.0
	0/39	0/55	0/55	0/59	0/101	0/101	0/104	0/111	0/50	0/50	0/50	0/84	0/65	0/49	0/34
B.	-	-	-	-	-	104.1	103.4	103.2	103.0	103.9	102.5	103.0	104.1	103.0	103.4
						5/12	8/20	9/18	13/30	10/22	15/38	15/38	16/38	16/38	11/22

* stop-time on the last step shortened

** skin itching or pain in the muscles or joints

Table 2

Flying After Diving

Simulated diving at normal ambient pressure without symptoms of DCS.
Decompression to altitude after a surface-interval.
Calculated PN_2 in the tissue at the end of the surface-interval
in % of the limits ZH-L16A (Averaged $\geq$ 90 %)

A. 5 series without symptoms of DCS at altitude 0/59
B. 9 series with symptoms of DCS at altitude 16/131*

N_2-½ t min	77.0	109.0	146.0	187.0	239.0	305.0	390.0	498.0	635.0	Interval min	Altitude P amb. bar
A. PN_2 t. $\leq$ 95 %	-	91.2	92.5	93.0	92.4	92.0	92.0	92.3	91.1	20 - 75 $\bar{x}$ 48	0.687
		0/47	0/59	0/59	0/47	0/47	0/35	0/24	0/24		
B. PN_2 t. > 95 %	95.5	96.4	97.6	97.2	95.8	95.2	95.4	95.1	97.6	40 -200 $\bar{x}$ 68	0.587 - 0.853
	7/64	15/101	15/101	15/101	16/116	16/131	14/93	14/93	6/46		

* skin itching and/or pain in the joints, disappearing at altitude.
Never disturbances of the CNS.

Table 3

Flying After Diving

Comparison with Swiss Decompression Table and PDC
Diving at 0 - 700 m above sea level

	Depth m	BT min	Stops m	 min	Total min	RG	✈ h
			6	3			
ZH-86 Table	42	18	4	6	13.6	F	4
ALADIN PRO	42	18	3	7	13.6	-	3
Interval	0	30	-	-	-	D	3
ZH-86 Table	24	(60) 30	4	24	29.8	G	5
ALADIN PRO	24	30	-	30	32.1	-	8
ZH-86 Table	42	18	4	6	13.6	F	4
ALADIN PRO	42	18	3	7	13.6	-	3
Interval	0	90	-	-	-	A	2
ZH-86 Table	24	(40) 30	-	8	10.1	F	4
ALADIN PRO	24	30	-	12	14.1	-	7

ZH-86 Table: Flying 4000 m above sea level
ALADIN PRO : Flying 4800 m above sea level

Discussion of Dr. Buehlmann's Paper

CHAIRMAN SHEFFIELD: Can you tell me approximately how many manned dives have been done using your tables?

DR. BUEHLMANN: The new tables began in 1986. Swiss divers make 200,000 to 300,000 dives every year. This is the official Swiss Table, but there are many divers who use other tables. For altitude diving, there is no control, perhaps 300, 400, or 500. That's not the same as for free diving or vacation diving -- 200,000 to 300,000 dives.

CHAIRMAN SHEFFIELD: Thank you very much, Dr. Buehlmann for being here and sharing your data with us. In the next presentation, Colonel Bob Ingle will discuss the Air Force flying after diving studies conducted at Brooks Air Force Base, Texas.

REVIEW OF AIR FORCE FLYING AFTER DIVING RESEARCH

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ABSTRACT:

I review work published by B.E.Bassett in 1982 as USAFSAM Technical Report 82-47 (1). This study predicted safe tissue supersaturation values (M-values) for reduced ambient pressures. These M-values were validated with multiple human altitude exposures after controlled dives. The results of the paper are then reinterpreted in light of current knowledge. Finally, I compare the derived M-values with those of Prof. Bühlmann(2).

M-VALUE DEVELOPMENT:

The purpose of USAFSAM-TR-82-47 was to derive and then validate a procedure for safe decompression to altitude after diving. Since the same basic physiologic mechanism is responsible for disease in both diving- and altitude- related decompression sickness (DCS), the process of determining safe limits should be similar.

Most current theories of DCS prevention are based on the theory of M-values, i.e. the theory that every tissue has a maximum tolerable tissue supersaturation of inert gas. Empirically, it has been found that tissues which rapidly exchange gas can tolerate more supersaturation than can the tissues which do so slowly. Quantifying this relationship led to the USN dive tables and their elaboration by Workman (Reference 3). (Fig.1)

The maximum tolerable tissue supersaturation at sea level, M0, varies with tissue half time. At depth, every increase in pressure is associated with a linear increase in the tolerable tissue supersaturation.

However, continued extrapolation of the depth-derived Workman M-value to altitude is clearly erroneous. It predicts that it is safe to ascend to about 29,000 ft before the sea-level saturated human would begin to be at risk of DCS. Because the linear extrapolation to altitude is invalid, Bassett chose to use a ratio method to determine tolerable supersaturation. His predicted safe ratio at altitude, R0, was the sea level value of (tolerable tissue inert gas pressure)/(ambient pressure) (Table 1). This ratio, when extrapolated to altitude, accurately predicts the onset of DCS at about 18,000 ft.

Thus, having predicted a safe level of tissue supersaturation at altitude, it was then appropriate to validate the prediction.

EXPERIMENTAL PROTOCOL:

Each of six depth exposures (Table 2) was to have 20 manned validations. The depth exposure included "moderate" step-test exercise half time at depth (except the prolonged exposure). Ascent to the surface was at 1 fsw/sec, with a one minute transfer to the altitude chamber. Ascent to 10,000 ft pressure equivalent was accomplished in 5 min, followed by a 4 hr exposure with further 5 min exercise periods every half hour. The subjects were then decompressed in 1.5 min to 16,000 feet pressure equivalent, where diluter demand oxygen regulator was used to prevent hypoxia.

Each subject was frequently monitored for venous gas embolism (VGE) by Doppler ultrasound. Each measurement lasted 2 min, the first with the subject at rest, the second minute with extremity movements. Altitude exposure was stopped for bends or for elevated VGE scores (Spencer [reference 4] grade 3 at rest or grade 4 with movement).

Because of the comparatively large number of aborts due to VGE and some bends cases, it was concluded that the predictions were invalidated, and a safer profile was suggested. This newer profile involved ascent to 8,500 ft and 14,250 ft, but used the previously determined M values for 10,000 ft and 16,000 ft respectively.

RESULTS:

The results of the initial series of Flying After Diving (FAD-I) protocol are presented in Table 3. The results of the later, more conservative, series (FAD-II) are given in Table 4.

DISCUSSION:

Interestingly, when calculated exactly for each exposure profile, the most supersaturated tissue half-time compartment ranged between 42.3 min to 45.3 min. Although the different profiles had markedly diverse depth-time parameters, one narrow compartment range was truly validated. This is a result of the underlying disjoint nature of the Workman M-values, which show two different slopes when plotted logarithmically. The most supersaturated tissue always lies just beyond the break in slopes which occurs at the 40 min compartment. Thus it is appropriate, in retrospect, to combine all the data for analysis, as it all pertains to a tissue half-time compartment with a rough value of 44 min.

At present, the consensus of researchers is that the presence of venous gas is not sufficiently strongly correlated with overt DCS to warrant equating the two phenomena. The criteria for abort in the protocol was thus overly sensitive. Seven VGE aborts in FAD-I and two in FAD-II unnecessarily shortened the exposures; exposures which might have been otherwise uneventful.

In spite of the preceding caveat, we have only one case of actual DCS at 10,000 ft following the described protocol. This roughly 1 per cent incidence of DCS with a deliberately provocative protocol would now likely be considered vindication of the underlying extrapolation, at least to 10,000 ft. As would be expected, no DCS and no significant venous gas embolism occurred at the level of 8,500 ft when using 10,000 ft safety factors.

The linear relationship of M-value with ambient pressure is well validated over a large range of pressures in diving. However, within only a 33 fswa change from sea level we are at a hard vacuum, where no valid M-value can be entertained. Clearly the extrapolation of M-values to altitude will break down over a pressure change that is minor when compared to diving pressures. The real question is not whether it breaks down but at what altitude. This protocol study helps us to determine a maximum level to which we can comfortably extrapolate.

The FAD-I essentially validated the modified M-values for 10,000 ft, but four cases of bends occurred at 16,000 ft, and seven cases were aborted there before bends could develop. Any supersaturation at depth was well treated by 4 hrs of desaturation at 10,000 ft. Importantly then, 3 of these 4 bends cases at 16,000 ft did not have ANY compartment within 3.8 fsw of its calculated limit when ascent began to the final altitude. Clearly, the roughly 4 per cent incidence of DCS so far from predicted oversaturation is reason to conclude that the suggested extrapolation is invalid at 16,000 ft.

Whether any safe extrapolation can be made to this altitude is probably a moot point. Altitude DCS is usually stated to become possible at 18,000 ft. For altitude DCS, continued exposure results in a typical sigmoid dose response curve: the more exposure the more people will develop the bends. Given the provocative nature of this protocol, perhaps this is the normal incidence of DCS for this altitude.

Finally, and most worrisome, there were two cases of VGE severe enough to warrant discontinuing the exposure at 14,250 ft. This degree of supersaturation is completely at variance with the model, especially after 4 hrs of off-gassing at 8,500 ft.

Thus, a ratio model based on the Workman M-values is reasonable up to 10,000 ft. Results clearly at variance with predictions of safety begin to occur at 14,250 ft and 16,000 ft.

COMPARISON WITH BÜHLMANN MODEL:

In order to properly appreciate the range of values tested here, I present a comparison with those calculated by the Bühlmann method for an ascent to 10,000 ft (Fig.2). Clearly, the Bassett values are much more conservative, in that they do not allow as much tissue supersaturation. Further, the difference is greatest at exactly the 40 min tissue half-time compartment that was validated by the protocol. This would suggest that we have a conservative validation for part of the Bühlmann parameters. Importantly, Bassett continued to test at higher altitudes and the limits of his model are known.

CONCLUSIONS:

The Workman M-value model can be modified to allow safe extrapolation to altitudes of 10,000 ft.

This conservative extension to low altitude has been validated by human studies.

Human validation showed that the extrapolation to altitudes of 14,250-16,000 ft is not valid.

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REVIEW OF AIR FORCE FLYING AFTER DIVING RESEARCH

ACKNOWLEDGMENTS:

This review is based on an original study designed, conducted and evaluated by LtCol Bruce Bassett. It is a tribute to his methodological accuracy and completeness that the data can now be reevaluated in the light of newer theories. Both the original study and this review were conducted at the School of Aerospace Medicine, Brooks AFB, TX.

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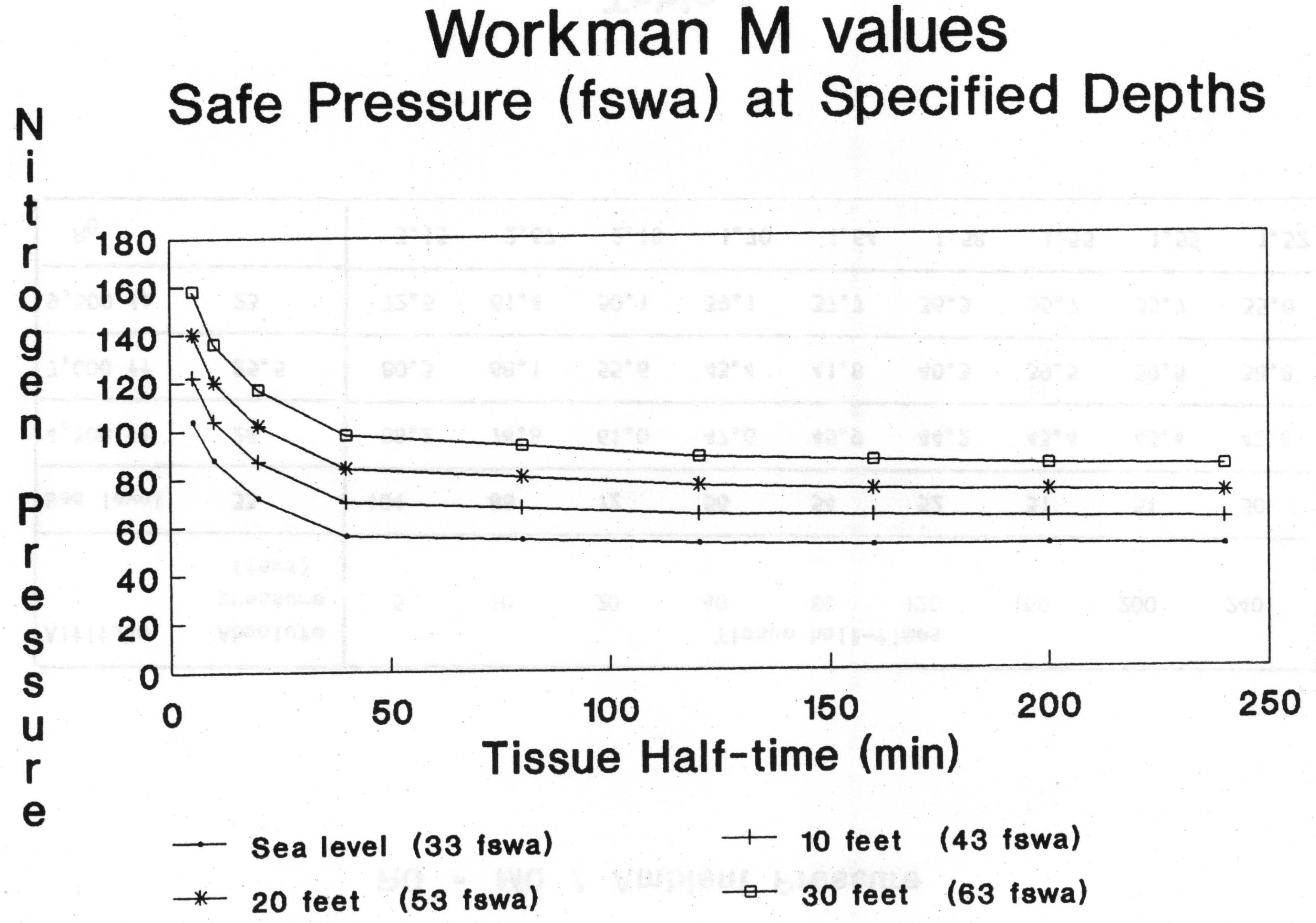
Workman M values
Safe Pressure (fswa) at Specified Depths
Nitrogen Pressure
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
Tissue Half-time (min)
Sea level (33 fswa)
10 feet (43 fswa)
20 feet (53 fswa)
30 feet (63 fswa)

Figure 1.

Generation of Modified Workman Tables by Extrapolation of Constant Ratio

RO = MO / Ambient Pressure

Altitude	Absolute pressure (fswa)	Tissue half-times 5	10	20	40	80	120	160	200	240
Sea level	33	104	88	72	56	54	52	51	51	50
4,500 ft	28	88.2	74.8	61.0	47.6	45.9	44.2	43.4	43.4	42.6
7,000 ft	25.5	80.3	68.1	55.6	43.4	41.8	40.3	39.5	39.5	38.8
9,500 ft	23	72.5	61.4	50.1	39.1	37.7	36.3	35.7	35.7	35.0
R_0		3.15	2.67	2.18	1.70	1.64	1.58	1.55	1.55	1.52

Table 1

Calculated Exposure Limits and Validation Profiles

Depth (fsw)	No-decompression limit (min) for direct ascent to 10,000 ft
10.75[a]	1440 +
20	120
30	52
40[a]	34
50	26
60[a]	20
70	16
80[a]	14
90	12
100[a]	10
110	9
120	8
130[a]	7

---

[a] Profiles selected for manned validation tests.

Table 2

Flying After Diving Initial Validation
Stops at 10,000' and 16,000'

A. The FAD-I actual exposure parameters

Mean values	Schedules					
	130/7	100/10	80/14	60/20	40/34	10.75/1440
Mean descent time (min)	2.53	1.68	1.64	1.10	1.10	N/A
Mean exposure time (min)	4.47	8.33	12.36	18.90	32.90	1440
Mean ascent time (min)	2.68	2.08	1.76	1.33	0.96	0.88

B. Calculated mean tissue PN_2d (fswa) upon reaching 10,000 ft

Half-times	M-value	Mean tissue PN_2 (fswa)					
5	71.5	51.2	50.2	48.2	44.4	38.7	28.0
10	60.6	50.7	51.3	51.1	49.0	44.5	30.8
20	49.5	43.4	44.5	45.4	45.0	43.5	32.5
40	38.6	36.3	37.2	38.1	38.3	38.5	33.5
80	35.9	31.7	32.2	32.8	33.1	33.6	34.1
120	35.2	29.9	30.3	30.7	30.9	31.4	34.2
160	35.2	29.0	29.2	29.5	29.7	30.2	34.3
200	35.2	28.5	28.7	29.0	29.1	29.4	34.4
240	34.5	28.0	28.2	28.5	28.6	28.9	34.3

C. RESULTS

Groups	Number of:					
Manned exposures	20	18	16	18	18	20
vge at 10,000 ft	0	1	3	3	3	3
vge aborts at 10,000 ft	0	0	2	1	1	2
Bends at 10,000 ft	0	0	1	0	0	0
vge at 16,000 ft	0	7	3	3	3	2
vge aborts at 16,000 ft	0	0	1	0	0	0
Bends at 16,000 ft	0	1	0	1	1	1
Total aborts	0	1	4	2	2	3
Skin "bends"	18	14	7	6	0	0

Table 3

Flying After Diving Final Validation Stops at 8,500' and 14,250'

A. The FAD-II actual exposure parameters

Mean values	Schedules 100/10	 80/14	 60/20
Mean descent time (min)	1.83	1.36	1.09
Mean exposure time (min)	8.17	12.64	18.91
Mean ascent time (min)	2.00	1.55	1.19

B. Calculated mean tissue PN_2 and R_S values (fswa) upon reaching 8,500 ft

Half-time	M-value	PN_2	R_S	PN_2	R_S	PN_2	R_S
5	71.5	50.5	2.11	48.9	2.04	44.9	1.87
10	60.6	51.4	2.14	51.5	2.15	49.2	2.05
20	49.5	44.5	1.85	45.6	1.90	45.1	1.88
40	38.6	37.3	1.55	38.2	1.59	38.5	1.60
80	35.9	32.3	1.35	32.8	1.37	33.1	1.38
120	35.2	30.3	1.26	30.8	1.28	31.1	1.29
160	35.2	29.3	1.22	29.7	1.24	29.8	1.24
200	35.2	28.8	1.20	29.1	1.21	29.2	1.22
240	34.5	28.3	1.18	28.5	1.19	28.7	1.20

C. RESULTS

Groups		Number of:	
Manned exposures	20	19	18
vge at 8,500 ft	4	5	2
vge aborts at 8,500 ft	0	0	0
Bends at 8,500 ft	0	0	0
vge at 14,250 ft	6	6	6
vge aborts at 14,250 ft	1	0	1
Bends at 14,250 ft	0	0	1
Total aborts	1	0	2
Skin "bends"	11	1	0

Table 4

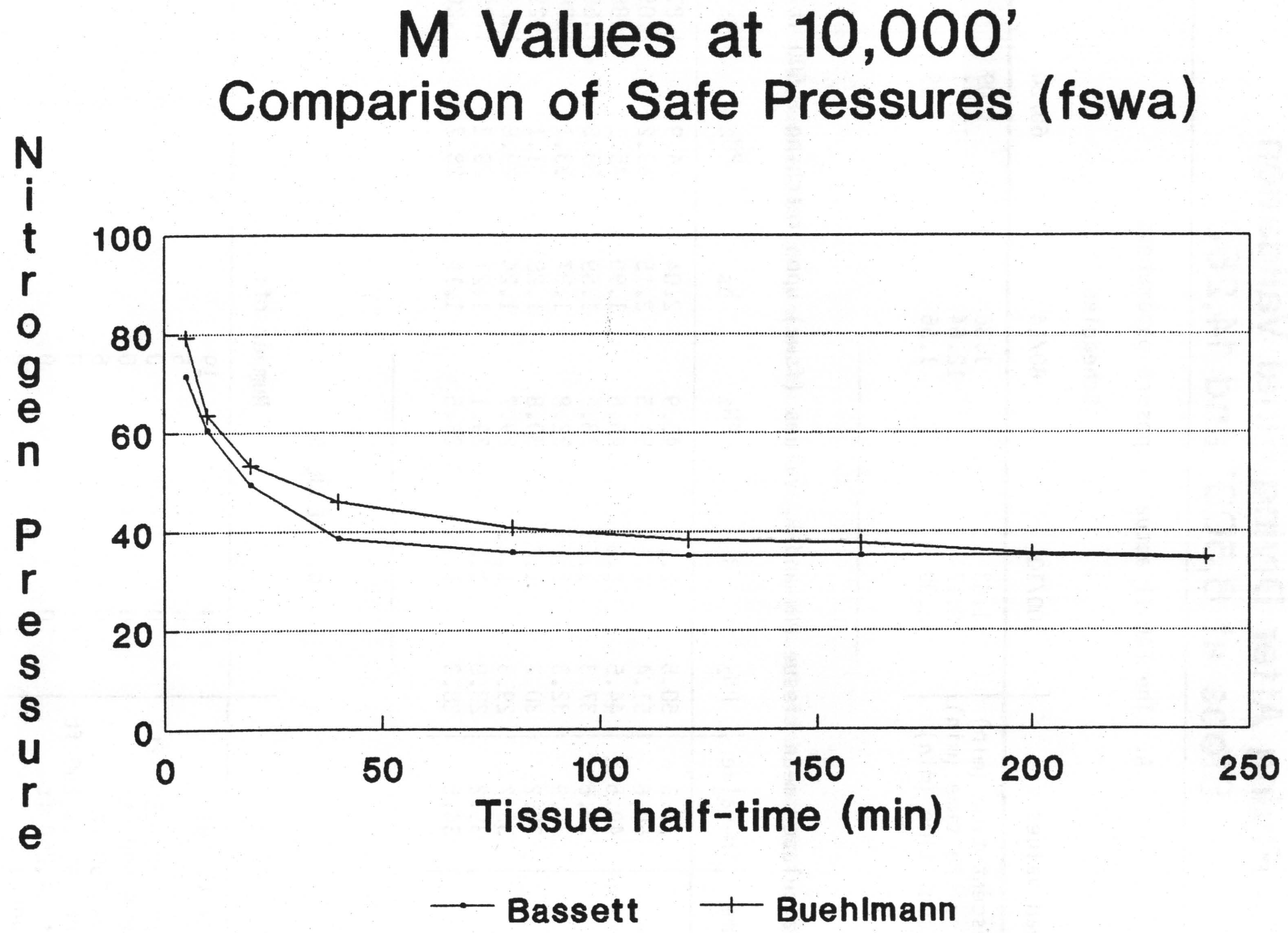
M Values at 10,000'
Comparison of Safe Pressures (fswa)
Nitrogen Pressure
100
80
60
40
20
0
0
50
100
150
200
250
Tissue half-time (min)
Bassett
Buehlmann

Figure 2.

Discussion of Dr. Ingle's Paper

DR. INGLE: Are there any questions about the conclusions, the way I would interpret them now and the way Bassett interpreted them?

DR. BELL: What was the VGE?

DR. INGLE: A Spencer Grade 3 at rest or Spencer Grade 4 while flexing the extremities. That was determined at altitude.

DR. BELL: This was strictly a Doppler determination?

DR. INGLE: Strictly a Doppler, that's correct. These people who aborted for so-called venous gas embolism (VGE) had absolutely no symptoms. They were aborted prophylacticly to avoid the onset of symptoms.

DR. BELL: In one of your early figures you showed the way you modified the Workman M values. You said he maintained a constant ratio between altitude and the allowable tissue nitrogen pressure.

DR. INGLE: This is not a standard constant ratio, the way other people talk about constant ratios, for example, in the U.S. Navy Diving Medical Officer Course.

DR. BELL: If I understand what you said, though, that implies a constant slope on that linear relationship driving that through zero. It's simply that this uses the original as one point on the line?

DR. INGLE: That's right.

DR. BELL: It gives a constant slope from there on?

DR. INGLE: Quite a lot more conservative, as you can see, in comparison with Dr. Buehlmann's studies.

DR. BENNETT: I think there's one point that's got to be made, though. The mathematics are fine. You play your little games with tissue half-times, and this has been going on for 36 years in my life. I'm totally unconvinced it means anything except that its a mathematical tool for playing all the games.

DR. INGLE: It works.

DR. BENNETT: What you've got is fine and with this kind of evidence you can perhaps make a table safe, and maybe extrapolate it to altitude. But what you're doing is a single dive that nobody is doing anymore. In terms of the diving that I have to look after, with people diving multi day, multi-dives a day, this isn't going to be very helpful.

DR. INGLE: This helps to set a limit for what we can do in terms of extrapolation to altitude. I think that gives us a fixed point from which we can start. We can start extrapolating from that point and then start extrapolating from the surface.

DR. BENNETT: But the point is, I don't think the model works even on the surface, let alone taking it up to altitude. That's the problem.

DR. INGLE: I wouldn't want to comment on repetitive dives. I wouldn't even want to guess.

DR. BUEHLMANN: There's the problem of nitrogen elimination into the lungs. There's a reduced nitrogen elimination for two hours or three hours, that's the question. You have seen my table 0-2500 meter above sea level. At 95 up to 100 percent of the limits, there is no problem. With a reduced interval time, 90 minutes, then we had symptoms. In other words, we have to correct for repetitive diving and for the interval for flying after diving. This correction is simple for the table; it is a little difficult for the computer. We can reduce our tolerance values. The simplest way is to go to 90 percent for the second dive or for flying after diving. The other way is a combination to reduce the elimination during the interval with a reduction of tolerance values, let us say to 95 percent.

MR. EMMERMAN: I want to add a third variable. Besides the dive and the surface interval, it's the length of time in the aircraft, using the aircraft exposure as the key. In the work I did, I used a meter to simulate 12 different tissues. It took me two and a half hours to get them to reach their full limitation. The point being, we don't even have the data on the cases that have been reported to know how long the exposure was and when these people started symptoms in the aircraft. Where could you show an exposure of X time? I notice that on two of them, there was less than two hours exposure at altitude. Possibly that number is on these flights of four to five hours. These people may be presenting three hours later. The first two hours, they may be fine. It's a variable we know nothing about on top of the other two variables that we know very little about. All of these cases were non-smokers who didn't smoke because they were in a control group, and they were not drinking. They do not represent the divers that we deal with who end up in chambers for treatment.

MR. HORRIGAN: One comment I could make on the altitude incidence. NASA and the Air Force did a considerable number of six-hour altitude runs. We have probably done over 600 subjects and the curve of incidence shows the highest percentage at about the three-hour mark. Very few in the first hour. Some in the second, but then it peaks at three hours, then tends to tail off. Some symptoms disappear before the end of the six hours; they're mild symptoms. There are cases where we actually got altitude bends in the fifth and sixth hours.

DR. BUEHLMANN: I agree. Symptoms after dives at normal pressure react the same. Sometimes they came six to eight hours later. But most of them in experimental diving, came in the first two hours.

CHAIRMAN SHEFFIELD: Two issues need to be addressed. The first is Dick Vann's earlier question: What risk are we willing to accept? Under special circumstances, one out of a hundred persons having bends might be an acceptable risk for a special military diving and flying operation. If I'm on vacation in the Caribbean and have to fly back home, a one-percent chance that I'm going to bend is not going to be acceptable to me. In terms of an acceptable risk, you have to say what group you're talking about. Are you talking about a commercial diver who must dive, a military diver who must fly, or a person who goes on a recreational dive with the option of flying afterwards?

The second point, among the Air Force series of 766 altitude decompression sickness cases, only four involved ascent to altitude after diving. But we have had several DCS cases produced by reascent after flying. I had the privilege of heading a 1978 study group that reviewed the high incidence of decompression sickness among Air Force Academy cadets. The freshman cadets were mostly young healthy males within very carefully controlled weight standards who were on a vigorous exercise program. During their altitude chamber training, their incidence of bends was tenfold that of the rest of the Air Force. Because some of the cases were Type II, CNS decompression sickness, they were restricted from a flying career. This caused the Superintendent of the Air Force Academy and the Surgeon General to be very concerned. Most of the cases occurred after the cadets returned to the Academy. To receive their altitude chamber flight, the cadets would descend from the 7,200 foot elevation at the Academy to the 6,000-foot level, at Peterson Air Force Base. Two to three hours after the altitude chamber flights were completed, they would reascent a thousand feet to the Air Force Academy. At about the four-hour point, some cadets reported in with bends. We believe that reascent was a factor.

Our training program at the time seemed to contribute to the incidence. For example, we gave the cadet two exposures in the altitude chamber. There was a 35,000-foot exposure, followed by a rapid decompression flight to 23,000 feet. In our first attempt to solve the problem, we held the cadets to the lower altitude at Peterson AFB for a period of eight hours after the exposure. We restricted the diet. The maximum chamber flight exposure was 25,000 feet, for a maximum of ten minutes at 25,000 feet. They were required to pre-breathe oxygen for 45 minutes before the exposure. Despite these new restrictions, we had our worst CNS case on the first exposure to that profile. The next step was to eliminate training of freshmen cadets, delaying training until the sophomore year. The cadets remained over night at Peterson AFB before reascent to the Air Force Academy. In addition to the altitude restrictions, the cadets were restricted from exercise for 12 hours before and 24 hours after the chamber flight. With all these restrictions, the bends problem was solved.

DR. LAMBERTSEN: Well, you just raised something that I thought came out of Peter Edel's comment regarding the kinds of divers and the model not being able to predict such things. A model does what it's supposed to do. If the model doesn't predict things that it wasn't supposed to predict that doesn't mean that the model is no good. It can still be good for what it was intended to do. What's happening when people dive is that, in addition to the physics of gas exchange and other things involved in the model, the person changes and, therefore, the matrix for that model changes with time. The model cannot sensibly be made to include all the unpredictable, very complex physiological changes that include severe dehydration, severe thermal changes, and other unrecognized effectors. The model has to be the baseline around which these other things can be brought in. But to try to make one model encompass all of these unknown and varied things just doesn't make sense. What you want to do is fix the situations that are fouling up the model, or else add these as other conditions. I think Dr. Buehlmann was beginning to insert that thought when he asked if you would change the arithmetic of the interval. You don't even have to do that necessarily. The important thing is that you have to do something, and it won't always be the same thing. If you build it all into one model then the model is never going to be useful.

MR. EMMERMAN: My guidelines for the ultimate Flying after Diving Table diagram would be an entire table which had listed: Are you a smoker? Are you a drinker? A whole series of questions. At the bottom, it would say we don't know that this works anyway. But have the entire matrix of possibilities. I don't believe we have the data to come to that conclusion.

DR. BELL: In any design problem you run into the same difficulty. When you're doing a distillation model, you apply the theory and do the calculus, and that gives you a number that you can use. Ordinarily what happens is that you won't come up with a number that you are comfortable with. Someone could get all military divers making the parameters. I think ultimately that's what has to be done. I think what's coming out of this discussion is that there does exist a number like that. You can use computer models and you can get some kind of number for departure. Then if you want to increase your safety factor you multiply it by two. If you don't like that, you multiply it by four. At least you've got a number that you can multiply.
There's one other point that comes out of this discussion. Your divers are all military divers making dry chamber dives?

DR. INGLE: That's correct.

DR. BELL: All of Dr. Buehlmann's divers were non-military divers (men and women) in mountain lakes and the results were about the same.

CHAIRMAN SHEFFIELD: Dr. Ingle, thanks so much for sharing those data with us. In the next paper, Mr. Ron Nishi will compare the calculations of a number of decompression models for flying after diving.

THEORETICAL CONSIDERATIONS FOR CALCULATING FLYING AFTER DIVING

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ABSTRACT

The prediction of flying after diving times based on decompression models used to generate dive tables requires the consideration of other factors which may not be as important when calculating dive tables. Most commonly used decompression tables and dive computers are based on models that have an ascent criterion in which the allowable nitrogen value (M-value) is linearly related to the ascent depth. The M-value cannot be extrapolated to altitude and must be changed for calculating flying after diving times. Compartments with longer half-times must also be considered since flying after diving can be considered to be analogous to calculating the decompression requirements following excursion diving during a saturation dive. In addition, no clear-cut distinctions can be made between no-decompression dives and those requiring decompression stops. These are illustrated by examples based on a number of Haldanian decompression models.

INTRODUCTION

The calculation of flying after diving times requires the consideration of a number of factors associated with the type of decompression model used. Most commonly used decompression tables and dive computers are based on the Haldanian model of a number of theoretical tissue compartments in parallel. A few tables are based on other configurations, for example, a series arrangement of compartments in the DCIEM decompression tables [1], or a single slab model in the British air tables[2]. Regardless of the type of configuration, all of these models use a similar ascent criterion to calculate the decompression back to the surface. This ascent criterion is sometimes referred to as a supersaturation ratio or M-value. In calculating flying after diving times, it is necessary to extend this supersaturation concept to altitude.

In this study, the effect of the different parameters on flying after diving will be investigated. Calculations will be based on a number of Haldanian decompression models and results compared. Although the Haldanian decompression calculation method may not be the most realistic or satisfactory model for decompression, it provides a quick and convenient way to calculate decompression profiles. Despite attempts in the past to relate the Haldane model to more rigorous gas exchange models or bubble growth and decay models, the Haldanian model still remains primarily an empirical method rather than a physiological model.

MATHEMATICAL CONSIDERATIONS

In the Haldanian model, all compartments are in parallel, thus being independent of each other. Each compartment is assigned a half-time. The range of half-times depends on the number of compartments involved. Table 1 shows the number of compartments and the range of half-times for a number of air diving models.

Table 1. Haldanian Decompression Models

Model	No. of Compartments	Range of Half-times (min)	Reference
US Navy - air	6	5–120	3
Workman - air	6	5–120	3
Workman - nitrogen	9	5–240	3
PADUA	10	5–480	4
Swiss ($ZH\text{–}L_{12}$)	16	4–635	5,6
Huggins - No D air	6	5–120	4
Edge Dive Computer	11	5–480	4
Rogers (PADI)	8	5–120	7

The allowable nitrogen pressure, commonly referred to as the "M-value", in each compartment at a specific depth, D (gauge pressure units), is given by the equation

$$M = M_0 + \Delta M \times D \tag{1}$$

where M_0 is the value allowed for ascending to the surface and ΔM is the change in M per unit pressure. The supersaturation ratio, R, at any given depth is given by

$$R = \frac{M}{(D + P_{SURF})} = \frac{M}{P_{SA}} \tag{2}$$

where P_{SURF} is the absolute pressure at the surface and $P_{SA} = D + P_{SURF}$ is the safe ascent pressure. Equation 1 can be rewritten as

$$P_{SA} = \frac{P_T}{a} - b \tag{3}$$

where

$$P_T = M,$$

$$a = \Delta M \text{, and}$$

$$b = \frac{M_0}{\Delta M} - P_{SURF}.$$

Table 2 gives the values of M_0, ΔM, a, and b for four of the models shown in Table 1 (pressure in feet of seawater (fsw) and half-times, $T_{1/2}$, in minutes). These four models were selected since they covered a range of half-times from 120 to 635 min. The Huggins, Edge and Rogers versions are not shown since they were designed only for no-decompression profiles and do not specify ΔM's.

Table 2. Parameters for Models Used

Workman (Air)										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00				
M_0	104.00	88.00	72.00	58.00	52.00	51.00				
ΔM	1.80	1.60	1.50	1.40	1.30	1.20				
a	1.80	1.60	1.50	1.40	1.30	1.20				
b	24.78	22.00	15.00	8.43	7.00	9.50				
Workman (Nitrogen)										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00	160.00	200.00	240.00	
M_0	104.00	88.00	72.00	56.00	54.00	52.00	51.00	51.00	50.00	
ΔM	1.80	1.60	1.50	1.40	1.30	1.20	1.15	1.10	1.10	
a	1.80	1.60	1.50	1.40	1.30	1.20	1.15	1.10	1.10	
b	24.78	22.00	15.00	7.00	8.54	10.33	11.35	13.36	12.45	
PADUA (Pennsylvania Analysis of Decompression for Undersea and Aerospace)										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00	160.00	240.00	320.00	480.00
M_0	100.00	84.00	68.00	53.00	52.00	51.00	50.00	49.00	49.00	48.00
ΔM	1.60	1.50	1.40	1.30	1.20	1.10	1.10	1.00	1.00	1.00
a	1.60	1.50	1.40	1.30	1.20	1.10	1.10	1.00	1.00	1.00
b	29.50	23.00	15.57	7.77	10.33	13.36	12.45	16.00	16.00	15.00
Swiss (Buhlmann - $ZH-L_{12}$)										
$T_{1/2}$	4.00	8.00	12.50	18.50	27.00	38.30	54.30	77.00	109.00	146.00
M_0	102.60	87.94	74.26	68.16	61.90	56.60	52.68	50.43	49.39	48.23
ΔM	1.25	1.25	1.25	1.21	1.18	1.16	1.15	1.11	1.10	1.06
a	1.25	1.25	1.25	1.21	1.18	1.16	1.15	1.11	1.10	1.06
b	49.08	37.35	26.41	23.33	19.46	15.79	12.81	12.43	11.90	12.50
$T_{1/2}$	187.00	239.00	305.00	390.00	498.00	635.00				
M_0	46.45	46.45	42.16	42.16	42.16	42.16				
ΔM	1.06	1.06	1.04	1.04	1.04	1.04				
a	1.06	1.06	1.04	1.04	1.04	1.04				
b	10.82	10.82	7.54	7.54	7.54	7.54				

The supersaturation ratio, $R = P_T / P_{SA}$, can then be written in two alternative forms as

$$R = a \left[1 + \frac{b}{P_{SA}} \right] \tag{4}$$

$$R = a \left[1 - \frac{ab}{P_T} \right]^{-1} . \tag{5}$$

With these two equations, it is easy to calculate the supersaturation ratio for any value of P_{SA} or P_T. It can be observed that R is depth-dependent, being more conservative at deep depths, and increases as the pressure decreases. In fact, when P_T is equal to ab, R becomes infinite and then becomes negative for lower pressures. This indicates that the M-value concept of a linear relationship between M and D, although adequate for calculating decompression tables from exposures to pressures greater than 1 atmosphere, becomes inadequate when excursions to altitude are considered and cannot be extrapolated to altitude. The most serious effect is on the short half-time compartments where the value ab is large and greater than the inert gas tissue pressure at the surface. In this range of pressures, R and P_{SA} for these compartments are meaningless. Table 3 shows the safe ascent pressure, P_{SA}, calculated for P_T equal to 26.07 fsw, the inert gas pressure for an individual saturated at sea level. (The value for the Swiss model is less since water vapor in the inspired breathing gas has been taken into account). Also shown are the supersaturation ratio, R_{SL}, for sea level and the equivalent altitude (expressed in thousands of ft) obtained from

$$Alt = 145.53 \left[1 - \left[\frac{P_{SA}}{P_{SURF}} \right]^{0.1903} \right] . \tag{6}$$

Observations of flying after diving have shown that the safe maximum altitude for an individual saturated at sea level is approximately 18,000 ft (0.5 atm). The allowable safe ascent altitude based on M-values is over 25,000 ft for the first three models. Thus, the use of the supersaturation ratios based on the extrapolation of M-values to altitude are unsafe for these three models. Although the situation is similar in the Swiss model for half-times less than 300 min, it has been designed so that for half-times greater than 300 min, the maximum allowable altitude is approximately 18,000 ft. It should be noted, however, that compartments with half-times shorter than 300 min are involved as the controlling compartments in calculating the safe ascent altitude in the time period immediately after a dive, and as a result, the calculated safe ascent altitude will be unsafe.

Bassett, in his study of flying after diving for the US Air Force [8], recognized this problem of the unsafe altitudes based on the M-values in the US Navy and Workman models. He changed the ascent criterion by assuming a constant supersaturation ratio, R_0, based on that derived from M_0, i.e., the value used to reach the surface after a

Table 3. Maximum Altitude Based on Extrapolation of M-Values

					Workman (air)					
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00				
P_T P_{SA} R_{SL} *Alt*	26.07 -10.29 -2.53 *	26.07 -5.71 -4.57 *	26.07 2.38 10.95 57.30	26.07 10.19 2.56 29.16	26.07 13.05 2.00 23.55	26.07 12.23 2.13 25.06				
					Workman (nitrogen)					
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00	160.00	200.00	240.00	
P_T P_{SA} R_{SL} *Alt*	26.07 -10.29 -2.53 *	26.07 -5.71 -4.57 *	26.07 2.38 10.95 57.30	26.07 11.62 2.24 26.21	26.07 11.52 2.26 26.42	26.07 11.39 2.29 26.67	26.07 11.32 2.30 26.81	26.07 10.34 2.52 28.84	26.07 11.25 2.32 26.96	
					PADUA					
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00	160.00	240.00	320.00	480.00
P_T P_{SA} R_{SL} *Alt*	26.07 -13.21 -1.97 *	26.07 -5.62 -4.64 *	26.07 3.05 8.55 53.03	26.07 12.28 2.12 24.95	26.07 11.39 2.29 26.67	26.07 10.34 2.52 28.84	26.07 11.25 2.32 26.96	26.07 10.07 2.59 29.42	26.07 10.07 2.59 29.42	26.07 11.07 2.36 27.31
					Swiss (Buhlmann - $ZH\text{-}L_{12}$)					
$T_{1/2}$	4.00	8.00	12.50	18.50	27.00	38.30	54.30	77.00	109.00	146.00
P_T P_{SA} R_{SL} *Alt*	24.79 -29.25 -0.85 *	24.79 -17.52 -1.42 *	24.79 -6.58 -3.77 *	24.79 -2.84 -8.72 *	24.79 1.55 15.98 64.20	24.79 5.58 4.44 41.77	24.79 8.75 2.83 32.49	24.79 9.90 2.50 29.80	24.79 10.64 2.33 28.21	24.79 10.89 2.28 27.69
$T_{1/2}$	187.00	239.00	305.00	390.00	498.00	635.00				
P_T P_{SA} R_{SL} *Alt*	24.79 12.57 1.97 24.43	24.79 12.57 1.97 24.43	24.79 16.30 1.52 18.28	24.79 16.30 1.52 18.28	24.79 16.30 1.52 18.28	24.79 16.30 1.52 18.28				

(P_T, P_{SA} in fsw, Altitude in 1000 ft)

dive. However, he combined the US Navy values (similar to the Workman air values) and the Workman nitrogen values and took the most conservative of the two. He concluded that since the altitude for $P_T = 26.07$ fsw was approximately 17,000 ft for the Workman nitrogen model, using these constant ratios would be safe.

Table 4 shows the maximum safe altitudes using the constant supersaturation ratio, $R_0 = M_0/P_{SURF}$ for an individual saturated at sea level ($P_T = 26.07$ fsw). The use of the constant ratio gives more reasonable values for the maximum safe altitude for each compartment compared to the results shown in Table 3. For half-times less than 80 min, the maximum safe altitude is still greater than 18,000 ft (i.e., $R_0 > 1.58$). This is probably acceptable since experience has shown that the faster tissues can tolerate a higher degree of supersaturation than the slower tissues. However, for the half-times greater than 120 min, the maximum altitude allowed becomes less than 18,000 ft ($R_0 < 1.58$) and for the longest half-times, may be more conservative than necessary. For example, the maximum altitude allowed for compartments with half-times greater than 300 min is only 14,000 ft in the Swiss model. Thus, the use of the constant ratio based on M_0 also has its limitations. This is particularly true for some other models as shown in Table 5.

Table 4. Maximum Altitude Based on Constant Ratio, $R_0 = M_0/P_{SURF}$

Workman (air)										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00				
P_T	26.07	26.07	26.07	26.07	26.07	26.07				
R_0	3.15	2.67	2.18	1.76	1.58	1.54				
P_{SA}	8.27	9.78	11.95	14.83	16.54	16.87				
Alt_0	33.69	30.08	25.58	20.54	17.92	17.45				
Workman (nitrogen)										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00	160.00	200.00	240.00	
R_0	3.15	2.67	2.18	1.70	1.64	1.58	1.54	1.54	1.52	
P_T	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	
P_{SA}	8.27	9.78	11.95	15.36	15.93	16.54	16.87	16.87	17.21	
Alt_0	33.69	30.08	25.58	19.71	18.83	17.92	17.45	17.45	16.96	
PADUA										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00	160.00	240.00	320.00	480.00
R_0	3.03	2.54	2.06	1.61	1.58	1.54	1.52	1.48	1.48	1.46
P_T	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07
P_{SA}	8.60	10.24	12.65	16.23	16.54	16.87	17.21	17.56	17.56	17.92
Alt_0	32.85	29.05	24.27	18.38	17.92	17.45	16.96	16.48	16.48	15.96
Swiss (Buhlmann - $ZH{-}L_{12}$)										
$T_{1/2}$	4.00	8.00	12.50	18.50	27.00	38.30	54.30	77.00	109.00	146.00
R_0	3.11	2.66	2.25	2.06	1.88	1.72	1.60	1.53	1.50	1.46
P_{SA}	7.97	9.30	11.02	12.00	13.22	14.45	15.53	16.22	16.56	16.96
P_T	24.79	24.79	24.79	24.79	24.79	24.79	24.79	24.79	24.79	24.79
Alt_0	34.47	31.16	27.42	25.48	23.26	21.16	19.45	18.40	17.89	17.31
$T_{1/2}$	187.00	239.00	305.00	390.00	498.00	635.00				
R_0	1.41	1.41	1.28	1.28	1.28	1.28				
P_T	24.79	24.79	24.79	24.79	24.79	24.79				
P_{SA}	17.61	17.61	19.40	19.40	19.40	19.40				
Alt_0	16.39	16.39	13.99	13.99	13.99	13.99				

(P_T, P_{SA} in fsw, Altitude in 1000 ft)

Table 5. Maximum Altitude Based on Constant Ratio, $R_0 = M_0/P_{SURF}$

	Huggins (Univ. Michigan)										
$T_{1/2}$	5.00	10.00	20.00	40.00	80.00	120.00					
M_0	102.00	85.00	67.50	54.50	47.50	43.00					
R_0	3.09	2.58	2.04	1.65	1.44	1.30					
P_T	26.07	26.07	26.07	26.07	26.07	26.07					
P_{SA}	8.43	10.12	12.75	15.79	18.11	20.01					
Alt_0	33.28	29.31	24.10	19.05	15.70	13.22					

	Rogers (PADI)										
$T_{1/2}$	5.00	10.00	20.00	30.00	40.00	60.00	80.00	120.00			
M_0	102.90	84.10	67.20	59.80	55.70	51.40	49.10	46.90			
R_0	3.12	2.55	2.04	1.81	1.69	1.56	1.49	1.42			
P_T	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07			
P_{SA}	8.36	10.23	12.80	14.39	15.45	16.74	17.52	18.34			
Alt_0	33.46	29.08	24.00	21.27	19.58	17.64	16.52	15.39			

	Edge Dive Computer										
$T_{1/2}$	5.00	11.00	17.00	24.00	37.00	61.00	87.00	125.00	197.00	392.00	480.00
M_0	100.00	81.80	71.50	63.70	55.90	50.70	46.80	43.00	39.10	33.90	33.00
R_0	3.03	2.48	2.17	1.93	1.69	1.54	1.42	1.30	1.18	1.03	1.00
P_T	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07	26.07
P_{SA}	8.60	10.52	12.03	13.51	15.39	16.97	18.38	20.01	22.00	25.38	26.07
Alt_0	32.85	28.46	25.42	22.75	19.66	17.30	15.33	13.22	10.80	7.10	6.38

(P_T, P_{SA} in fsw, Altitude in 1000 ft)

Table 5 shows the allowable altitudes calculated from M_0 for the Huggins, Rogers and Edge, which are intended for no-decompression dives only. Since in-water stops are not necessary or permitted in these models, no ΔM's are specified or defined to accompany the M_0 values for each compartment. Because these models are designed for recreational divers, they are more conservative than those shown in Table 4. As a result, the final ascent altitude calculated from R_0 is low, particularly for the Edge dive computer model.

For those compartments where the maximum altitude is less than 18,000 ft, a better method than using the constant ratio is to let the supersaturation ratio vary from the value shown in Table 4 (R_0) according to Eqn. 5 until it reaches a maximum of 1.58 and then maintain it at that value. In this way, the maximum safe altitude for any of the compartments will never be less than 18,000 ft. Thus, the safe ascent altitude, P_{SA}, for $P_{SA} < P_{SURF}$, can be computed from

$$P_{SA} = P_T / R_0, \qquad R_0 > 1.58 \tag{7}$$

$$P_{SA} = P_T / a - b, \qquad R_0 < 1.58, \quad R < 1.58 \tag{8}$$

$$P_{SA} = P_T / 1.58, \qquad R_0 < 1.58, \quad R > 1.58 \tag{9}$$

CALCULATION OF FLYING AFTER DIVING

For the no-decompression models where ΔM's are not specified, a and b can not be calculated and there is no way to extrapolate the M-values to altitude. It may probably be better to impose a supersaturation ratio of 1.58 for all compartments to carry out flying after diving calculations. This would also provide more conservatism during the time period immediately after the dive.

PREDICTIONS OF FLYING AFTER DIVING TIMES

A number of different conditions were investigated to determine which factors were important for flying after diving predictions. An investigation of the compartment pressures during most dives using a Haldanian model shows that half-times greater than 120 min are rarely involved and in most cases, only half-times less than 80 min are involved. As a result, unless exceptional exposure dives or extensive repetitive dives are conducted, it is not necessary to consider long half-time compartments when calculating decompression tables. However, the situation is different for calculating flying after diving and longer half-time compartments must be considered. Flying after diving is analogous to calculating the decompression requirements following excursion diving from saturation.

Figures 1-4 show the maximum allowable altitude as a function of time on the surface following no decompression dives calculated from the four models shown in Table 2. (Figures 1-3 are based on the US Navy No-D limits. Figure 4 is based on the Swiss No-D limits). It can be seen that the models with the longer maximum half-times give more conservative predictions and that it would appear essential that long half-times be considered.

Figures 5 and 6 show how the altitude varies with half-time in the Swiss model for 30 metres of seawater (msw)/60 min and 30 msw/20 min (98.4 fsw). The maximum half-time is not as critical for the shorter bottom-time dive whereas for the longer bottom-time, the results are considerably different for altitudes above 8000 ft. The question is to determine what the maximum half-time should be. One method of determining this half-time would be to keep adding longer half-times to the model until there is very little difference in the altitude prediction for the range of dives normally done.

Figure 7 shows how the altitude prediction varies with bottom time at 30 msw (98.4 fsw)for the Swiss model. A comparison with the times for no decompression dives shown in Figure 4 shows that there is a large overlap. Because of this overlap, the common rule of "12 hours after no decompression dives, 24 hours after decompression dives" does not make too much sense. It is better to make some grouping of dives, based on some parameter similar to a repetitive group. For example, Figure 8 shows that Repetitive Group G dives in the Swiss tables give almost identical altitude profiles from a 15 msw (49.2 fsw) no decompression dive to a 54 msw (177.2 fsw) for 20

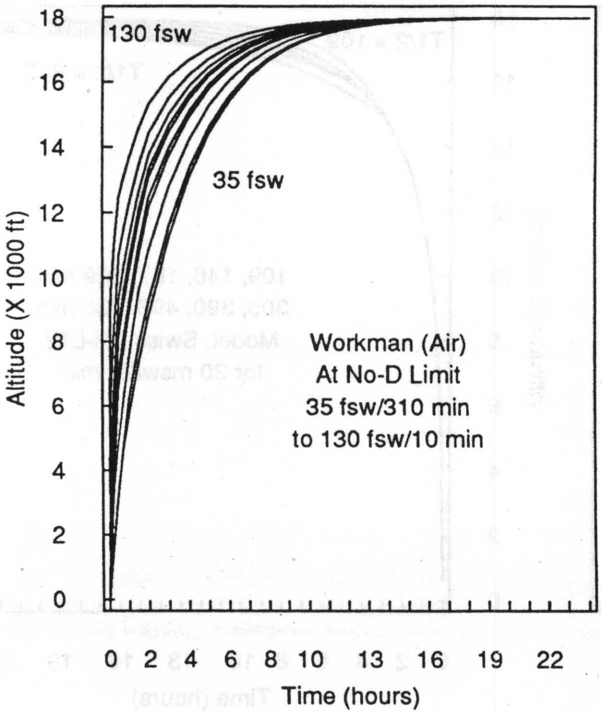

Fig. 1. Maximum altitude allowable after NoD dives

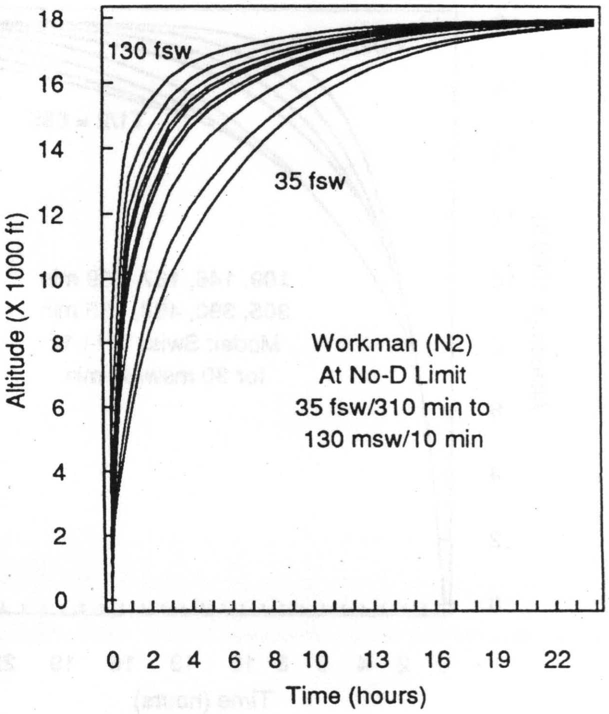

Fig. 2. Maximum altitude allowable after NoD dives

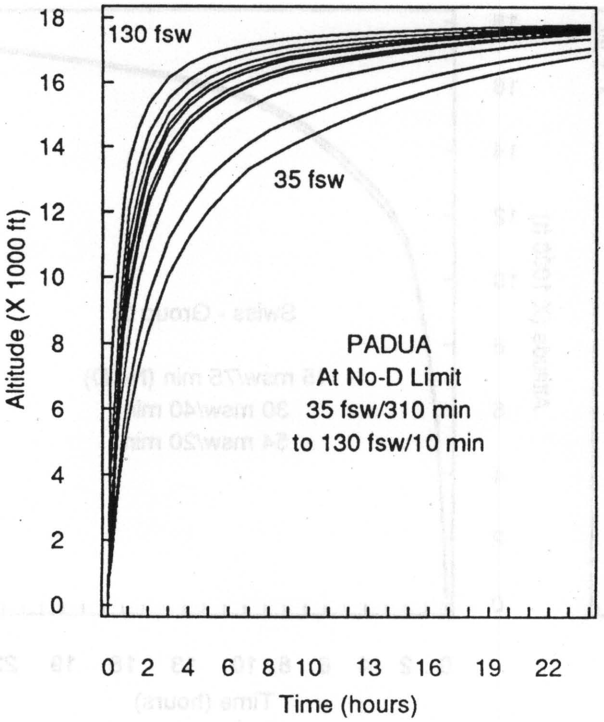

Fig. 3. Maximum altitude allowable after NoD dives

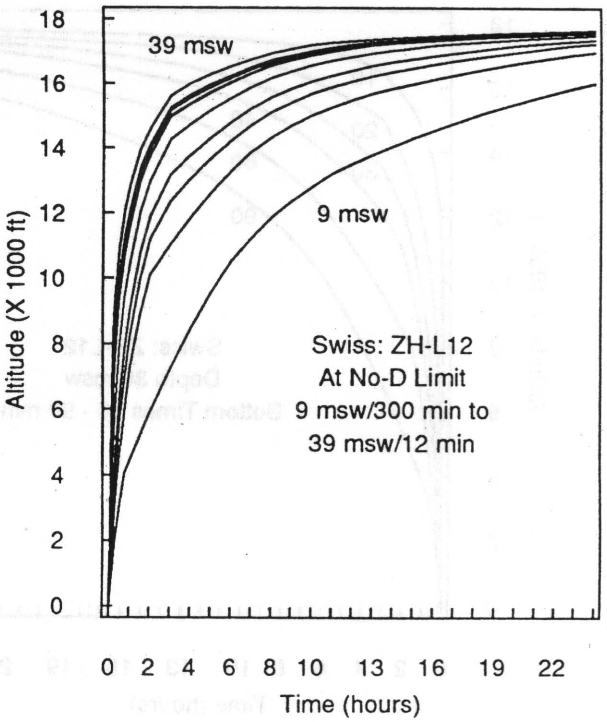

Fig. 4. Maximum altitude allowable after NoD dives

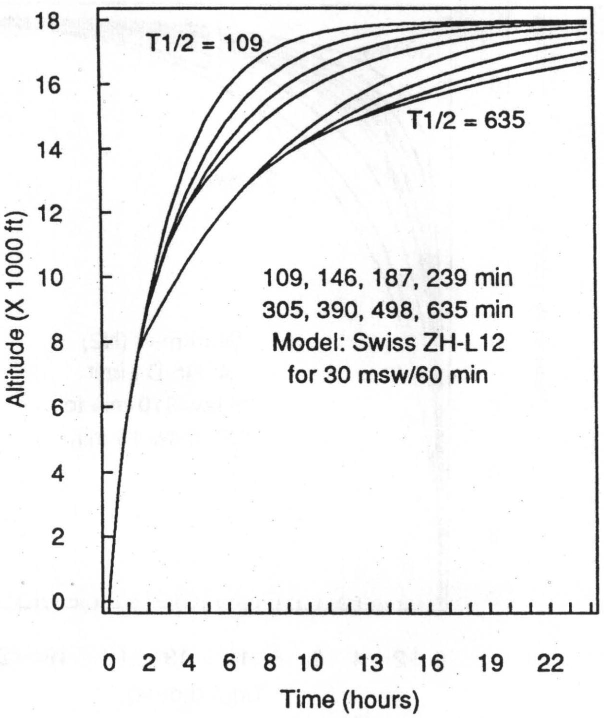

Fig. 5. Altitude as function of half-time

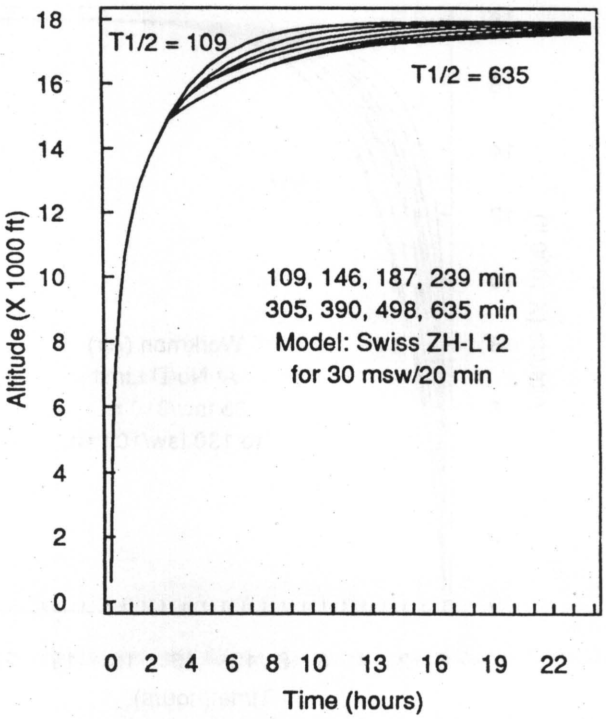

Fig. 6. Altitude as function of half-time

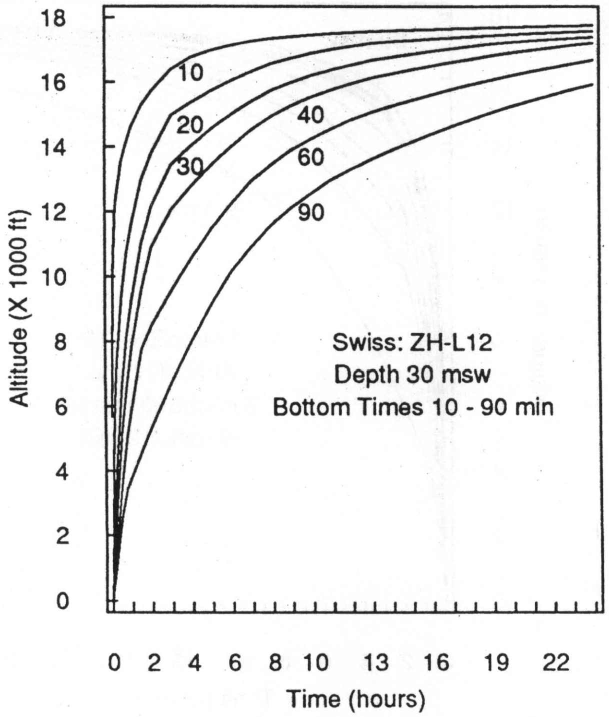

Fig. 7. Altitude as a function of bottom-time

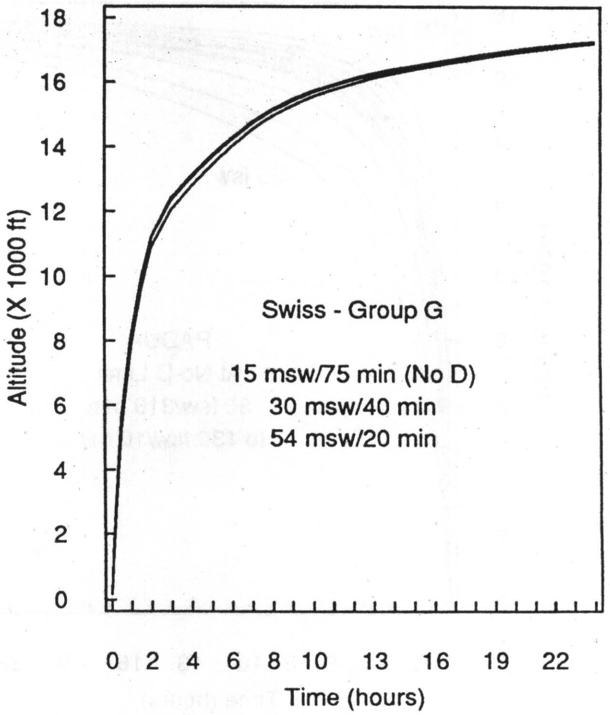

Fig. 8. Altitude for Equivalent Dives

min decompression dive. All groups were not investigated to see whether the equivalency held over the depth range for each group.

Calculations were done for USN Repetitive Group D since this is the group commonly believed to allow flying immediately to 8000 ft (commercial aircraft cabin pressure). Figure 9 shows that this is not the case. Since Group D appears to be too conservative for shallow dives and is perhaps unsafe for the deeper dives, Hennessy [9] has suggested that Group C or B be used for dives deeper than 50 fsw, and Group E for depths less than 50 fsw. However, this is probably academic since only a few minutes are required before the predictions show that 8000 ft is possible at all depths.

Figure 10 shows the prediction for a shallow air saturation dive at 25 fsw for the four models investigated. For saturation, a long half-time must be considered. With the 635 min half-time from the Swiss model, it will be 11 hours before the prediction reaches 8000 ft. In terms of the time required before all the excess inert gas can be considered to be eliminated, three or four days are required.

All the calculations have shown that the permissible time for flying after diving, even for the worst case, is far shorter than is normally believed to be safe. If the flying after diving model is accurate, then it should be possible for some individuals to fly according to the model. However, there will probably be a large risk involved. All the predictions are valid only if the decompression profiles generated by the models give safe decompression. If the decompression is not adequate, then excessive asymptomatic bubbles can be generated which can persist for hours after the dive has been completed. During decompression studies at DCIEM, we have observed bubbles in the circulatory system for up to 9 hours after surfacing in some individuals after high risk dives [10]. Bubbles have also been observed in some individuals in no-decompression dives. Such individuals would not be able to fly safely according to these predictions. Thus it is necessary to provide a sufficient safety factor to the times predicted theoretically. The theoretical times should be used only as a guideline. The safety factor must be decided from actual observations and experimentations [8, 11] and may differ depending on whether the application is intended for recreational divers (in which case it should be very conservative), or for those who must fly soon after diving, such as search and rescue crews.

This analysis is not intended to condone or endorse the use of the Haldanian method or the models shown here for calculating decompression profiles. Some of the models shown here may produce decompression tables with an unacceptable risk of decompression sickness. In fact, the Haldanian model is probably not the best model because of the large number of parameters (3 times the number of compartments) which are required to define the model [9]. The Haldanian models were used because they were more convenient to illustrate the factors to be considered for flying after diving calculations.

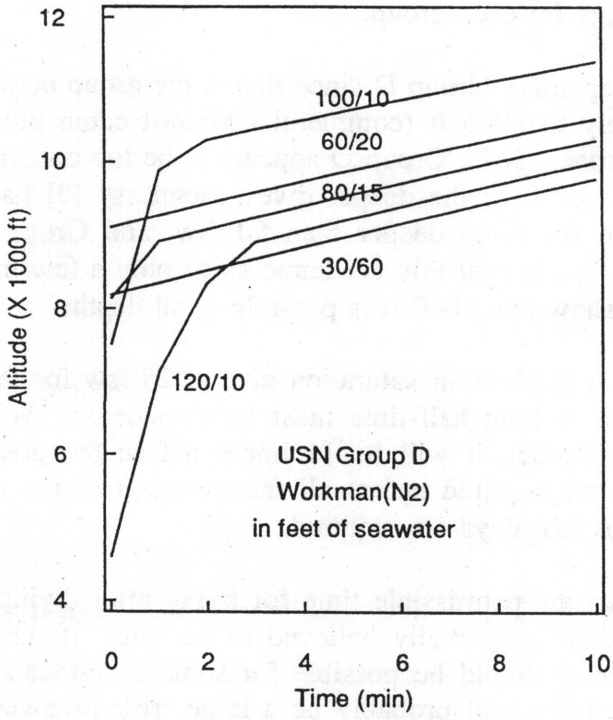

Fig. 9. Altitude after Group D dives

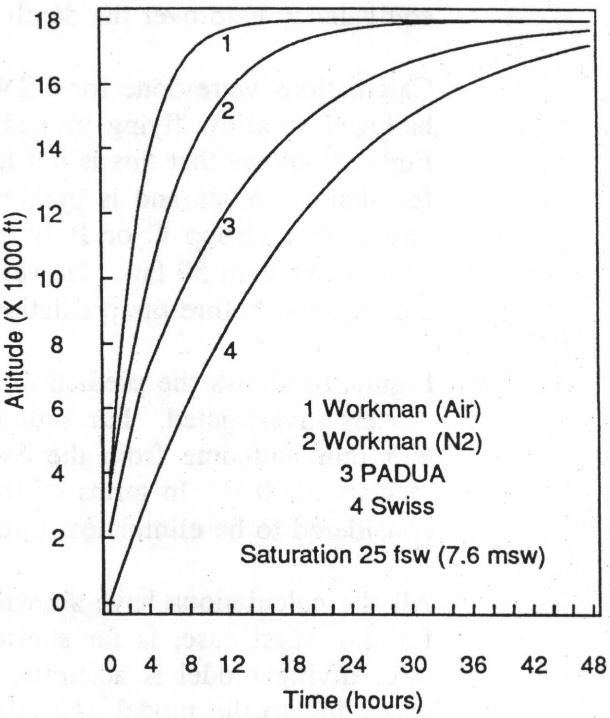

Fig. 10. Altitude allowed after saturation dive

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Discussion of Mr. Nishi's Paper

CHAIRMAN SHEFFIELD: Thank you so much for that excellent analysis, Mr. Nishi.

DR. BUEHLMANN: I think you bring it all together, all the different models.

DR. BENNETT: I think he's made a good analysis and it's helped me to be convinced that it's not all over by a long way. I get very concerned when I hear, "Are we going to have safety factors for these rules?" It reminds me of many years ago when decompression tables were coming out and someone said, ah, the problem is that everybody's different and they're all going to have their own little coefficient. They're going to modify the table so that they can all come up with their own table and nobody will have decompression sickness. I feel I'm hearing the same thing here now, in terms of flying after diving. I don't know how you do it.

CHAIRMAN SHEFFIELD: Any other thoughts?

LCDR. O'DOUGHERTY: My name is Hugh O'Dougherty. I'm a lieutenant commander in the U.S. Coast Guard. I'm a helicopter pilot and an airplane pilot. I fly both types of aircraft for rescue missions. I am a former sport diver and former emergency medical technician. My current job at Coast Guard Headquarters is to run the Aviation Life Support Branch that oversees aviation rescue equipment, policies, and training; aviation survival equipment policies and training; the Rescue Swimmer Program (rescuers who jump out of aircraft to rescue incapacitated people in the water); and the medical technician program for the entire Coast Guard.

In 1972, as a recent university graduate, I took a YMCA course on sport diving. When they talked about air embolism and the bends, they described the factors that could lead to a situation where you may suffer from these problems. "If you have any problems, get on oxygen and radio a call to the Coast Guard. They'll send a helicopter right away." Eighteen months later I found myself flying a rescue helicopter. Not really having a lot of guidance, I went out and picked up a patient from a dive boat off the coast of New York City and put him on oxygen in the back of the helicopter. I talked to him on the intercom system all the way in to St. Barnabas Hospital. I didn't have any idea at what altitude I was supposed to fly. As it ended up, I flew no higher than 1,000 feet all the way in because of ridge lines in New Jersey.

When I arrived at St. Barnabas Hospital, the people who ran the recompression chamber gave me some good advise as to how to handle a scuba patient in the future. They said don't fly any higher than 1,500 feet. I asked where they got that from? They said the Navy Dive Manual. Sure enough, when I checked, it was in the 1970 Navy Dive Manual.

It's still not very clear to everybody in the Coast Guard what they're supposed to do. Some people say talk to DAN, some people say go to the Navy Dive Manual. I don't know what DAN is saying now, but I know they have said don't transport a dive patient any higher than 500 feet. The Navy Dive Manual has now changed to read no higher than 1,000 feet.

I'd like to have you come up with some sort of simple guidance for Coast Guard air crews since things seem to be changing. I'm concerned that when we carry diving patients in pressurized aircraft, we may be fooling ourselves because, after flying pressurized aircraft quite a few years, I know there are lots of problems in maintaining stability of pressure in a cabin. This stability is influenced by anti-icing systems in the aircraft, health of the engines and possible malfunctioning of the piping system that pushes air around the aircraft. Various leaks are acceptable in the aircraft, such as air conditioner and compressor malfunctions. Another problem relates to inadequate information on the diver. I might pick up a diver who claims to have been down to 130 feet for 30 minutes. He appears to be overweight. I don't know if he's been drinking or smoking. I don't know what kind of shape he's in. I don't know how old he is. All I have is a distress call that I've responded to. What I'm saying is, I'd like to be able to get some sort of guidance, and I'd like it to be simple so that a pilot can understand it. If you don't want to discuss it now, just decide later and let me know what I'm supposed to be telling my people.

DR. INGLE: Move the patient as low as possible and as fast as possible.

LCDR. O'DOUGHERTY: That's another thing I'd like to mention. When I first got in the Coast Guard the guys who flew the seaplanes would go out and land next to the boat, pick up the patient, take off, climb to 50 feet and fly at 160 knots, which is all that a seaplane is capable of doing. Other people would say they were endangering their crew because, at 50 feet, a two-engine aircraft that loses an engine has an excellent chance of crashing. What is the safe (safe for the patient) maximum altitude for flying? If I fly them in a C-130, do I pressurize the airplane? Do I just stay at 1,000 feet and fly as fast as I can, which may involve more turbulence and a rougher ride but at least provide a stable pressure the whole way? Do I fly at 50 feet? If there's a ridge line that's 1,000 feet high and there's a recompression chamber on the other side of that ridge line, do I fly 150 miles down the beach to another recompression chamber so that I don't have to go over the 1,000 foot ridge? These are the sorts of things -- real life situations -- that rescue pilots run into when they transport a scuba patient.

CHAIRMAN SHEFFIELD: Thank you for your input, Commander O'Dougherty. I appreciate those comments. It introduces the next paper in which I will summarize the flying after diving guidelines that exist in print.

FLYING AFTER DIVING GUIDELINES

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INTRODUCTION:

Many guidelines for flying after diving have been proposed since the 1960s. In fact, there are so many "rules" that a conscientious sports diver has great difficulty sorting through them. For dives that require no decompression stops, surface intervals ranging from zero to 24 hrs have been proposed (1,2). However, few of the recommendations have been validated by manned testing. Less restrictive flying after diving rules have a special appeal to divers who fly into a remote diving paradise with a desire to make the maximum number of dives before departing on the flight home. More conservative rules are sought by those who wish to reduce the risk of decompression sickness from flying after diving.

DECOMPRESSION SICKNESS:

Ascent to altitude after diving has been reported to result in decompression sickness. Miner (1961) reported an in-flight incident in which several members of a commercial airliner crew suffered decompression sickness (DCS) after scuba diving (3). Sheffield and Cramer (1988) reported 4 cases secondary to flying after diving or secondary to ascent in an automobile after diving (4). Bennett and associates (1989) reported that 1987 Divers Alert Network (DAN) data revealed 87 cases involving flying after diving, but most of the cases included air ambulance transport of diving accident cases to a treatment area. In the DAN series, decompression sickness occurred in 6 cases during flight, in 11 cases after flight, and in 3 cases during ascent by automobile to approximately 1,000 ft (5). Charles and Wirjosemito (1989) reported a case that occurred during a commercial flight 30 hrs after an uneventful 4-day diving activity (6).

In 1969, Edel and associates (7) recommended a minimum 2 hr surface interval after a dive requiring no decompression stops, before flying in commercial aircraft (8,000 ft cabin pressure). For dives requiring decompression stops, a 24 hr interval was recommended. These flying restrictions were published in the 1972 British Sub-Aqua Club Diving Manual (8) and were subsequently reprinted in the Feb 1976 issue of Pressure. This prompted a number of letters to the Editor by members who insisted that the surface interval was too short and offered alternatives (9,10,11,12).

FLYING AFTER DIVING GUIDELINES

DIVING AT ALTITUDE AND FLYING AFTER DIVING TABLES:

Most of the flying after diving recommendations are based on "diving at altitude" calculations. In 1970, Cross proposed altitude corrections to the US Navy diving tables and suggested that the corrected tables could also be used for flying after diving (13).

The 1972 British Sub-Aqua Club (BS-AC) Diving Manual contained adjustments to the air decompression table for diving at altitude and recommended flying restrictions of 2 hrs for no-stop dives and 24 hrs for dives needing stops (8). The 1988 BS-AC Decompression Tables recommended restrictions for flying in pressurized aircraft until the diver reaches current tissue code B (a 4-hour surface interval) and restrictions for flying in unpressurized aircraft until the diver reaches current tissue code A, equating to a 15-16 hour surface interval (14).

Bell and Borgwardt (1976) examined the theoretical basis of the Cross high altitude corrections and reported that the Cross corrections resulted in decompression times that were substantially longer than required. Based on the results of man dives at an elevation of 6200 ft in Lake Tahoe, Bell and Borgwardt published revised tables for altitude diving in fresh water (15).

Buhlmann's (1976) decompression tables for diving at altitude were developed for use in the mountain lakes of Switzerland (16). Buhlmann's 1986 revised tables were based on 573 simulated air dives and 544 actual dives in mountain lakes. Buhlmann's' Repetitive Dive Timetable 0-2500M above SL provides repetitive groups that suggest surface intervals of 2 to 7 hrs following a dive before flying (17).

The Canadian Forces (1985) Air Diving Tables were based on the Defense and Civil Institute of Environmental Medicine (DCIEM) computer model, which is a modified Kidd-Stubbs Model. The tables contain depth corrections for diving at altitude but have not yet been verified experimentally with human subjects (10). Based on the DCIEM model, Nishi (1985) recommended that recreational divers delay flying for 12 hrs after no-decompression dives and 24 hrs after dives requiring decompression stops (18).

FLYING AFTER DIVING RESEARCH:

Duffner and Kiessling (1960) exposed human subjects to depths of 90 ft for 30 min. After adequate decompression and a 15-min surface interval, the subjects were taken to an 18,000 ft altitude, with a subsequent incidence of decompression sickness of 55 percent (19).

Furry, Reeves, and Beckman (1967) exposed dogs to depths of 54-89 FSW for 7 hrs, and after a surface interval of 1 to 12 hrs, subjected them to an altitude of 10,000 ft. A surface interval of 12 hrs was necessary to protect against decompression sickness after these shallow, long exposures (20).

FLYING AFTER DIVING GUIDELINES

Edel, Carroll, Honaker and Beckman (1969) subjected experienced divers to the no-decompression limits of the US Navy Air Diving Tables with depths of 30 to 120 ft followed by ascent to 8,000 ft altitude. The surface interval at sea level prior to ascent to altitude was varied from 5 min to 5 hrs. Most of the exposures were "bends free." In the 40/200 exposure, two of the 10 subjects (20 percent) experienced bends pain for the 5-min surface interval. Following saturation exposures of 30 to 33 ft for 24 hrs, all six subjects (100 percent) experienced bends pain at 8,000 ft after a surface interval of 2 to 5 hrs. The authors recommended a 2 hr surface interval before flying in pressurized aircraft (8,000 ft cabin) after no-decompression dives and a 24 hr surface interval following dives that required decompression stops (7).

In the studies of Balldin (1979), ten subjects were exposed to simulated dives of 39m (129 ft) for 10 min and 15m (50 ft) for 100 min followed by a surface interval of 3 hrs before exposure to 3,000m (10,000 ft) altitude. Intracardiac bubbles were registered in 60 percent of subjects after 2-52 min (mean 16 min), leading to the conclusion that the safe interval between ordinary scuba diving and commercial flight seemed to be more than 3 hrs (21).

Using 60 volunteer military divers, Bassett (1982) performed 120 manned validation tests of the US Navy Air Diving Table and monitored subjects for intravascular bubbles with the Doppler Ultrasonic Bubble Detector. The validation schedule was based on diving at sea level, followed by immediate ascent to 10,000 ft above sea level. From data obtained in the study, Bassett published for military divers the no decompression limits for flying after diving and diving at altitudes above sea level (22). For recreational divers, he recommended a 12 hr surface interval before flying after dives with more conservative no-decompression limits (i.e., subtract 10 min from the USN "no-decompression limits" for depths shallower than 90 fsw and subtract 5 min for depths of 90 to 130 fsw) (23). Bassett's work questioned whether arrival at a representative group designator D would allow a diver to ascend safely to 8,000 ft altitude (24).

FLYING AFTER DIVING RECOMMENDATIONS:

In 1976, a series of articles appeared in Pressure that presented conflicting views on how long to wait before flying after diving. Kusic questioned the conflicting views and suggested a poll of the membership (9). In response, Smith, a NAUI instructor, suggested that the sport and institutional diving community was trending away from the 12 hr surface delay and moving toward a figure more like 4 hr. He also introduced the concept of waiting at the surface until a repetitive Group D before flying commercially (12).

Flying after diving recommendations entered a tug-of-war. On one side, conservative recommendations were offered, intent on "zero bends." On the other side were the liberal recommendations that provided the diver the maximum amount of dive time before the inevitable flight home. Flying after diving guidelines for military aviators tended to be very conservative, requiring longer surface intervals (2,25,26); while guidelines for commercial divers tended to be more liberal, requiring shorter surface intervals (27,28). In addition to the guidelines, commercial and military divers were also provided information about availability of treatment facilities, should they experience decompression sickness. Recommendations for recreational divers spanned the entire range of guidelines.

Both NOAA (29) and civilian diving groups (30) suggest arrival at repetitive group designator D as an acceptable indicator that flying at 8,000 ft can be done safely. The NOAA Diving Manual (1979) suggested that the surface interval can be shortened by breathing oxygen (29). Other diving groups (17,27,30) recommend surface intervals that vary with the total bottom time of the dive.

In 1982, the United Kingdom Diving Medical Advisory Committee held a Flying Following Diving Workshop and made recommendations for commercial divers (28). Two altitude limits were considered: 2,000 ft for helicopter flights and 8,000 ft for commercial aircraft flights. For no-decompression air-dives, where the total time under pressure was less than 60 minutes within the previous 12 hours, the advisory committee recommended that the surface interval be a minimum of 2 hours before flying to 2,000 ft; and a minimum of 4 hours before flying to 8,000 ft. For all other nonsaturation air dives, where the total time under pressure was less than four hours within the previous 12 hours, the Advisory Committee recommended a minimum surface interval of 12 hours for flights up to 8,000 ft. These recommendations have been widely circulated in the open literature (32,33,34), but some feel that they are too liberal for recreational divers (5).

In 1988, the American Academy of Underwater Sciences conducted a Dive Computer Workshop (35). According to data presented, several dive computer models have a "safe to fly" mode. For one model, Digitek, "safe to fly" is 12 hrs after the last dive. For other models, "safe to fly" is indicated when the dive computer outgases to a preset value above ambient pressure. The workshop listed the values for various dive computers:

Computek:	2 fsw over ambient
MicroBrain:	0.58 bars as the ceiling
Skinny Dipper:	2 fsw (1 psi) over ambient
Suunto:	2 psi over ambient
Digitek:	12 hrs after last dive

Although 12 hours was noted by the workshop editors as a safe post-dive time to go flying, it was also noted that 19 to 20 hrs would be required to clear the 480-min compartment to 2 psi above ambient (35).

As Vann (1989) has suggested, one cannot establish a rule that is "safe to fly." Rather, one can try to limit the degree of risk (36). Since some theoretical assumptions must be made in order to calculate decompression schedules, there can never be a flying after diving rule that is totally "bends free." Rather, there can be a guideline that represents a best estimate for a conservative, safe, surface interval for the vast majority of divers. There will always be an occasional diver whose physiology functions outside the guideline and results in bends. In order for one to absolutely avoid decompression sickness, one would have to avoid both diving and flying..

There is scientific evidence to support a range of options for the recreational diver who plans to fly after diving. The diver who plans to make a single, short duration, no-decompression dive can take comfort in the fact that some manned validation studies have been done (7,17,21,22). However, the diver who plans to make daily multiple dives for several days must take special precautions and delay the flight home. Those who plan to make more than 3 dives in a 24 hr period must be especially cautious. Not only have there been no validation studies for flying after such a dive schedule, there are few statistics that can be used to evaluate the safety of doing more than two repetitive dives in a 24 hour period (37).

One reason to take special precautions is a limitation of the dive tables: The assumption that total off-gassing of residual nitrogen occurs within 12 hours after surfacing. For dives separated by more than a 12 hr surface interval, the tables assume that residual nitrogen is negligible. A second reason to take special precautions is a limitation of one's own physiology. Should bubble nuclei form in the body during ascent, the bubbles will enlarge during subsequent flight, increasing the chance for decompression sickness. The best prevention is to avoid the formation of bubble nuclei by never pushing the tables, and then allowing a substantial surface interval before flying.

Table 1 is a compendium of recommendations for flying after diving within standard air tables. As shown in Table 1, many flying after diving recommendations have been published. The recommendations vary by type of dive (no-decompression versus dives that require decompression stops), by total bottom time (TBT) in a recent period, by total time under pressure, and by altitude of the flight following the dive. Each of the recommendations have merit in that they were based on the level of scientific knowledge at the time and were designed to fit a specific audience with a specific dive/flight need. Advances in knowledge of decompression sickness risk factors and treatment data from the Divers Alert Network now encourage more conservative guidelines for recreational divers who plan to fly after diving. Table 2 is a compendium of recommendations for flying after saturation diving. Table 3 includes recommendations for in-flight management of decompression sickness. Table 4 includes recommendations for flying after hyperbaric treatment of decompression sickness.

FLYING AFTER DIVING GUIDELINES

SUMMARY:

Recreational divers face a difficult choice when trying to select the appropriate surface interval between diving and flying. Many options are presented in the literature, but few have been man-tested. For dives requiring no decompression stops, surface intervals ranging from zero to 24 hours have been proposed. Because of differences in diving techniques and lack of readily available hyperbaric treatment, the guidelines provided for military and commercial divers may not be applicable to recreational divers. Recommend that the UHMS Flying After Diving Workshop establish a guideline for recreational divers.

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Table 1

COMPENDIUM OF RECOMMENDATIONS FOR FLYING AFTER DIVING:

FLYING AFTER DIVES WITHIN STANDARD AIR TABLES

SOURCE	RECOMMENDATION
Edel PO et al, 1969 Aerospace Medicine 40(10) p. 1105-1110. (7)	Scuba divers who stay strictly within the limits (depth-time) of the standard U.S. Navy's No-decompression limits and repetitive group designation table for no-decompression dives, for a period not exceeding 12 hours, will not develop decompression sickness if, after diving, they allow a minimum two-hour surface interval before flying in a pressurized commercial aircraft (8,000 ft cabin). Divers who make dives beyond these no-decompression limits should allow a surface interval of 24 hours before decompression to a commercial aircraft's cabin altitude pressure
Zanelli L, 1972 British Sub-Aqua Club Diving Manual p. 490. (8)	For no-stop dives, wait 2 hours and for dives needing stops, wait 24 hours before flying at commercial cabin altitudes of 1,500-3,000m (5,000-10,000 ft).
BS-AC '88 Decompression Table, 1988 (14)	Flying in a pressurized aircraft is not permissible until the surface interval table indicates that the diver has reached current tissue code B. Before flying in an unpressurized aircraft, the diver must reach current tissue code A. (On the BS-AC table, all no-stop dives result in tissue code F. Tissue code B is reached after 4 hrs and tissue code A is reached after 15 hrs. For decompression dives, tissue code G reaches code B in 4 hrs and code A in 16 hrs.)

FLYING AFTER DIVING GUIDELINES

CIRIA Underwater Engr GP, 1975. Emergency flying after diving restrictions. Principles of Safe Diving Practice, p. 28. (27)	For dives requiring no stops: With a surface time interval (SI) up to 1 hour, fly at a maximum cabin altitude of 300 m (1000 ft); for 1 to 2 hours SI, fly at maximum cabin altitude of 1,500m (5,000 ft); for over 2 hours SI, cabin altitude is unlimited. For dives requiring stops: With an SI of up to 4 hours, fly at a maximum cabin altitude of 300 m (1,000 ft); for 4 to 8 hours SI, fly at a maximum cabin altitude of 1,500m (5,000 ft); for 8 to 24 hours SI, fly at a maximum cabin altitude of 5,000m (16,500 ft); for over 24 hours SI, cabin altitude is unlimited.
US Navy Diving Manual, Vol I, 1980. p. 7-22. (1)	Flying in aircraft with cabin pressure above 2,300 ft may be done after a 2 hour surface interval following a no-decompression dive, and 12 hours after a decompression dive. If aircraft pressure is below 2,300 ft, flying can be done immediately.
Buhlmann AA, 1988 Repetitive Dive Timetable 0-2500m above SL. (17)	Buhlmann table 0-2500m above sea level: When the Repetitive Group (RG) at start of surface interval is "A" or "B", wait 2 hours before flying; for "C" "D" or "E" wait 3 hours; for "F" wait 4 hours; for "G" wait 5 hours; for "H" wait 7 hours before flying.
UK Diving Medical Advisory Committee, 1982. (28)	For no-stop dives: When total time under pressure is less than 60 minutes within previous 12 hours, wait 2 hours before flying at 2,000 ft and 4 hours before flying at 8,000 ft. For other non-saturation air dives, where the total time under pressure was less than 4 hours within the previous 12 hours, wait a minimum of 12 hours before flights up to 8,000 ft.

Horrigan DJ et al, 1989 NASA JSC mgt dir 1830.3F (38)	For no-decompression dives: For dives shallower than 20 feet, there are no flying after diving restrictions. For no-decompression dives of less than 4 hours duration at depths of 20 to 62 feet, the surface interval is 12 hours on air or 2 hours on oxygen before flying above 8,000 feet cabin. For decompression dives: For dives greater than 4 hours TBT, or multiple dives, the SI is 24 hours on air before flying at any altitude. All other diving not controlled by NASA requires 24 hours on air at surface before flying.
Balldin UI, 1978 Preprints Aerosp Med Assn Meeting, p. 103. (21)	A safe interval between ordinary scuba diving and flying at 2,500-3,500m (8,500 to 11,500 ft) seems to be more than 3 hours.
PADI Dive Tables, 1985 The Dive Master Manual p. 143. (31)	For flying up to 8,000 ft after diving: If you are doing a single no decompression dive with less than 1 hour TBT, wait 4 hours prior to flying. If you perform a single dive with greater than one hour TBT or do repetitive dives, then you must wait 12 hours before flying.
Smith CL, 1975 NAUI Pub No. 5. Altitude Procedures in the Ocean Diver. (30)	Wait at the surface until Repet Group D is achieved before commercial flight (cabin altitude up to 10,000 ft).
NOAA Diving Manual, 1979 Table 6-6, p. 6-16. (29)	Complete any number of dives and decompress in accordance with USN diving tables. Before flying at 8,000 ft cabin, wait at sea level breathing air for the computed surface interval (SI) that classifies as a "D" diver on USN Repetitive Dive Table. To shorten the necessary SI before flying, the diver has the option to breathe oxygen during the SI. For Repet Groups M-Z, breathe oxygen 1.5 hours before flight. For Repet Groups H-L, breathe oxygen 1 hour. For Repet Groups E-G, breathe oxygen 30 minutes before flight.

FAA Airman's Information Manual, 1988, p. C7-S1-3. (39)	The recommended waiting time before flight to cabin pressure altitudes of 8,000 ft or less is at least 4 hours after diving which has not required controlled ascent (nondecompression diving), and at least 24 hours after diving which has required controlled ascent (decompression diving). The waiting time before flight to cabin pressure altitude above 8,000 ft should be at least 24 hours after any scuba diving.
Kusic G, 1976 Ltr to Editor, Pressure 5(3):7-8. Cites 1974 US Naval School of Diving & Salvage Crse (9)	No-decompression dives required 8 hours of waiting before flying in pressurized aircraft; decompression dives required a 24-hour wait, and flight crews may fly 12 hours after diving if cleared by a flight surgeon.
Bassett BE, 1980 Sport Diver, p. 126. (24)	Until further validation tests can be conducted on revised schedules, it is recommended that any dive made within the present no-decompression limits should be followed by a 12 hour surface interval before flying in pressurized commercial aircraft or in unpressurized private aircraft at altitudes greater than 3,000 feet.
NAUI Textbook, 1985 p. 89. (40)	For recreational diving, dive conservatively the day before a planned flight and wait at least 12 hours before flying. If you push the tables or make decompression dives, which you are advised not to do, you should wait no less than 48 hours.
NAUI Advanced Diving, 1989 p. 156. (41)	The altitude in an unpressurized aircraft should not exceed 8,000 feet which is equivalent to the cabin pressure of a commercial airliner. Wait at least 12 hours before flying following no-decompression diving. (Safety stops are not considered decompression for this procedure.) Wait at least 24 hours before flying following any dive with required decompression. Shorter, deeper dives are preferable over long, shallow dives when flying is planned.

Davis JC, 1988 The Physician & Sportsmedicine p. 121. (42)	Do not fly, even in pressurized commercial airlines, for at least 12 hours. If aircraft cabin pressure will exceed 8,000 ft, or if decompression stops were required, wait 24 hours to fly.
Buckingham I, 1981 DCIEM, Canada (A personal communication)	Use 12 hour surface interval after no-decompression dives (150 fsw maximum). For search and rescue missions, with no surface interval, use 100% oxygen aboard the helicopter for in-flight duration.
Nishi R, 1985 Canadian Diving Journal, p. 26. (18)	For recreational diving, wait 12 hours before flying after no-decompression dives, and 24 hours after dives requiring decompression.
Sharp GR, 1978 Aviation Medicine Ernsting J, ed. p. 184. (43)	Exposure to breathing air at pressures greater than 1 atmosphere during the 24 hours prior to flight increases the susceptibility of decompression sickness. This effect may be avoided by not undertaking ascents to altitude for at least 12 hours after exposure to a pressure of up to 2 atm abs (33 fsw) and at least 24 hours when the pressure to which the individual has been exposed exceeds 2 atm abs.
Workman RD, 1974 Medical Unscrambler. (44)	Wait 24 hours before flying, whether or not the dive requires decompression stops.
The New Science of Skin & Scuba Diving, 1980, p. 168. (45)	Final evidence is lacking, but a simple rule that is almost certainly reliable is to put a 24 hour interval between surfacing from a dive and flying.
Heimbach RD, Sheffield PJ 1985, Fundamentals of Aerospace Medicine DeHart, ed. p. 139. (46)	Any exposure to compressed gas breathing occurring within 24 hours of altitude exposure will increase the chance of decompression sickness.
US Air Force, 1965, 1987 AFR 50-27, p. 9. (2)	Personnel must not take part in aerial or chamber flights within 24 hours following compressed gas diving. This includes scuba, surface supplied diving, or hyperbaric chamber exposure.
US Air Force, 1985 AFR 60-1, p. 46. (47)	Personnel must not fly in any capacity within 24 hours of compressed gas diving (including scuba), surface supplied diving, or hyperbaric (compression) chamber exposure.

US Navy, 1987 OPNAV Instr. 3710.7 M p. 8-10. (25)	Flight personnel shall not fly or participate in low pressure chamber flights within 24 hours following scuba diving, compressed air dives, or high pressure chamber evolutions. Where an urgent operational requirement dictates, flight personnel may fly within 12 hours of scuba diving provided no symptoms of aeroembolism develop following surfacing, and the subject is examined and cleared by a flight surgeon.
U.S. Coast Guard, 1987 Air Operations Manual, Ch 6 Commandants Instr M3710.1 p. 7-5. (26)	Personnel shall not fly or perform low pressure chamber runs within 24 hours after scuba diving, compressed air dives, or high pressure chamber runs unless examined and cleared by a flight surgeon.
Mebane GY, Dick AP, 1985 DAN Underwater Diving Accident Manual, p. 48.(48)	Flying within 24 hours of a dive increases the risk of decompression sickness.

Table 2

COMPENDIUM OF RECOMMENDATIONS FOR FLYING AFTER DIVING:

FLYING AFTER SATURATION DIVING

SOURCE	RECOMMENDATION
UK Diving Medical Advisory Committee, 1982. (28)	For air or nitrox saturations with more than 4 hours under pressure, wait 24 hours before flying at 2,000 ft and 48 hours* before flying at 8,000 ft. (*Experience in this range is extremely limited--interpret with caution). For mixed gas diving (diver on air at sea level), no flying for at least 12 hours after return to atmospheric pressure following heliox and trimix bounce and saturation diving.
NOAA Diving Manual, 1979 p. 12-18. (49)	Before flying after a saturation dive, a delay of 36 hours is recommended. (Author's note: Actual practice is 48 hours)
US Navy Diving Manual, Vol II, 1987, p. 14-24. (50)	Divers must not fly for 72 hours after saturation diving.
DCIEM, Canada, 1988 A personal communication	Wait 72 hours to 1 week depending on the depth of the saturation dive.
Divers Alert Network Duke University, 1988 A personal communication	Wait 96 hours (preferably 1 week) after a saturation decompression.

Table 3

COMPENDIUM OF RECOMMENDATIONS FOR FLYING AFTER DIVING:

IN-FLIGHT MANAGEMENT OF DECOMPRESSION SICKNESS

SOURCE	RECOMMENDATION
UK Diving Medical Advisory Committee, 1982 (28)	Where the diver's symptoms consist only of pain in a limb, he should be treated with analgesic, oxygen if available, and the plane can continue to its destination without diversion or adjustment in altitude. When the diver has any other symptoms, seek immediate advice from a diving medical specialist. It may be necessary to reduce the cabin altitude or divert to the nearest airport. In the meantime, the patient should be given oxygen, if available.
NOAA Diving Manual, 1979 p. 6-16. (29)	If it is necessary to transport a diver suffering from decompression sickness, the flight should be conducted at the lowest safe altitude possible, or in a pressurized aircraft in which the cabin atmosphere does not exceed 800 ft of altitude. In addition, the victim should breathe pure oxygen until arrival at the recompression chamber.
USN Diving Manual, 1980 Vol I, p. 7-22. (1)	When moving patients, fly as low as possible, preferably less than 1,000 ft.
US Air Force, 1985 General Flight Rules AFR 60-16, p. 21. (51)	If an occupant appears to suffer from decompression sickness, the individual should be administered 100 percent oxygen. The pilot will descent as soon as practical, and land at the nearest suitable installation where medical assistance can be obtained. Before the person affected can continue the flight, the individual must have a consultation with a flight surgeon or a civilian aeromedical examiner.
Sharp GR, 1978 Aviation Medicine Ernsting J, ed. p. 188. (43)	Surface transport is preferable. Flight to a suitable chamber should be at an altitude below 1,000 feet, if possible, and not higher than 3,000 feet.

Table 4

COMPENDIUM OF RECOMMENDATIONS FOR FLYING AFTER DIVING:

FLYING AFTER HYPERBARIC TREATMENT OF DECOMPRESSION SICKNESS

SOURCE	RECOMMENDATION
UK Diving Medical Advisory Committee, 1982 (28)	Successfully treated, flights to 2,000 ft cabin are permitted after 24 hours; flights to 8,000 ft are permitted after 48 hours. Cases with residual symptoms must be directed on an individual basis by a diving medical specialist.
NOAA Diving Manual, 1979 p. 6-16. (29)	If necessary to fly immediately after a recompression treatment, the diver should be transported at low altitude, by helicopter or aircraft, or in a pressurized aircraft at a cabin atmosphere of not more than 800 feet of altitude.
PADI, 1985 The Dive Master Manual p. 143. (31)	Anytime you require compression chamber treatment, you must wait 72 hours (before flying) or get a physician's approval.
US Air Force, 1983 Hyperbaric Chamber Ops AFP 161-27, p. 66.(52)	Return to flying duty no earlier than 72 hours after successful treatment.
Heimbach RD, Sheffield, PJ Aerospace Medicine, 1985 DeHart RL, ed., p. 144.(46)	Return to flying duty no earlier than 72 hours.
Divers Alert Network 1987, News Letter 3(1), Alert Diver, p. 4. (53)	Divers treated for severe decompression sickness requiring saturation hyperbaric treatment should not fly for 72 hours to 1 week, depending upon the success of the treatment and the advice of the treating diving medicine physician.
Sharp GR, 1978 Aviation Medicine Ernsting J, ed. p. 189. (43)	After recovery of decompression sickness, the patient should not be allowed to fly at a cabin altitude of 18,000 feet or above in an aircraft or be exposed to reduced atmospheric pressure in a decompression chamber until specialist medical opinion has been sought. It may well be necessary, when the symptoms have been severe, to recommend that he should never again be exposed to a pressure altitude in excess of 18,000 feet.

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Discussion of Dr. Sheffield's Paper

MR. HORRIGAN: Paul, I'd like to point out one thing. In the Navy, there is some variance between the OPNAV Rule and the Navy Diving Manual. OPNAV instructions require 24 hours while the Navy Diving Manual says 12 hours.

DR. WELLS: Although the NOAA diving manual requires 36 hours surface interval after saturation diving, in practice, we use forty-eight hours.

MR. EDEL: About five or six years ago, the U.K. Medical Advisory Group (MAG) had a meeting and they had a rule requiring no flying for at least 12 hours following return to atmospheric pressure after heliox diving.

CHAIRMAN SHEFFIELD: But they had the 24 and 48-hour rules for air diving, depending on the altitude at which the flying exposure would be. Peter Edel is familiar with the MAG guidelines because he attended that meeting and reported on it in <u>Pressure</u>.

DR. BENNETT: Paul, you made a comment about managing DCS aboard aircraft by lowering the altitude and breathing oxygen. This doesn't occur because no oxygen is available for one individual on commercial aircraft, even flying back from the Caribbean. The pilots would have to turn on oxygen for all passengers, which they won't do. Therefore, you'll have to fly without oxygen. That's one of the reasons why I want the 24-hour surface interval, because you cannot get effective treatment in a commercial aircraft. It's just not available.

DR. BELL: Would it be possible to indicate in the list of guidelines when one source references another source so that people won't be confused, thinking it's an independent source?

CHAIRMAN SHEFFIELD: That would be difficult because the origin and lineage of the guideline is frequently unclear.

DR. LAMBERTSEN: Paul, is it to be understood that you are merely trying to summarize what exists in print?

CHAIRMAN SHEFFIELD: Yes. That is the purpose of this paper. The next step should be to develop specific recommendations to assist a diver in determining which guideline to follow.

WORKSHOP DISCUSSION ON THE DEVELOPMENT OF GUIDELINES FOR RECREATIONAL DIVING.

DR. BENNETT: I could make a proposal. From the point of recreational diving, I'd like to suggest a 24-hour guideline.

MR. EDEL: I think what Peter Bennett is saying gets right to the point. Who are we going to write the guidelines for? One guideline should relate to the recreational scuba diving community, in view of their unique risks. Commercial divers could very well have a different rule, since they are usually located near a chamber facility with treatment capabilities. The military would, of course, have its own needs. They would probably have some modification of the guidelines. One thing that we could think about is the subdivision of categories of divers that we're addressing.

LCDR. O'DOUGHERTY: Being a pilot of pressurized aircraft, I recommend that you get away from assuming that pressurized aircraft will provide you with a certain pressure. I think you can end up being surprised. The airlines will tell you that they keep their cabins pressurized somewhere around 5,000 feet. It could go up as high as 10,000 feet and they wouldn't necessarily have to tell any passengers in the aircraft that they have changed pressure.

MR. EMMERMAN: The actual exposure in the aircraft has not gotten to 10,000 feet in 150 flights that I have monitored.

DR. LAMBERTSEN: You need hard numbers temporarily in terms of how long one waits and at what maximum altitude one should never fly above. There are at least four diver categories: one military, one industrial, one scientific, and one that amuses itself. There's no reason why we should think we can impose upon those different communities a piece of paper that will foul up their operations. Therefore, I wonder if it wouldn't be wise to emphasize Peter Edel's point. Begin with sports divers who have no constituency or administrative arm in the government to tell them about regulations. We could begin with sports divers, and concentrate on them. The experts in other agencies might be able to use some of what we recommend.

CHAIRMAN SHEFFIELD: Can I get a consensus from the group that we're willing to concentrate on the recreational diving community?

DR. BELL:: If we're trying to target a community, I agree that's probably the one to target. But, on the other hand, these other groups have already been targeted, they've already got their rules. The Air Force has a rule, the Navy has a rule and so on. It may be that we can learn something from that experience. DAN has given a lot of sport diving statistics. But also, the Air Force has never had a case using a 24 hour restriction.

MR. EMMERMAN: My impression is that we should state that we can mathematically prove that some people can enter an aircraft almost minutes after they finish a dive. That can be proven mathematically. Obviously that's not the answer because DAN and others have reports of people who have presented 41 hours or longer after a dive. None of those guidelines that you've discussed included a statement that if a diver has certain pre-dispositions (smokes, drinks alcohol, etc) that 24-hour guideline may not be effective. Whatever time frame is set must be qualified.

DR. BENNETT: The difficulty is those qualifications. We have a list of about 20 qualifications as to why 58 percent of the divers who bend get DCS when they dive within the US Navy Tables. If you can automatically transfer those to the same risks for flying after diving, they would be different. I hope that when we conclude this workshop, we will have at least suggested a guideline because the recreational divers, as I prefer to call them, want information. I had a lot of calls only last week about it, asking what do we do? What are the guidelines? And so we're going to have to make some kind of guideline. If we don't have any guidance the divers can understand, DAN will have to provide the guidance. I think the risk of DCS will support a guideline of 12 to 24 hours. At least we would halt most of the accidents that I presented in these 20 cases, because only two of those occurred in excess of 24 hours.

DR. BUEHLMANN: Our recommendation for recreation divers is that after diving for six days, they stop diving for 24 hours before flying. After diving on holiday in the Caribbean or Mediterranean, wait 24 hours. But if there are mild symptoms after the dive, such as skin itch or a little pain that is not treated, wait two days before flying.

DR. BENNETT: Highly logical, I must say.

MR. EDEL: I agree with what Peter Bennett says. I think that some solution is necessary but I think we have to look at what we're addressing. I saw some figures on the DAN slide of flying after diving cases in which I believe it was mentioned that three cases occurred before the men entered the aircraft. I don't think that they should be included in data for flying after diving. If symptoms had occurred before flight, they should be excluded.

DR. BENNETT: About 20 of those cases, in fact, did occur during flight or after flight, not before. Of those 20, six cases occurred in the first six hours post-flight, two between seven and twelve hours, five between 13 and 24 hours, three between 24 to 36 hours, one case at 72 hours, and one case at over 110 hours. The vast majority occurred within 24 hours. Some of the cases that we presented in that original number were treatment cases as well. But 20 cases were the result of flying.

MR. EDEL: Excuse me, Peter. Can we be absolutely sure it occurred as a result of flying? Let me give you one example of why I ask this question. During the first study I did in 1969, we made a chamber dive at 33 feet for 24 hours. We surfaced, waited five hours and then went to altitude. I was the subject. I got the bends before we reached 1,500 feet altitude. It was quite obvious to me that what I was experiencing was bubbles that had already developed a long time ago and now was being expanded by the pressure reduction at altitude.

DR. VANN: That's absolutely right. But the pressure reduction is going to cause a bubble to expand in all these subjects.

MR. EDEL: If I had not gotten in the altitude chamber, I suspect very strongly that I would have gotten that hit, not at that time, but eventually.

DR. VANN: Certainly.

MR. EDEL: I don't know for sure, but I think there's a good chance of it. And I think we have to consider the procedures to be used. If we're going to have just an unqualified system where the diver can do anything he wants, anytime he wants, then we need a 24 hour or 48 hour surface interval. But I think we ought to leave the door open for a better system. For example, a better assessment of multiple dives or restrictions on multiple dives, if you like.

DR. BENNETT: That broadens the program too much, I think.

MR. EDEL: No. I'm just saying that we don't want to restrict that possibility for the future, because most of the rules that were made in the past, have closed the door to something better in the future.

DR. BELL: We're dealing with a population of divers that are being hit in airplanes, who are probably out on the edge of the distribution curve, if they've been following correct procedures. So the question is, how many standard deviations away from the mean can we go? We know that if we go more than three or four hours, we are moving in a conservative direction. That's the important thing that you learn. How far do we want to go? Well, I think that depends on actuarial data and I don't think we can predict that. Chris Lambertsen said you can't predict that kind of actuarial. So we have to depend on data to give us the distribution and then decide on how far you want to go. Peter Bennett is suggesting 24 hours. That's six times what you might predict.

MR. EMMERMAN: I can go with 24 hours until we get the rest of the data.

DR. BELL: I'm not promoting 24 hours, I'm simply saying that we're moving in the right direction.

DR. VAN LIEW: I don't want to make mandatory rules for people, but we could make recommendations.

DR. LANPHIER: I got kind of gun shy about making rules or even recommendations when I edited the <u>Navy Diving Manual</u> in 1958 and we needed something on the acceptable oil content of divers' air. When I went to the literature and found a couple of papers on the subject, I figured that it was better to print something rather than nothing, so I put down some numbers. I learned ten or more years later that people were quoting those numbers as if they had come down from heaven. And the mere fact that they had gotten into print had done this. The same thing could happen here.

On the other hand, I think these divers need something. Twenty-four hours seems reasonable to me. We ought to state plainly that it is on the basis of best present knowledge. That will probably get edited out the next time NAUI or PADI or somebody picks up on it, but at least it will be there if anybody cares to look. Then we should try hard to figure out where we go from here to get better rules, but give them something now. I think 24 hours is plausible and it would take care of most of Peter Bennett's concerns. If the diver had waited 24 hours and then gotten the bends, then he would have known. He could have said "My God, if I'd gone to altitude in 5 hours..."

CHAIRMAN SHEFFIELD: If you tell divers that you want zero cases of DCS you've got to tell them to stay out of the water and don't fly. In this collective group, we ought to be willing to come up with a number that we could say is a reasonably acceptable risk.

DR. LEHNER: I think it's very difficult, without going to the populations, (sports divers, commercial divers, military divers and all the rest) to establish an acceptable risk. I made the statement that often times it's a matter of choice on the part of the diver. Like Hugh Van Liew, I don't want to make mandatory rules for people. I think it is part of our charge here to make recommendations that people can live with. I find that what Ed Lanphier said, from a standpoint of making recommendations for sports divers, is quite acceptable.

MR. HORRIGAN: When we prepared the NASA instruction that I discussed in my paper, we added a category at the end for uncontrolled situations where the people could do recreational diving on their own. We felt that 24 hours was reasonable in those cases, because we had no control, poor records were kept, and we wanted to be on the conservative side. It might penalize someone who had a very benign dive, but we felt it would prevent any problems if we use 24 hours.

DR. BELL: What's your rule for the controlled cases?

MR. HORRIGAN: The rule for the controlled cases was that for dives of less than 20 feet, there were no restrictions on flying. For no decompression dives of less than four hours, they could fly immediately up to 8,000 feet. For decompression diving, they must wait 24 hours to fly. We also included the possible use of oxygen to shorten the surface interval.

DR. BELL: What has been the incidence of decompression sickness?

MR. HORRIGAN: We have not had any reports of decompression sickness within the crew population. Of course, most of our diving has been around 20 feet in the Johnson Space Center tank and they usually are flying commercial or in the T-38 with a pressurized cabin. However, for the uncontrolled cases we felt that 24 hours was reasonable.

DR. BELL: Has that worked?

MR. HORRIGAN: Yes. We haven't had any problems develop.

CHAIRMAN SHEFFIELD: Ron Nishi, you compared the various decompression models. If we ignore commercial and military applications, and think only of recreational diving, what kind of surface interval would you support?

MR. NISHI: I think that 24 hours is probably a reasonable number. There is a danger in making recommendations. I was once asked to find out how long before an attendant in a dive chamber, using Table 6, must wait before he could fly to 43,000 feet in a high altitude run. I said 72 hours was reasonable based on how long it would take tissues to off-gas. I started getting phone calls from people saying, that they were diving on the weekend to ten feet in a pool at the local shopping mall, and; as a result, they were prohibited from altitude flights for three days. They wanted me to waive the rule. I had made a recommendation for a specific application. Someone had taken that recommendation and made it a general rule.

CHAIRMAN SHEFFIELD: Keep in mind the population we're dealing with. Let's assume it's a group from Toronto who fly down to Grand Cayman for a weekend of diving and fly back home. If we recommend 48 hours, they can't even go on the trip. If we recommend 24 hours, they can dive when they first land and then they have to sit around on the beach for the rest of the trip. That's one population we're dealing with. What is a realistic guideline for that population?

MR. NISHI: I would recommend 24 hours.

DR. BUEHLMANN: That's not realistic. It's a daily situation in Switzerland. The diver lives at, let us say, 2,000 meters and he comes down to Zurich to make some dives on one afternoon. He cannot wait 24 hours to go back to 2,000 meters. He will go back after two or three hours. It's the same situation as flying. If a diver lives in Zurich, at normal pressure, and he dives in the south part of Switzerland, at normal pressure, and he has to go over the Alps in a train, he must ascend 1,000 meters. In a car it is 2,000 meters over the pass. He cannot wait 24 hours to return home. For these one-day dive trips he can return to work with one to five hours waiting time, depending on the dive profile (repet group). For holidays, viz. diving every day, it's another situation. Then we suggest a 24 hour restriction. That's the reason I suggested different groups of divers. There are two populations.

CHAIRMAN SHEFFIELD: We have two recreational diving groups to deal with. In one group, we're dealing with perhaps a Dallas dive group that flies down to Curacao for a weekend of diving and then flies home. The second group is perhaps a group of diving physicians who fly to the Caribbean for one to two weeks of diving, and makes two to three dives every day before they fly home. These are the two groups, as I see it, that we should address. These are two different groups of divers in terms of nitrogen-loading and risks.

DR. BELL: It may be that we're trying to solve the wrong problem. The diver is out pushing the limits. After years and years of experience with recreational divers, I have found that they don't pay much attention to rules. If we're trying to tell those divers that they now have to impose another rule on top of having abused certain rules already, it may be that that's not the problem to address. The problem to address is to try to determine what schedule would allow them to fly in a reasonable time. In other words, set up a prophylactic schedule rather than one suggesting they wait 24 hours after an abusive schedule.

MR. EDEL: Which probably won't do anything anyway except transfer a large number of bends from the plane to the ground later on.

DR. BENNETT: We'd rather have them on the ground where we can deal with them than on a Commercial aircraft flying over the Caribbean at 31,000 feet.

In fact, we do need to have a recommendation. I think the word recommendation is a good one. If it turns into a rule, that's okay, but we need a recommendation. Every day we get 30 to 40 phone calls through our advisory line asking, "What are the recommendations for flying after diving now?" I'd like to have the considered advice of this workshop to make that statement.

MR. EDEL: One recommendation for unrestricted diving with 24 hours delay is as good as anything else. In a second recommendation for divers with special procedures, he can do whatever that procedure requires.

DR. BENNETT: What do you mean by special procedure?

MR. EDEL: I mean some special table and procedures that are specially made for this problem. They're not in existence now, but they can be in the future. I'm just afraid that a recommendation could turn into a rule and stop their development in the future.

DR. BENNETT: I don't think progress stops because we have a recommendation to save people from losing their spinal cords. We still try to get a better decompression table because we still have the problem of multi day diving. At DAN we're advising the diver to take a day off in the middle of the week. Per diver the risks range from 0.2 percent in the worst case to 0.017 percent in the best. That's the DCS incidence in the tables that the divers use today. What we are saying is that 0.2 percent is not acceptable. What number are we going to be prepared to accept? If 0.2 percent is not acceptable, what is?

DR. BELL:: Peter Bennett, you talked about 500 incidents. Do you have any idea what the total population is that is diving in the Caribbean?

DR. BENNETT: Enormous. The last statistics on numbers of divers gave about 2 million recreational divers. A recent analysis showed that the majority of divers were making at least ten dives a year. So there's an enormous amount of diving going on in the Caribbean, and off the coast of California. Those are the areas where most of the diving accidents occur.

DR. BELL: These people are flying down and coming back?

DR. BENNETT: Yes.

DR. BELL: Out of two million divers (making 20 million dives), you've had 500 cases reported? Flying after diving only accounted for 20 cases out of 2 million reported divers? If you multiply the 20 cases by 10 so that you take into account that only 10 percent of the people reported their symptoms, you're still only talking about 200 cases out of 2 million divers.

DR. BENNETT: Well, the numbers of accidents alone aren't all that high.

DR. BELL: One of the points we haven't discussed, is at what confidence level do you want to cut off the risk. In your case, you see 20 cases that represent the universe and you'd like to reduce them to zero. You'll never reduce it to zero because there's always going to be an outlier.

DR. BENNETT: The point really is, as I said, that the vast majority of those cases would have been eliminated if you applied a 24-hour rule. You might have had three or four cases. You cut it down significantly by merely changing 12 hours to 24 hours. But this might be too severe for weekend divers. The 24-hour guideline is quite correct for the multi-day exposures where the length of dives are very long and there's a lot of build-up of nitrogen in the slow tissues. It takes slow tissues a long time to off-load. I see no reason why in the short dives, one or two days, we couldn't institute a 12-hour guideline. We're not having trouble with that type of schedule. We're having bends in divers who dive for longer periods of time.

MR. EDEL: He wouldn't be able to dive the U.S. Navy no-decompression schedules. He would have to use something more conservative, and I think most divers have gone to something more conservative. If he follows more conservative procedures, then perhaps he could have a greater period of time to dive and a safer situation.

DR. WELLS: I just checked the official NOAA policy. We're sticking with the D diver rule and the oxygen breathing guidelines. It is going to be published as NOAA policy unless this workshop recommends something to cause us to change it. I firmly believe that it's the nature of the diving activity rather than the time interval between diving and flying that is more important. I would like to suggest that there may be a number of divers walking around with asymptomatic decompression sickness that does not progress, until the ambient pressure is reduced by going to altitude. It's my firm belief that the nature of the diving activity prior to flying is equal to or more important than arguing about 12 to 24 hour time intervals.

DR. BENNETT: I think Professor Buehlmann's recommendation has merit, distinguish between multi-day diving and single-day diving.

MR. HORRIGAN: From a scientific point of view, I think that we should do away with the phrase of "Flying After Diving" and try to integrate the hyperbaric and hypobaric environments. The diving tables of the past have had the objective of returning to sea level. If we disregard sea level and look at the ascent as a physiological continuum, as Dr. Lambertsen suggested, then scientifically we end up with a set of guidelines for human pressure change that would apply if the diver returns to sea level or flies afterwards.

CHAIRMAN SHEFFIELD: In 1982, the U.K. Medical Advisory Group (MAG) held a workshop and made the following recommendations: If the diver had 60 minutes total bottom time in the last 12 hours, he could fly at a cabin altitude of 2,000 feet after a surface interval of two hours. If the cabin altitude was 8,000 feet, the surface interval should be four hours. For all other non-saturation diving with greater than 60 minutes total bottom time in the last 12 hours, the diver must wait for 12-hours on the surface before flying. There were other restrictions for saturation diving and heliox diving but those do not apply to recreational divers.

DR. WELLS: I think one of the problems with the individual diver is that the individual who may be waiting the 12 hours, or the 24 hours you recommend, may start feeling some symptoms that he would ignore, like itching or aching. When he feels itching or aching, he's also looking at the airline ticket that he bought at a special rate. If he now changes the reservation, he's out another 200 dollars. That gives a person with bubbles extra incentive to fly.

MR. EDEL: If the diver is unrestricted, he's going to have problems, no matter what you do. You can only minimize the damage.

DR. BELL: Did the U.K. MAG group mention what the dive incidence was?

MR. EDEL: No, the incidence rate was never discussed. It was the philosophy and not the incidence that was at stake.

CHAIRMAN SHEFFIELD: They were targeting a different group than we are targeting?

MR. EDEL: That's absolutely correct. They were targeting commercial oil field divers. Oil field divers who were diving on a rig and then flying in a helicopter to land and then, presumably, having to fly back to some other destination within a given period of time.

DR. BENNETT: Professor Buehlmann, what would the Swiss view be for unrestricted diving for a week? How long should the diver delay before he flies?

DR. BUEHLMANN: Twenty four hours.

CHAIRMAN SHEFFIELD: Based on the DAN diving accident data and the Swiss experience, will you all agree to a guideline that restricts flying for 24 hours after multi-day, unrestricted diving with no DCS symptoms? Okay, I have your

CONCLUSION

Recreational divers face a difficult choice when trying to select the appropriate surface interval between diving and flying. Many options are presented in the literature, with surface intervals ranging from zero to 24 hours, but few have been human tested. Because of differences in diving techniques and lack of readily available hyperbaric treatment, the guidelines provided for military and commercial divers do not appear to be applicable to recreational divers.

There is scientific evidence to support a range of options for recreational divers who plan to fly after diving. Divers who plan to make a single, short duration, no-decompression dive can take comfort in the fact that some manned validation studies have been done. The separate studies of Edel et al (1969), Balldin (1979), Bassett (1982), and Buehlmann (1988) would indicate that, under some circumstances, flying could be done after a brief surface interval of a few hours. However, the patient treatment data of the Divers Alert Network (DAN) and the United States Air Force School of Aerospace Medicine would indicate that a minimum surface interval of 12 hours is required in order to assume that the diver will remain symptom-free upon ascent to altitude. Divers who plan to make daily, multiple dives for several days, or make dives that require decompression stops, should take special precautions and wait for an extended surface interval before flight.

Since some theoretical assumptions must be made in order to calculate decompression schedules, there can never be a flying after diving rule that is guaranteed to prevent decompression sickness completely. Rather, there can be a guideline that represents a best estimate for a conservative, safe, surface interval for the vast majority of divers. There will always be an occasional diver whose physiological makeup or special diving circumstances will result in bends, even though the guidelines are followed. In order for one to be absolutely assured of avoiding decompression sickness, one would have to avoid both diving and flying.

RECOMMENDATION

The UHMS Flying After Diving Workshop participants recommend the following guideline for recreational divers.

FLYING AFTER DIVING GUIDELINES FOR RECREATIONAL DIVERS

DIVE SCHEDULE FOR DIVER ON AIR	SURFACE INTERVAL IN HOURS BEFORE A DIVER SHOULD FLY AT CABIN ALTITUDES UP TO 8,000 FT.
NO-DECOMPRESSION DIVES (Diver is without decompression sickness symptoms)	
a. Less than 2 hrs total accumulated dive time (surface to surface time) in the last 48 hours	12
b. Multiday, unlimited diving	24
DIVES THAT REQUIRE DECOMPRESSION STOPS (Diver is without decompression sickness symptoms)	24-48*

**Flying must be delayed for at least 24 hrs and, if possible, for 48 hrs.*

Note: Because of the complex nature of decompression sickness and because unverifiable assumptions are involved in decompression schedules, there can never be a flying-following-diving rule that is guaranteed to prevent bends completely. The guidelines above are "best estimates" based on current scientific information and expert opinion, and are expected to be conservative, safe surface intervals for the vast majority of divers. In a few individuals, their physiological makeup or special circumstances of the dives may result in decompression sickness even though the guidelines are followed. These guidelines may be amended in the future as further data and knowledge are developed.

APPENDIX A

Summary of comments on the Development of Guidelines for Recreational Divers.

In response to Chairman Sheffield's request, Dr. A.A. Buehlmann, M.D., (Zurich, Switzerland) proposed the following Flying After Diving recommendation for an altitude limit of 3,000 m above sea level (0.716 ATA). The proposal was subsequently submitted by letter ballot to the workshop presenters.

Dive Schedule	Surface Interval
1. Less than 60 minutes total bottom time in previous 12 hours without symptoms of DCS.	4 hours
2. 1-2 hours total bottom time in previous 48 hours without symptoms of DCS	12 hours
3. Multiday nonrestricted diving without symptoms of DCS	24 hours

Comments from First Letter Ballot (1 Mar 89)

Col. Robert M. Ingle. A recent review of USAFSAM altitude decompression sickness (DCS) reveals 221 cases that occurred at ground level after an altitude exposure, 25% of which had onset of DCS symptoms after a 4-hour symptom-free interval. Four hours is not enough time to document the absence of DCS for these rare individuals. I would recommend a minimum 12 hour limit after any scuba dive to confirm that DCS has not occurred. Multiday scuba diving should have a 24-hour surface interval before flying.

Mr. David J. Horrigan. Restrict recommendation to no-decompression dives.

The Rev. Ed Lanphier. Restrict the recommendation to no-decompression dives. What about dives requiring stops? >24h? If so, let's say it.

Mr. Peter Edel. I disapprove it as a workshop recommendation. The pleasure one can obtain from an additional dive or two must be considered in light of a possible attack of DCS at altitude which could result in permanent damage to the individual. The original study I made on flying after diving was designed for commercial divers. Such a group, like military divers, must be considered to be better controlled and, in general, better informed than recreational divers. In addition, chamber treatment facilities are available to them on site or within a short distance of their destination. It would be inappropriate to apply such decompression concepts to recreational divers whose activities may often take place at remote sites far from treatment facilities. I can see no objection to Dr. Buehlmann's proposals #2 (12-hr) and #3 (24-hr) since the majority of asymptomatic bubbles (though not all) should have been dissolved within a 12 to 24 post-dive period. In the case of proposal #1 (4-hr), however, this is not the case and the possibility of an unacceptable number of asymptomatic bubbles being present during the ascent to altitude offers too great a risk to endorse the recommendation.

Mr. Ron Nishi. I desire to restrict the recommendation to no-decompression dives. I have reservations about a 4 hour option. I think there is probably a requirement for a 4 hour option, but I'm not convinced that this is it. I don't have anything better to offer at the moment without becoming very complicated. In my mind, total bottom time (TBT) is the time at the bottom and does not include the decompression time back to the surface. If we are talking just no-decompression dives, there is no problem. However, if we are talking decompression dives, there is a problem since the total in-water time could be longer than 60 minutes. I think that "TBT" should be replaced by total dive time or total time in-water. Restrict to no-decompression dives. It's possible to have a dive with a total in-water time of 60 min for instance which includes say a 30 min bottom time and 30 min decompression. I would not consider 4 hours sufficient for this case.

Dr. Hugh Van Liew. I abstain. I do not have background or experience enough to make a meaningful vote on this matter.

Dr. Peter Bennett. Restrict the recommendation to no-decompression dives. While it remains general DAN policy that, whenever possible, 24 hours should be required between diving and flying, it is recognized that this may not be necessary if only one or two no-decompression dives have been made in the last 12-48 hours. Until further data are available, the Buehlmann version, which has good credibility in the practical utilization of the 4 hrs and 12 hrs guidelines, as well as the general 24 hrs guideline, is appropriate for no-decompression recreational diving.

Dr. Charles E. Lehner. Accept Buehlmann's proposal with the restriction that the recommendation be advisory and limited to no-stop dives. There will be greater risk encountered when diving is conducted at the limit of allowable TBT just before the surface interval begins. I suspect that some diver will use this practice to finish a dive four hours before their flight departs as permitted in the recommendation. Some mention of this fact in the workshop recommendation seems advised. In my opinion, the risk would be unacceptable for some divers if it were quantified.

Chairman Sheffield: In your response to the first letter ballot, several workshop members expressed concern and opposed a four-hour surface interval. In the altitude decompression sickness series of the USAF School of Aerospace Medicine (USAFSAM) 221 cases occurred at ground level after an altitude exposure, and 25% of those had onset of symptoms after a four-hour symptom-free interval.Dr. Peter Bennett's presentation at the workshop showed that in the DAN series of 270 cases, 20 involved flying after diving: Eight (40%) occurred 4-11 hours after diving, 6 (30%) occurred 12-23 hours after diving, and 6 (30%) occurred after 24 hours on the surface. Based on the DAN and USAFSAM patient treatment data, one would feel more comfortable recommending a minimum surface interval of 12 hours to assume that the diver is symptom-free before ascending to altitude. Furthermore, comments pertaining to the 12-hour surface interval favor restricting the guideline to no-decompression diving of less than two hours total in-water time (surface to surface) during the previous 48 hours.

Additionally, the comments pertaining to multiday, unlimited diving favored restricting the guideline to no-decompression diving and requiring a surface interval of 24 hours (without symptoms of DCS) before flying. Comments also raised questions about how to handle those dives that require decompression stops and what altitude limitations should be observed.

Comments from the first letter ballot were incorporated into the proposed UHMS guideline for recreational divers and submitted as a second ballot to the workshop presenters.

Comments from Second Letter Ballot (20 May 89)

The second letter ballot was unanimously approved as a workshop recommendation for recreational divers making dives while breathing air. For no-decompression dives:

a. With less than 2 hrs Total Dive Time (surface to surface) during the previous 48 hrs, divers should wait 12 hrs before flying.

b. With multiday, unlimited diving, divers should wait 24 hrs before flying.

c. Recreational divers should not make dives that require decompression stops. But if it should occur, delay flying for at least 24 hrs and, if possible, for 48 hrs. Divers with DCS symptoms should not fly unless it is required to obtain hyperbaric treatment for their diving illness.

This guideline is based on current, scientific information and expert opinion and is anticipated to be conservative, safe surface intervals for the vast majority of divers.

Professor A.A. Buehlmann kindly provided the following observations: "I approve the proposed guidelines, but I have some remarks to make.

a. There is, in my experience, no difference between no-decompression diving and dives that require decompression stops.

b. There is a big difference between the 1958 U.S. Navy Standard Air Decompression Table and the modern tables. (Comparison included in Table A-1). The U.S. Navy tables tolerate a higher nitrogen-over pressure in the tissues than modern tables. Using the old tables, perhaps there are more asymptomatic bubbles.

c. In central Europe, we need a recommendation for the day of the dive to be able to fly or to use a car over the mountains. In these cases--some hundred in the year - the time of the diver at 2000-2500 m above sea level lasts only some minutes, and not some hours as between the Caribbean and New York."

DEVELOPMENT OF DECOMPRESSION TABLES SINCE 1908

Dive Depth 30 m Airbreathing

	Bottom time	Stops		(m, min)			Total
	min	15	12	9	6	3	min
Haldane 1908 (108 Feet)	15 - 20				4	8	15
U.S.-Navy, 1958	25	--	--	--	--	--	2
GERS, 1965	30	--	--	--	--	--	2
Royal Navy, 1972	20	--	--	--	--	--	2
ZH-86, 1986	20	--	--	--	--	--	3
Canadian Forces, 1985	15	--	--	--	--	--	2
ZH-86, 1986	17	--	--	--	--	1	4
Comex, 1987	15	--	--	--	--	--	3
Haldane 1908 (108 Feet)	60	--	--	10	15	20	47
U.S.-Navy, 1958	60	--	--	--	9	28	39
GERS, 1965	60	--	--	--	--	37	39
Royal Navy, 1972	60	--	--	5	10	30	46
ZH-72, 1976	60	--	--	6	8	32	48
Canadian Forces, 1985	60	--	--	6	9	40	56
ZH-86, 1986	60	--	--	3	13	35	53
Comex, 1987	60	--	--	3	15	35	55
Haldane 1908 (108 Feet)	120	--	5	15	25	35	82
U.S.-Navy, 1958	120	--	--	12	41	78	133
Royal Navy, 1972	120	5	10	30	40	50	136
Canadian Forces, 1985	110*	--	4	8	38	106	158
ZH-86, 1986	120	--	6	22	37	98	165
Comex, 1987	110*	--	3	20	40	75	140

*120 Bottom time will no longer be considered.

Table A-1

APPENDIX B

Emmerman, M.N. Commercial Aircraft Cabin Differential Pressure Settings and Actual Cabin Altitudes During Flights. The American Academy of Underwater Sciences, Eighth Annual Scientific Diving Symposium, La Jolla, CA, September 1988.

EDITOR'S NOTE: While these data were not collected under a rigorous scientific protocol they provide a useful approximation of the flight environment to which the diver can be exposed.

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COMMERCIAL AIRCRAFT CABIN DIFFERENTIAL PRESSURE SETTINGS AND ACTUAL CABIN ALTITUDES DURING FLIGHTS.

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ABSTRACT

The general assumption in the diving community is that most commercial aircraft expose passengers to a **cabin** altitude of 8000 feet. Of the 123 flights monitored with a passenger carried altimeter, only 7 flights experienced an 8000 foot cruising cabin altitude; and all 7 of these readings were on DC-9 series aircraft. The vast majority of maximum cabin altitudes during all 123 flights ranged from 4500 to 5500 feet. On 91 out of the 123 flights, minutes from "take-off to cruising altitude" and minutes from "start of descent to landing" were monitored. On average it took 19 minutes to go from take-off to cruising and 24 minutes from start of descent to landing. The differential pressure settings of the most commonly used commercial aircraft were studied. The various actual settings are covered in the full report. This data is important to all divers who travel by commercial aircraft.

DIFFERENTIAL PRESSURE SETTINGS

All commercial aircraft are designed to pressurize the cabin at no higher than 8,000 feet while the aircraft itself is flying at its "maximum cruising altitude." The difference between the air pressure "outside" the aircraft and "inside" the aircraft is called Differential Pressure (Diff.PSI). The ability of the aircraft to pump air into the cabin, thereby creating this Diff.PSI, is a function of aircraft design. The flight crew has limited control of the cabin pressure, other than by altering the actual aircraft cruising altitude.

If two aircraft were cruising at 30,000 feet and one them had a Diff.PSI setting of 6.55 and the other 7.87, the aircraft with the higher setting would carry the passengers at a lower cabin altitude. In this case, the aircraft with the 6.55 setting would create an 8,000 foot cabin altitude, while the aircraft with the 7.87 setting would create a 5,000 foot cabin altitude. (The actual math is 4.36 psi @ 30,000 feet + 6.55 Diff.PSI = 10.91 psi, or 8,000 feet. For the second aircraft it would be: 4.36 psi @ 30,000 feet + 7.87 Diff.PSI = 12.23 psi, or 5,000 feet.)

Information was gathered from the major commercial aircraft manufacturers; including Boeing, Lockheed, and McDonnell Douglas. Table 1 lists the Automatic Differential Pressure settings for the most commonly used aircraft (alphabetically by aircraft).

TABLE 1

COMMERCIAL AIRCRAFT AUTOMATIC DIFFERENTIAL PRESSURE SETTINGS

Diff.PSI	AIRCRAFT & MODEL
8.2	A 300
8.6	B 727
8.6	B 727-100 / 200 / 231(TWA ONLY)
7.8	B 737-100 / 200 / 300 / 400
8.5	B 747, B 747B
8.9	B 747SP
8.6	B 757, B 767
5.5	DASH 8
8.4	DC 10 OVER WATER
7.4	DC 9, DC 9-30
7.0	DC 9-32
7.6	DC 9-80
6.5	ELECTRA (LOCKHEED)
8.5	L 1011

MONITORING ACTUAL AIRCRAFT ALTITUDES

With the aid of a hand held altimeter, the author was able to monitor the actual cabin altitude during flights. One of the three major commercial aircraft manufacturers indicated that such monitoring would only approximate the actual cabin altitude. This is due to the flight rules that instruct crews to set the aircraft altimeter to 29.92 inHg when the aircraft passes above 18,000 feet. On each flight, a note was sent to the pilot (or flight engineer) requesting the Diff.PSI setting, cruising altitude of the aircraft and cabin altitude according to the flight deck altimeter. The cabin altitude numbers were compared with the hand held altimeter. The largest difference between the two altimeters was only 300 feet. This variance was found to be a function of the barometric pressure on the ground before the aircraft doors were closed. For the purpose of this study, a variance of 300 feet or less was considered insignificant.

DIFFERENTIAL PRESSURE TABLE

Table 2 shows Altitude in Feet from sea-level to 48,000, relative absolute p.s.i. from sea-level to 48,000 feet, and various Diff.PSI settings from 5.5 to 9.0. This table was used to try to determine cabin altitude without the use of an altimeter. By knowing the type of aircraft (and therefore its Diff.PSI setting, from Table 1) and the cruising altitude; the cabin altitude could be determined by entering the table at the cruising altitude number and moving to the right to find the p.s.i. number under the appropriate Diff.PSI column. For example, the aircraft cruising at 30,000 feet having a Diff.PSI setting of 7.5 would have a cabin p.s.i. of 11.86. If you compare the 11.86 p.s.i. number to the absolute p.s.i. numbers in the second column of Table 2, you would find the equivalent cabin altitude to be slightly less than 6,000 feet. This exercise proved very accurate when compared to the flight deck cabin altitude readings.

Table 2. Differential pressure table.

AIRCRAFT ALTITUDE IN FEET	ABSOLUTE P.S.I.	CABIN P.S.I. @ _._ OF DIFFERENTIAL P.S.I.							
		5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
0	14.70	*BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
1000	14.17	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
2000	13.66	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
3000	13.17	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
4000	12.69	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
5000	12.23	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
6000	11.78	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
7000	11.34	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
8000	10.91	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
9000	10.50	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
10000	10.11	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
11000	9.72	BSL	BSL	BSL	BSL	BSL	BSL	BSL	BSL
12000	9.35	14.85	BSL	BSL	BSL	BSL	BSL	BSL	BSL
13000	8.98	14.48	BSL	BSL	BSL	BSL	BSL	BSL	BSL
14000	8.63	14.13	14.63	BSL	BSL	BSL	BSL	BSL	BSL
15000	8.29	13.79	14.29	14.79	BSL	BSL	BSL	BSL	BSL
16000	7.96	13.46	13.96	14.46	BSL	BSL	BSL	BSL	BSL
17000	7.64	13.14	13.64	14.14	14.64	BSL	BSL	BSL	BSL
18000	7.34	12.84	13.34	13.84	14.34	BSL	BSL	BSL	BSL
19000	7.04	12.54	13.04	13.54	14.04	14.54	BSL	BSL	BSL
20000	6.75	12.25	12.75	13.25	13.75	14.25	14.75	BSL	BSL
21000	6.47	11.97	12.47	12.97	13.47	13.97	14.47	BSL	BSL
22000	6.20	11.70	12.20	12.70	13.20	13.70	14.20	14.70	BSL
23000	5.94	11.44	11.94	12.44	12.94	13.44	13.94	14.44	BSL
24000	5.70	11.20	11.70	12.20	12.70	13.20	13.70	14.20	14.70
25000	5.45	10.95	11.45	11.95	12.45	12.95	13.45	13.95	14.45
26000	5.22	10.72	11.22	11.72	12.22	12.72	13.22	13.72	14.22
27000	4.99	10.49	10.99	11.49	11.99	12.49	12.99	13.49	13.99
28000	4.77	10.27	10.77	11.27	11.77	12.27	12.77	13.27	13.77
29000	4.56	10.06	10.56	11.06	11.56	12.06	12.56	13.06	13.56
30000	4.36	9.86	10.36	10.86	11.36	11.86	12.36	12.86	13.36
31000	4.17	9.67	10.17	10.67	11.17	11.67	12.17	12.67	13.17
32000	3.98	9.48	9.98	10.48	10.98	11.48	11.98	12.48	12.98
33000	3.80	9.30	9.80	10.30	10.80	11.30	11.80	12.30	12.80
34000	3.62	9.12	9.62	10.12	10.62	11.12	11.62	12.12	12.62
35000	3.46	8.96	9.46	9.96	10.46	10.96	11.46	11.96	12.46
36000	3.29	8.79	9.29	9.79	10.29	10.79	11.29	11.79	12.29
37000	3.14	8.64	9.14	9.64	10.14	10.64	11.14	11.64	12.14
38000	2.99	8.49	8.99	9.49	9.99	10.49	10.99	11.49	11.99
39000	2.85	8.35	8.85	9.35	9.85	10.35	10.85	11.35	11.85
40000	2.72	8.22	8.72	9.22	9.72	10.22	10.72	11.22	11.72
41000	2.59	8.09	8.59	9.09	9.59	10.09	10.59	11.09	11.59
42000	2.47	7.97	8.47	8.97	9.47	9.97	10.47	10.97	11.47
43000	2.36	7.86	8.36	8.86	9.36	9.86	10.36	10.86	11.36
44000	2.25	7.75	8.25	8.75	9.25	9.75	10.25	10.75	11.25
45000	2.14	7.64	8.14	8.64	9.14	9.64	10.14	10.64	11.14
46000	2.04	7.54	8.04	8.54	9.04	9.54	10.04	10.54	11.04
47000	1.95	7.45	7.95	8.45	8.95	9.45	9.95	10.45	10.95
48000	1.86	7.36	7.86	8.36	8.86	9.36	9.86	10.36	10.86

***Resulting P.S.I. would indicate Below Sea Level (BSL) pressure.**

The 8,000 foot altitude line (10.91 psi) has been carried across the table. By looking at the Diff.PSI setting for a particular aircraft, and moving down the column until the 10.91 psi line is reached; you can estimate the maximum cruising altitude for that aircraft (based on the FAA 8,000 foot cabin altitude guidelines).

ACTUAL FLIGHT DATA

Table 3 shows the complete record of all 123 flights. The study began in December of 1985, and was completed in June of 1988. (Future flights will continue to be monitored.) The data shows that a cabin altitude of 8,000 feet or more was experienced on only 7 flights. All 7 of these exposures were on DC-9 series aircraft. You will note that 4 flights show a 9,223 cabin altitude. These flights landed at or left from Quito Ecuador. The airfield at Quito is at 9,223 feet elevation. Of the 123 total, 75 flights never exceeded 6,000 foot cabin altitude.

The data also shows that the elapsed time from take-off to cruising altitude averaged 19 minutes. The number of minutes from the beginning of descent to actual landing averaged 24 minutes.

DISCUSSION

If we assume that a diver has completed a series of dives at sea level and then travels by car, bus or train to his home which is at 5000 to 8000 foot elevation, the elapsed time for that diver to go from sea level to altitude would probably be much longer than 19 minutes. Relative to the other means of transportation, this 19 minute average elapsed time from take-off to cruising altitude in a commercial aircraft is very short.

The Diver's Alert Network at Duke University has information on symptomatic decompression sickness cases that presented while the diver was in a commercial aircraft as much as 41 hours after the diver's last dive.(1) The rapid change in pressure experienced in the commercial aircraft as compared to other means of travelling to altitude may play a large part in the presentation of these symptoms.

The assumption in the diving community is that divers should be prepared to be exposed to an 8,000 foot altitude when entering a commercial aircraft. The data shows that such an exposure is rare (except when flying in a DC-9 series aircraft). The present author has knowledge of 47 cases of symptomatic decompression sickness that presented during (or shortly after) commercial aircraft travel. The reference material for these cases do not list the particular aircraft on which the divers travelled. If the data in this study is accurate, it is likely that most of these divers experienced DCS symptoms at altitudes between 4000 and 6000 feet. The critical cabin altitude, therefore, is probably less than 8,000 feet. The actual risk altitude remains unknown.

CONCLUSIONS

From the information shown in the Duke University cases reviewed in the "Alert Diver" DAN publications (2), it is possible to determine that each diver who presented symptomatic DCS while aboard a commercial aircraft was at least a D diver (repetitive group designation) at the time of boarding the aircraft.

A few things are obvious: 1) going from sea level to 5000 or 8000 feet elevation in 19 minutes is very fast; 2) very few commercial aircraft actually expose the passenger to an 8000 foot cruising altitude; 3) divers have suffered symptomatic DCS while in a commercial aircraft as much as 41 hours after diving; and, 4) it is statistically unlikely that all of the symptomatic DCS cases that presented in the aircraft were exposed to an 8000 foot cabin altitude.

From all of this, I believe that: 1) the basis for determining a critical altitude for flying after diving should be re-evaluated; and, 2) the D diver "OK to fly" protocol used by various training agencies is inappropriate. The diver's personal physiological profile and health habits are probably more important in determining the risk of DCS while exposed to the commercial aircraft environment than an impersonal mathematical evaluation of the dive profile. From the data presented here, it is not possible to determine a universal guideline relative to surface interval before travelling in a commercial aircraft.

The Flight Data Record (Table 3) is logged on Lotus 123 software. This Lotus file is available by contacting the author.

REFERENCES

1) Emmerman (M.N.), "Flying and Diving, A New Look", Proceedings, International Conference On Underwater Education, National Association of Diving Instructors, Nov 1987. Appendix A, Case #102086.

2) Alert Diver, The Newsletter of the Divers Alert Network, Duke University Medical Center, Durham, North Carolina 27710. Vol.3, No.1, Winter 1987.

Table 3. Differential pressure readings, flight record.

FLT #	DAY	DATE	TIME FROM TAKE-OFF /LANDING	FROM	TO	AIRLINE FLIGHT NUMBER	TYPE OF AIRCRAFT	CRUISING ALTITUDE FEET	CABIN ALTIT. FEET	DIFF PSI SET@	MINUTES FROM TAKE-OFF /CRUISE	MINUTES FROM CRUISING /DESCENT	MINUTES FROM DESCENT /LANDING
1	SAT	DEC 14 5	04:16	NY-JFK	ARUBA	LM980	DC-9-80	33000	6400	7.6	--	--	--
1		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				LM980	DC-9-80	37000	8000	7.72	--	--	--
2	SAT	DEC 14 5	00:16	ARUBA	CURACAO	LM980	DC-9-80	12000	2000	? 4.2	--	--	--
3	SAT	DEC 14 5	00:20	CURACAO	BONAIRE	LM821A	STAL	3000	3000	0	--	--	--
4	SAT	DEC 28 5	00:27	BONAIRE	ARUBA	ALM971	DC-9-32	14000	0	5.4	--	--	--
5	SAT	DEC 28 5	02:45	ARUBA	MIAMI	ALM971	DC-9-32	35000	8400	6.95	--	--	--
6	SAT	DEC 28 5	01:57	MIAMI	NY-JFK	EA976	L-1011	37000	?		--	--	--
7	FRI	MAY 23 6	02:17	NY-LAG	MIAMI	EA11	L-1011	35000	5750		20	90	27
8	FRI	MAY 23 6	00:18	MIAMI	FREEPORT	EA181	B727-200	?	500		--	--	--
9	MON	MAY 26 6	00:34	FREEPORT	MIAMI	EA836	B727-200	16000	0		--	--	--
10	MON	MAY 26 6	02:30	MIAMI	NY-LAG	EA28	A300WIS	33000	6000		23	90	37
11	FRI	MAY 30 6	00:34	NY-LAG	BOSTON	NYAIR	DC-9-30		2300		--	--	--
12	MON	JUL 21 6	02:33	NY-NWK	MINNEAPOLI	NW593	727-100	35000	5950		20	106	27
13	MON	JUL 21 6	01:50	MINNEAPOLI	BILLINGS	NW105	727-200	35000	6250		12	75	19
14	MON	AUG 4 86	01:32	BILLINGS	MINNEAPOLI	NW72	727-200	33000	5550		12	63	17
15	TUE	AUG 5 86	02:01	MINNEAPOLIS	NY-NWK	NW208	727-200	33000	5400		16	76	29
16	THU	AUG 21 6	02:24	NY-NWK	FREEPORT	BAHA967	BA737	28000	5000		32	76	36
17	SUN	AUG 24 6	02:39	FREEPORT	NY-NWK	BAHA966	BA737	33000	6800		20	112	27
18	FRI	SEP 5 86	00:54	NY-LAG	MONTREAL	AC751	DC-9	34000	8150		31	3	20
19	FRI	SEP 5 86	01:09	MONTREAL	HALIFAX	AC636	DC-9	33000	8200		27	27	15
20	FRI	SEP 5 86	00:32	HALIFAX	SYDNEY,NS	AC636	DC-9	23000	4100		11	7	14
21	SUN	SEP 7 86	00:35	SYDNEY,NS	HALIFAX	CP133	BA737	19000	2100		--	--	--
22	SUN	SEP 7 86	01:19	HALIFAX	MONTREAL	CP133	BA737	31000	6500		18	38	23
23	SUN	SEP 7 86	01:00	MONTREAL	NY-LAG	AC752	DC-9	28000	5500		15	18	27
24	SUN	OCT 5 86	13:41	NY-JFK	TOKYO	UAL803	B747SP	33000	5700		10	795	16
24		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				UAL803	B747SP	41000	6900	8.9	CHANGED CRUISE ALTITUDE		
25	SAT	OCT 11 6	11:54	TOKYO	NY-JFK	UAL800	B747SP	35000	4900		8	671	35
25		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				UAL800	B747SP	41000	6700		CHANGED CRUISE ALTITUDE		
25		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				UAL800	B747SP	43000	7300		CHANGED CRUISE ALTITUDE		
26	WED	NOV 5 86	00:34	NY-NWK	BOSTON	PIED60	727-200	13000	0		--	--	--
26		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				PIED60	727-200	17000	0		--	--	--
27	WED	NOV 5 86	01:04	BOSTON	NY-NWK	NYAIR363	DC-9-30		0	7.5	--	--	--
28	SAT	NOV 22 6	04:00	NY-JFK	STMAARTEN	ALM982	DC-9-80	35000	7800	7.6	21	193	26
28		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				ALM982	DC-9-80	37000	8500	7.6	CHANGED CRUISE ALTITUDE		
29	SAT	NOV 22 6	01:16	STMAARTEN	CURACAO	ALM982	DC-9-80		7350		17	35	24
30	SAT	NOV 22 6	00:23	CURACAO	BONAIRE	ALM ?	STAL DEH	3000	3000	0	--	--	--
31	SUN	NOV 30 6	00:14	BONAIRE	CURACAO	ALM1562	DC-9-30		0		--	--	--
32	SUN	NOV 30 6	01:20	CURACAO	STMAARTEN	ALM983	DC-9-80	33000	6750		21	34	25
33	SUN	NOV 30 6	03:51	STMAARTEN	NY-JFK	ALM983	DC-9-80	31000	5800		22	178	31
34	SAT	DEC 20 6	05:09	NY-JFK	LOS ANGELES	UA 7	DC-10 OW	35000	5600	8.4	25	261	26
35	SAT	DEC 20 6	05:38	LOS ANGELES	HONOLULU	QANTAS28	B747-B	35000	5220	8.5	24	293	21
36	SUN	DEC 21 6	05:51	HONOLULU	NADI,FIJI	QANTAS28	B747-B	35000	5250	8.6	7	276	20
37	SAT	JAN 3 7	05:56	NADI,FIJI	HONOLULU	QANTAS17	B747-B	33000	4500	8.6	7	325	24
38	SAT	JAN 3 7	00:22	HONOLULU	MAUI	ALOHA206	B737		0	14.7	--	--	--
39	WED	JAN 7 7	00:22	MAUI	HONOLULU	ALOHA117	B737		0	14.7	--	--	--
40	SAT	JAN 10 7	04:40	HONOLULU	LOS ANGELES	QANTAS17	B747-B	36000	5475	8.6	13	230	37
40		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				QANTAS17	B747-B	38000	6260	8.6	CHANGED CRUISE ALTITUDE		

Table 3. (continued)
Differential pressure readings, flight record.

FLT #	DAY	DATE	TIME FROM TAKE-OFF /LANDING	FROM	TO	AIRLINE FLIGHT NUMBER	TYPE OF AIRCRAFT	CRUISING ALTITUDE FEET	CABIN ALTIT. FEET	DIFF PSI SET@	MINUTES FROM TAKE-OFF /CRUISE	MINUTES FROM CRUISING /DESCENT	MINUTES FROM DESCENT /LANDING
41	SUN	JAN 11 7	05:07	LOS ANGELES	NY-JFK	UA28	DC-10 OW	33000	4800	8.4	34	242	30
		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				UA28	DC-10 OW	37000	6500	8.4	CHANGED CRUISE ALTITUDE		
42	WED	JAN 21 7	02:41	NY-LAG	MINNEAPOLIS	NW711	B757	39000	6600	8.6	82	42	37
43	WED	JAN 21 7	02:51	MINNEAPOLIS	LAS VEGAS	NW711	B757	39000	6600	8.6	21	127	23
44	SUN	JAN 25 7	02:14	LAS VEGAS	KANSAS CITY	EA 258	B727-200	29000	3900	8.6	33	86	22
45	SUN	JAN 25 7	02:14	KANSAS CITY	NY-NEWARK	EA 258	B727-200	29000	3900	8.6	20	88	26
46	FRI	FEB 20 7	00:56	NY-LAG	MONTREAL	AC 751	DC-9	33000	7100	7.4	23	14	19
47	FRI	FEB 20 7	01:10	MONTREAL	HALIFAX	AC 636	DC-9	33000	7100	7.4	18	31	21
48	FRI	FEB 20 7	00:34	HALIFAX	SYDNEY,NS	AC 636	DC-9	? 25000	4500		11	6	17
49	SAT	FEB 21 7	00:43	SYDNEY,NS	HALIFAX	AN2817	DASH 8	16000	3800	5.5	11	19	13
50	SAT	FEB 21 7	01:18	HALIFAX	MONTREAL	AC 621	DC-9	35000	8000	7.4	23	30	25
51	SUN	FEB 22 7	00:52	BURLINGTON	NY-NEWARK	CON4197	B737-100	26000	3900	7.0	14	11	27
52	THU	MAR 5 7	02:26	NY-LAG	W.PALM BEACH	EA 883	L1011	35000	5700	8.4	20	96	30
52		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				EA 883	L1011	39000	7200	?8.4	CHANGED CRUISE ALTITUDE		
53	FRI	MAR 6 7	02:16	W.PALM BEACH	PHILA, PA	USAIR618	B737	33000	7000	7.2	24	77	35
54	THU	MAR 19 7	01:08	NY-LAG	COLUMB.,OHIO	TW 353	B727-231	31000	4820	8.2	15	24	29
55	FRI	MAR 20 7	01:24	COLUMB.,OHIO	NY-JFK	TW 236	B727-231	33000	5000	?8.6	25	28	31
SP	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	PIPER-M	25000	8000	5.5	--	--	--
56	THU	APR 16 7	02:30	NY-NEWARK	FT.LAUD,FLA	DEL 801	L1011	31000	4600	8.4	15	117	18
57	THU	APR 16 7	00:48	FT.LAUD,FLA	ANDROS,BAH	N68105	CESSNA-T	2000	2000	0	18	--	--
58	SAT	APR 18 7	00:35	ANDROS,BAH	BIMINI,BAH	N.A.	PIPER-AE	2300	2300	0	5	22	8
59	SAT	APR 18 7	00:25	BIMINI,BAH	FT.LAUD,FLA	N.A.	PIPER-AE	2000	2000	0	5	12	8
60	SAT	APR 18 7	02:22	FT.LAUD,FLA	NY-NEWARK	EA 758	A-300	33000	5900	8.15	17	92	33
61	THU	APR 30 7	00:55	NY-LAG	MONTREAL	AC 743	B-727	33000	4800	8.4	19	17	19
62	THU	APR 30 7	00:45	BURLINGTON	NY-LAG	USA 479	DC-9	26000	4000	7.76	14	8	23
63	TUE	MAY 12 7	02:32	NY-NEWARK	MINNEAPOLIS	NW 771	B727-200	31000	4200	8.5	19	107	26
64	TUE	MAY 12 7	00:29	MINNEAPOLIS	FOREST CITY	WINNEBAG	BEECH E90	12500	1800	4.6	--	--	--
65	TUE	MAY 12 7	00:34	FOREST CITY	MINNEAPOLIS	WINNEBAG	BEECH E90	13000	2200	4.6	--	--	--
66	TUE	MAY 12 7	02:04	MINNEAPOLIS	NY-NEWARK	NW ?	DC-10	37000	6300	8.7	25	66	33
67	FRI	MAY 15 7	02:05	NY-NEWARK	ORLANDO,FLA	CONT 651	B727-200	31000	4800	8.6	28	65	32
68	SAT	MAY 16 7	01:59	ORLANDO,FLA	NY-NEWARK	EA 702	L1011	37000	6400	8.5	19	80	20
69	THU	JUL 2 7	02:14	NY-LAG	FT.LAUD,FLA	DEL 77	L1011	35000	6100	8.6	23	86	25
70	FRI	JUL 3 7	00:65	FT.LAUD,FLA	ANDROS,BAH	TTL4193	DC-3	4200	4200	0	15	40	10
71	MON	JUL 6 7	00:40	ANDROS,BAH	FT.LAUD,FLA	CHARTER	CES-TITAN	6500	6500	0	23	0	17
72	MON	JUL 6 7	02:06	FT.LAUD,FLA	NY-JFK	DEL 60	L1011	37000	6500	8.4	30	69	27
73	MON	JUL 27 7	04:56	NY-NWK	LOS ANGELES	UA 11	DC-10	35000	5700	8.5	33	358	25
74	THU	JUL 30 7	04:50	LOS ANGELES	NY-NWK	UA 14	DC-10	33000	4600	8.4	42	220	28
74		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				UA 14	DC-10	37000	6300	8.4	CHANGED CRUISE ALTITUDE		
75	WED	AUG 19 7	05:44	NY-JFK	LISBON	TW 900	L1011-100	33000	5000	8.4	12	313	19
76	THU	AUG 20 7	01:15	LISBON	BARCELONA	TW 900	L1011-100	?	5800	8.4	11	47	17
77	WED	SEP 2 7	01:23	BARCELONA	LISBON	TW901-7	L1011-100	37000	6400	8.3	14	47	22
78	WED	SEP 2 7	07:02	LISBON	NY-JFK	TW901-7	L1011-100	?	6700	8.3	14	361	47
79	TUE	SEP 15 7	01:28	NY-LAG	CINCINNATI	DEL 849	B767-232	41000	7500	8.6	30	37	21
80	TUE	SEP 15 7	01:13	CINCINNATI	LITTLE ROCK	DEL 895	B737-200	31000	5700	7.8	16	33	24
81	TUE	SEP 15 7	01:02	LITTLE ROCK	ATLANTA	DEL 772	B727-200	37000	6300	8.6	29	10	23
82	TUE	SEP 15 7	01:46	ATLANTA	NY-LAG	DEL 250	B757	41000	7200	8.6	37	30	37
83	SAT	SEP 26 7	02:00	NY-LAG	ST.LOUIS	TWA 403	L1011	?	5900	?	9	81	30

Table 3. (continued)
Differential pressure readings, flight record.

FLT #	DAY	DATE	TIME FROM TAKE-OFF /LANDING	FROM	TO	AIRLINE FLIGHT NUMBER	TYPE OF AIRCRAFT	CRUISING ALTITUDE FEET	CABIN ALTIT. FEET	DIFF PSI SET@	MINUTES FROM TAKE-OFF /CRUISE	MINUTES FROM CRUISING /DESCENT	MINUTES FROM DESCENT /LANDING
84	SAT	SEP 26 7	03:14	ST.LOUIS	LOS ANGELES	TWA 403	L1011	?	5800	?	12	147	25
85	SAT	SEP 26 7	00:51	LOS ANGELES	SAN FRANCISCO	TWA 403	L1011	?	5400	?	11	18	22
86	SAT	SEP 26 7	05:04	SAN FRANCISCO	HAWAII	QA 4	B747-B	35000	5080	8.5	10	265	29
86		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				QA 4	B747-B	?	5900	8.5	CHANGED CRUISE ALTITUDE		
87	SUN	SEP 27 7	09:35	HAWAII	SYDNEY	QA 4	B747-B	31000	3660	8.6	23	535	17
87		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				QA 4	B747-B	35000	5200	8.6	CHANGED CRUISE ALTITUDE		
88	MON	SEP 28 7	01:03	SYDNEY	BRISBANNE	ANIU 4	A300	33000	6200	8.3	14	26	23
89	MON	SEP 28 7	02:39	BRISBANNE	PORT MORSBEY	ANIU 4	A300	?	5600	8.3	24	113	22
90	TUE	SEP 29 7	00:32	PORT MORSBEY	LAE / PNG	ANIU 296	FOKK F28	24000	3500	7.2	12	10	10
91	TUE	SEP 29 7	00:24	LAE / PNG	MADANG / PNG	ANIU 296	FOKK F28	16500	0	7.2	..	..	..
92	TUE	SEP 29 7	00:39	MADANG / PNG	MANUS / PNG	ANIU 296	FOKK F28	25000	4000	7.2	13	14	12
93	TUE	SEP 29 7	00:44	MANUS / PNG	KAVIENG/PNG	ANIU 296	FOKK F28	23500	3400	7.2	12	17	15
94	MON	OCT 12 7	01:15	RABAUL / PNG	PORT MORSBEY	ANIU 267	FOKK F28	31000	7600	7.2	22	34	19
95	TUE	OCT 13 7	02:42	PORT MORSBEY	BRISBANNE	ANIU 270	A300	29000	4300	8.2	21	..	..
95		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				ANIU 270	A300	?	5300	8.2	CHANGED CRUISE ALTITUDE		
96	TUE	OCT 13 7	01:07	BRISBANNE	SYDNEY	ANIU 270	A300	31m ?	5500	8.2	15	29	23
97	TUE	OCT 13 7	09:00	SYDNEY	TOKYO	QA 21	B747-B	39000	6050	8.6	10	449	21
98	MON	OCT 19 7	11:38	TOKYO	NY-JFK	JAL 6	B747-LR	33000	4400	8.9	8	646	44
98		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				JAL 6	B747-LR	37000	5200	8.9	CHANGED CRUISE ALTITUDE		
98		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				JAL 6	B747-LR	41m ?	6500	8.9	CHANGED CRUISE ALTITUDE		
99	THU	NOV 5 7	05:19	NY-JFK	LOS ANGELES	TW 849	L1011-100	31000	4100	8.2	13	282	24
99		CHANGE IN CRUISING ALTITUDE DURING FLIGHT				TW 849	L1011-100	35m ?	5800	8.2	CHANGED CRUISE ALTITUDE		
100	SUN	NOV 8 7	04:27	LOS ANGELES	NY-JFK	TW 702	L1011	37000	6300	*8.2	14	234	19
101	SAT	NOV 21 7	02:18	NY-NWK	MIAMI	EA 5	L1011	35000	5800	8.4	13	95	30
102	SAT	NOV 21 7	02:26	MIAMI	BONAIRE	ALM 972	DC-9-80	33000	6800	7.6	26	102	18
103	SUN	NOV 29 7	03:03	BONAIRE	MIAMI	ALM 971	DC-9-80	31000	6100	7.5	23	117	43
104	SUN	NOV 29 7	02:34	MIAMI	NY-LAG	EA 24	L-1011	37000	6300	8.4	19	84	51
105	WED	JAN 27 8	02:32	NY-JFK	NEW ORLEANS	TWA 881	B727-231	31000	4400	8.6	15	120	17
106	SUN	JAN 31 8	01:02	NEW ORLEANS	ATLANTA	DEL 796	B767-232	29000	4100		21	13	28
107	SUN	JAN 31 8	01:30	ATLANTA	NY-NWK	DEL 784	L1011	37000	6800		14	47	29
108	THU	MAR 3 8	01:06	DUTCHES CNTY	BURLINGTON	PRIVATE	CES-421C	13500	1000		..	..	..
109	SUN	MAR 6 8	01:10	BURLINGTON	DUTCHES CNTY	PRIVATE	CES-421C	12500	1000		..	..	..
110	SAT	APR 16 8	02:28	NY-JFK	MIAMI	EA 9	L1011	35000	5650	8.4	13	108	27
111	SAT	APR 16 8	03:50	MIAMI	GUAYAQUIL	EA 9	L1011	33000	5000	8.4	13	183	24
112	SAT	APR 16 8	00:32	GUAYAQUIL	QUITO	EA 9	L1011	SEE NOTE	9223	8.4	..	..	..
113	TUE	APR 19 8	00:31	QUITO	GUAYAQUIL	TAME 662	B727-100	SEE NOTE	9223		..	..	..
114	TUE	APR 19 8	01:31	GUAYAQUIL	BALTRA	TAME 191	B727-100	31000	4600	8.3	11	65	14
115	FRI	APR 29 8	01:34	BALTRA	GUAYAQUIL	TAME 664	B727-100	33000	5500	8.3	—	—	—
116	FRI	APR 29 8	00:41	GUAYAQUIL	QUITO	TAME 664	B727-100	SEE NOTE	9223		—	—	—
117	SAT	APR 30 8	00:32	QUITO	GUAYAQUIL	EA 910	L1011	SEE NOTE	9223	8.4	—	—	—
118	SAT	APR 30 8	03:32	GUAYAQUIL	MIAMI	EA 910	L1011	35000	5700	8.4	—	—	—
119	SAT	APR 30 8	02:10	MIAMI	NY-NWK	EA 6	L1011	37000	6500	8.4	—	—	—
120	SUN	JUN 5 8	01:34	NY-NWK	ATLANTA	DEL 765	B757		5200		—	—	—
121	SUN	JUN 5 8	01:05	ATLANTA	NEW ORLEANS	DEL 493	B727-200	13000	3000		—	—	—
122	THU	JUN 9 8	01:08	NEW ORLEANS	ATLANTA	DEL 304	B727-200	29000	3100		—	—	—
123	THU	JUN 9 8	01:32	ATLANTA	NEW ORLEANS	DEL 748	DC-8	37000	6200	8.7	—	—	—

APPENDIX C

FLYING AFTER DIVING: A DATABASE

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I had long believed that there was little data on the interaction of diving and altitude exposure. Inquiry and a literature search, however, turned up some 700 experimental flying after diving exposures and 400 actual dives at altitude (Table 1). These studies are described below with detailed accounts of their pressure-time profiles and decompression sickness (DCS) incidents. The pressure profiles are given in the authors' units to facilitate cross-checking with original sources. Table 2 gives pressure conversion factors and the non-linear conversion from altitude to pressure.

The data collected below are best analyzed by maximum likelihood (Weathersby et al. 1984; Vann 1987; Weathersby 1989). This permits risk estimates for flying after diving (Vann 1989) as well as providing for hypothesis testing and decompression procedure calculation.

Maximum likelihood makes possible the investigation of specific effects if sufficiently detailed data exist, and data are presented as completely as the original sources will allow. Included are: gas mixes, travel rates, and pressure profile; temperature and exercise routines; diver characteristics; location, nature, and onset time of symptoms; and treatment and resolution of symptoms. Control studies with only hyperbaric or hypobaric exposure also are included. Such safe exposures are needed for accurate estimation of low decompression risk.

Missing information such as subject data, travel rates, etc. is reported as "missing". Exposures lacking more significant information were not included. Should the missing information be found, it will be reported in a subsequent addendum.

The diagnosis of decompression sickness was usually an easy matter as most symptoms were clear-cut and were relieved by descent or recompression. When symptoms were mild or transient, however, diagnosis could be more difficult. Rather than assign a diagnosis in these ambiguous cases, the reader is left to draw his own conclusions.

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Dr. Bruce Bassett deserves credit for conducting the initial literature search for flying after diving studies. He kindly forwarded pertinent papers and reports and spent time reviewing dive logs from his own study to provide additional information (Bassett 1982).

Dr. Ulf Balldin reviewed an early draft and provided supplementary references to ensure that his studies were described completely.

Professor Buehlmann generously provided records of original research much of which had not been previously reported. These records included the results of actual dives at altitude.

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Table 1. A summary of flying after diving reports.

Study	Dives		Surface Interval (hrs)	Flights		DCS/ Exposures	Comment
	Pressures (ATA)	Times (min)		Pressures (ATA)	Times (min)		
Kiessling and Duffner (1960)	3.99-5.16	30	0.75	0.50	60	31/45(a) 1/18(b)	No-stop dives
Kiessling and Wood (1961); Logan (1981)	1.92-6.2	5-180	0.75	0.50	60	102/121(a) 25/140(c)	No-stop, Decomp Heliox, Nitrox
Logan (1961)						25/140	
Edel et al (1969)	1.91-4.64	15-1440	0.1-3.0	0.54-0.74	5-112	15/45(a)	No-stop dives
Edel (1970)	2.42	120	0.5-15.0	0.36-0.69	10-120	11/50(a)	Repet no-stop dives O_2 in surface interval
Balldin and Borgstrom (1976)	1.0-2.0	30-45	0	0.20-0.35	120	3/4(a) 3/15(b)	No stop dives
Balldin (1978)	2.5-4.9	10-100	12-24	0.30	120	16/35(a)	No-stop dives
Balldin (1980)	2.5-4.9	10-100	3	0.68-0.88	120	2/32	No stop dives
Balldin (1979)	2.5-4.9	10-100	12	0.30	120	6/12(a)	No-stop dives. 02 in surface interval
Balldin and Sporrong (1980)	2.5	100	0.1	0.7	120	0/10(a)	No-stop dives
Bassett (1982)	1.33-4.93	7-1440	0	0.54-0.73	60-240	6/167(a)	No stop dives
Buehlmann	1.9-7.0	15-120 7-204	0-1 0-4.6	0.58-0.87	20-200	16/200(a) 45/299(e) 4/401(d)	Decompression. Repet .Surface Interval 02

Notes:		Total DCS/Exposures
	(a) Flying after diving	208/721
	(b) Hypobaric controls	4/33
	(c) Hyperbaric controls	15/140
	(d) Altitude diving	4/401
	(e) Repetitive diving at sea level	45/299

Table 2. Pressure Conversions

Altitude (feet)	Pressure (mmHg)
0	760.0
500	746.4
1000	732.9
1500	719.7
2000	706.6
2500	693.8
3000	681.1
3500	668.6
4000	656.3
4500	644.2
5000	632.3
5500	620.6
6000	609.0
6500	597.6
7000	586.4
7500	575.3
8000	564.4
8500	553.7
9000	543.2
9500	532.8
10000	522.6
10500	512.5
11000	502.6
11500	492.8
12000	483.3
12500	473.8
13000	464.5
13500	455.4
14000	446.4
14500	437.5
15000	428.8
15500	420.2
16000	411.8
16500	403.5
17000	395.3
17500	387.3
18000	379.4
18500	371.7
19000	364.0
19500	356.5
20000	349.1
20500	341.8
21000	334.6
21500	327.6
22000	320.8
22500	314.0
23000	307.4
23500	300.8
24000	294.4
24500	288.0
25000	281.8
25500	275.8
26000	269.8
26500	263.8
27000	258.0
27500	252.4
28000	246.8
28500	241.4
29000	236.0
29500	230.6
30000	225.6
30500	220.4
31000	215.4
31500	210.4
32000	205.6
32500	201.0
33000	196.3
33500	191.8
34000	187.3
34500	183.0
35000	178.7
35500	174.4
36000	170.3
36500	166.3
37000	162.4
37500	158.6
38000	154.8

From: U.S. Standard Atmospheric Pressure Table. Physiological Training. NASA, Johnson Space Center.

1 foot of altitude - 0.3048 meters
1 ATA = 760 mmHg
= 1.0132 BAR
= 33.071 fsw (feet of sea water)
= 10.132 msw (meters of sea water)

From: Shilling et al. (1976)

Kiessling and Duffner (1960)

This study used altitude exposure at 18,000 ft as a test of decompression adequacy after no-stop diving. The subjects were 18 U.S. Navy divers having a mean age of 32 years (range 22-39). Their mean weight was 16 lbs above the Navy standard (range 25-42 lbs). Nine had been treated for decompression sickness from one to nine times. Neither weight nor previous DCS treatment was statistically correlated with the study results. During control altitude exposures on air (no previous dive), several subjects complained of slight dizziness above 10,000 feet. Oxygen was used at altitude during subsequent experiments. The results of each dive were scored as the time at which symptoms occurred at altitude (including ascent time). The occurrence of DCS was verified by symptom relief upon recompression. Three of the 125 fsw experiments required hyperbaric treatment (USN Tables 2,3, and modified 4) after descent from altitude. The dives took place in a wetpot. The water temperature was 93 ±.2°F. DCS symptoms were not described by Kiessling and Duffner (1960) but were found in the original bound dive logs at the NEDU reference library (NEDU Volume 54). The logs indicated that initial trials used a 30 min altitude exposure rather than the 60 min that was reported. "Inkles" were a frequently reported symptom. An inkle (as in inkling - a hint, suspicion, or vague idea) is an unusual sensation or mild, transient pain. Inkles are similar to "niggles" (as in a niggling pain), a term sometimes used by Royal Navy divers to describe ambiguous or premonitory symptoms.

Workloads

Subjects were at rest unless otherwise noted.

A Swim on a trapeze in a wetpot against an 8 lb pull. (Equivalent to swimming at 0.8 knots).
B. Lift a 70 lb weight in a wetpot waist high between work bench and deck 10 times per minute (about 1750 ft lbs/min).
C. Five deep knee bends and five push ups every five minutes, (dry and on the surface).
D. Ten deep knee bends every five minutes in a dry altitude chamber.

Subjects. Many of these divers were subjects for Kiessling and Wood (1961) and Logan (1961). When a diver appears in both the 1960 and 1961 studies, add two years to his age for the later study.

Name	Age	Height	Weight
AND	33	66 in	167 lbs
ANG	32	69 in	160 lbs
AVI	36	68 in	156 lbs
BRA	31	70 in	189 lbs
BUL	30	72 in	165 lbs
CAR	35	69 in	170 lbs
DIM	33	69 in	158 lbs
GED	34	70 in	165 lbs
GWI	27	69 in	134 lbs
HUD	22	69 in	190 lbs
JAM	35	72 in	195 lbs
JAN	25	68 in	175 lbs
JOS	32-	72 in	190 lbs
KIE	26	76 in	205 lbs
LIN	30	70 in	130 lbs
MAL	32	68 in	160 lbs

Name	Age	Height	Weight
MIC	36	72 in	191 lbs
MIL	32	72 in	175 lbs
NAQ	31	69 in	190 lbs
NIC	41	73 in	182 lbs
PAR	38	73 in	175 lbs
POW	40	70 in	178 lbs
SIR	30	69 in	180 lbs
SMI	40	72 in	175 lbs
STE	38	68 in	150 lbs
TRI	32	66 in	171 lbs
VAI	31	67 in	183 lbs
WHI	39	68 in	150 lbs
WIL	24	66 in	156 lbs
WLY	32	66 in	147 lbs
ZAM	39	68 in	165 lbs
ZIE	40	71 in	163 lbs

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	75 fpm	Air	
D	T_1	Air	
D	10	Air	A
D	5	Air	
D	10	Air	B
Decompression	60 fpm	Air	
0 fsw	15 min	Air	
0 fsw	30 min	Air	C
Ascent	6,000 ft/min	Note (a)	
18,000 ft	2 min	O_2	
18,000 ft	T_2	O_2	D
Descent	6,000 fpm	O_2	
0 fsw	--	Air	

Note (a): Switch from air to O_2 at 10,000 ft.

Results

D = 0 fsw, T_1 = 0 min, T_2 = 27 min (Altitude controls)

Reference: NEDU V.54; NEDU V.53

Date	Run#	Subject	Comments
6 June 59	A1	AND	P.11, NEDU V.54
6	A2	AVI	P.13,
6	A3	BRA	P.15
6	A4	CAR	P.17
6	A5	GWI	P.19
6	A6	JAM	P.21
6	A7	LIN	P.23
6	A8	MIC	P.25
6	A9	WHI (1)	P.27
6	A10	WLY	P.29
6	A11	WIL	P.31

D = 0, T_1 = 0 min, T_2 = 57 min

Date	Run#	Subject	Comments
8 Sept. 59	A12	HUD	P.33, NEDU V.54
8	A13	JOS	P.35
8	A14	SIR	P.37
8	A15	DIM	P.39
8	A16	TRI	P.39
8	A17	VAI	P.39
8			

Notes:

(1) Very slight left knee pain during deep knee bends in first 5 min at 18K.

D = 90 fsw, T_1 = 28.7 min, T_2 = 27 min

Reference: NEDU V.54

Date	Dive #	Subject	Comments
7 July 59	1	LIN (1)	P.43, NEDU V.54
7	1	AND	P.45
7	2	GWI (2)	P.47
7	2	WIL	P.49
7	3	MIC	P.51
7	3	AVI	P.53
7	10	CAR	P.79
7	10	WLY	P.81
7	14	JAM	P.95
7	14	WHI	P.97
7	16	BRA (3)	P.103

Notes:

(1) Rapid onset of moderately severe left forearm pain after 25 min. Relieved at 10K during descent.
(2) Pain in both knees and shoulders after 19 min. Relieved at 6K on descent.
(3) Short pain in right shoulder at 12 min. No further symptoms. Completed 27 min at 18 K.

D = 90 fsw, T_1 = 28.7 min, T_2 = 57 min

Date	Dive #	Subject	Comments
9 Sept. 59	17	VAI (1)	P.109, NEDUV.54
9	19	SIR	P.113
9	20	ZAM	P.115
9	21	DIM (2)	P.117
9	23	TRI (3)	P.121
9	27	JOS	P.129
9	29	HUD (4)	P.133

Notes:

(1) Rash on left shoulder at 38 min. Moderate left calf pain at 47 min. Pain moved up leg and increased at 49 min. Complete relief at 8K on descent.
(2) Right knee pain at 38 min while exercising. Only slight pain at rest. The leg was weak and wold not support subject during last 2 exercise periods. Symptoms gone on descent to ground level.
(3) Slight pain in right hand at 3 min. Pain increased to moderate and spread up arm at 6 min. Slight rash on hand. Complete relief at 8K on descent. No residual.
(4) Slight pain in right hand at 3 min. Pain increased to moderate and spread up arm at 6 min. Slight rash on hand. Complete relief at 8K on descent. No residual.

D = 110 fsw, T_1 = 28.75 min, T_2 = 27 min

Reference: NEDU V.54

Date	Dive #	Subject	Comments
8 July 59	5	CAR (1)	P.59, NEDU V.54
8	5	WLY (2)	P.61
8	7	GWI (3)	P.67
8	7	WIL	P.69
8	9	JAM (4)	P.75
8	9	WHI (5)	P.77
8	11	BRA (6)	P.83
8	11	AND (7)	P.85
8	13	MIC (8)	P.91
8	13	AVI (9)	P.93

Notes:

(1) Slight pain in right pectoral at 17 min. Lasted 1 min. Rash on right shoulder at 18 min persisted until after flight. No further symptoms. completed 27 min at 18K.

(2) Left forearm and elbow pain with deep mottled discoloration at 4 min. Also right forearm rash. Complete relief at 4K on descent.

(3) Pain in coccyx and numbness down both legs from hips to knees after 15 min. Symptoms improved during descent and were gone after 3 min at ground level.

(4) Moderate right shoulder pain at 15 min. Moderate right forearm pain increasing to severe at 17 min. Slight residual pain at ground level after descent. Gone in 7 min.

(5) Severe pain in right and forearm at 18 min. Relieved on arrival at ground level.

(6) Left pectoral pain at 5K on ascent. Pain gone after 4 min at 18K. slight left shoulder pain at 5 min which was severe and spreading at 7 min. Complete relief at 7K on descent.

(7) Slight right shoulder pain after 6 min. Increased to moderate at 11 min. Complete relief at 8K on descent.

(8) Slight sting in right knee at 19 min. Relieved at 17.5K on descent. No residual.

(9) slight right chest pain after 5 min. disappeared after 1 min but returned at 13 min (apparently after exercise) and persisted. Relief at 16K on descent.

D = 110 fsw, T_1 = 28.8 min, T_2 = 57 min

Reference: NEDU V.54

Date	Dive #	Subject	Comments
9 Sept. 59	18	JOS (1)	P.111, NEDU V.54
10	22	HUD (2)	P.119
14	24	VAI (3)	P.123
14	25	SIR (4)	P.125
15	26	ZAM	P.127
15	28	TRI (5)	P.131
16	30	DIM (6)	P.135

Notes:

(1) Right elbow pain at 1 min. Gone at 5 min. Left calf pain at 18 min moved to entire shin bone and became increasingly severe. complete relief at 7K on descent.

(2) slight right chest pain at 30 min. slight pain in left arm at 36 min, spreading and increasing to moderate. Rash spreading on chest and back. Sudden complete relief at 8K on descent. No residual.

(3) Slight right wrist pain at 18 min. Gone after 2 min. Reappeared after 2 min, increasing and spreading. Complete relief at 14K on descent. No residual.

(4) Slight right shoulder pain at 25 min, lasting for 10 min. completed 57 min at 18K with no further symptoms.

(5) Chest pain at 10K on ascent, spreading to neck and shoulder at 17K and became chokes. Complete relief at 11K on descent. No residual.

(6) Mild itching at 1 min. Slight right elbow pain at 10 mins, increasing to moderate and spreading up arm and shoulder. Relief at 7K on descent. No residual.

D = 125 fsw, T_1 = 28.8 min, T_2 = 27 min

Reference: NEDU V.54

Date	Dive #	Subject	Comments
8 July 59	4	WHI (1)	P.57, NEDU V.54
8	4	JAM (2)	P.55
9	6	BRA (3)	P.63
9	6	AND (4)	P.65
13	8	MIC (5)	P.71
13	8	ALV (6)	P.73
15	12	GWI (7)	P.87
15	12	WIL	P.89
16	15	CAR (8)	P.99
16	15	WLY (9)	P.101

Notes:

(1) Chest pain on arrival at 18K, gone after 3 min. Head pain and right forearm pain at 5 min, increasing to severe. Complete relief at 6K on descent. Pain recurred 5 hrs later. Treated successfully on Table II.
(2) Rash on back. Disappeared on descent.
(3) Shooting pain (location not specified) 8 min post-dive. On ascent at 9K, right chest and shoulder pain. Severe at 10K. decreased during descent. Asymptomatic after 4 min at ground level.
(4) Moderate to severe pain in right shoulder at 10K on ascent. Relief at ground level, but mottled rash persisted. Weakness, paresthesia, and anesthesia developed along distribution of radial nerve on right side. Relief at 100 fsw on recompression. Treated successfully on Table III.
(5) Right shoulder inkle at 7 min. slight right shoulder nd knee pain at 18 min. Pain radiated down right leg at 18 min. Severe pain at 26 min. Cleared at 13K on descent.
(6) Right ankle inkle at 4 min. Moderate pain in right knee at 24 min, increasing at 26 min. Relief at 12K on descent. Residual soreness during night.
(7) Slight right shoulder pain at 2 min, increasing to severe and spreading to elbow at 11 min. Relief at 4K on descent. slight residual at ground level cleared after 7 min.
(8) No symptoms but descended with partner after 5 min at 18K.
(9) chest pain at 3 min. Descended 2 min later. Recompressed for treatment but details unavailable.

Kiessling and Wood (1961); Logan (1961)

These studies were conducted during the same period with the same subjects. (Subject characteristics were given earlier. The Kiessling and Wood study was the second phase (after Kiessling and Duffner 1960) in the development of the altitude technique for evaluating decompression accuracy. Logan's study was an evaluation of whether oxygen behaves as an inert gas in causing decompression sickness (the Equivalent Air Depth theory).

Neither report contained enough information to reconstruct the results. Much of the missing information was found in archived dive logs at NEDU, but logs could not be located for some dives. Logs of unreported dives also were found including 22 helium-oxygen exposures. Subjects listed as "Control" completed the hyperbaric exposure but did not make the hypobaric exposure. Subjects reported symptoms during or after 102 of the 121 combined hyper/hypobaric exposures and after 25 of 140 "control" hyperbaric exposures.

Workloads

Subjects were at rest unless otherwise noted.

A. Alternate swimming and weightlifting at 10 min intervals. Swim with fins on a trapeze ergometer at an oxygen consumption of 1.2-1.5 lpm. This is equivalent to swimming at about 0.8 knots. Lift a 70 lb weight between a workbench and deck 10 times per minute. This is about 1750 ft lbs/min. The water temperature was 93°F ± 2°.
B. 5 knee bends and 5 pushups every 5 mins
C. 10 deep knee bends every 5 mins.

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	75 fpm		
D1	T_1	G_1 Note (a)	A
Compression	60 fpm		
D2	T_2	G_2 Note (a)	
Decompression	60 fpm		
.	.	.	
.	.	.	
.	.	.	
0 fsw	15 min	Air	
0 fsw	30 min		B
Ascent	6,000 ft/min	Air	
10,000 ft	-	O_2	
Ascent	6,000 ft/min	O_2	
18,000 ft	2 min	O_2	
18,000 ft	57 min	02	C
Descent	18,000 ft/min	O_2	
0 fsw	--	Air	

Note (a): Air if not otherwise noted in Results.

Results

D_1 = 30 fsw, T_1 = 179 min, G_1 = Air

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
29 Mar 60	34	AVI (1)	CAR	P.47, NEDU V.55
30	35	WIL	SIR	P.48
31	36	MAL (2)	BUL	P.49
1 Apr	37	JOS	ANG	P 50
8	42	GWI (3)	ZIE	P.51

Notes:

(1) Left knee pain at 40 min. Relief on descent at 16.5 K.
(2) Left tibia pain at 37 min. spread from calf to ankle and knee at 39 min. Relief at 13.5 K on descent.
(3) Right shoulder rash for 4 min at 7 min. No other symptoms. Completed 57 min at 18 K.

D_1 = 50 fsw, T_1 = 179.5 min, G_1 = 40.2% O_2 in N_2

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
4 Apr 60	38	MAL (1,2)	BUL (1)	P.52, NEDU V.55
5	39	JOS	ANG	P.53
6	40	AVI (3)	SIR	P.54
7	41	WIL	CAR	P.55
8	43	GWI (4)	ZIE	P.56, NEDU V.55; NEDU V.53, date 11 Apr

Notes:

(1) D_1 - 47 fsw, T_1 = 178.5 min, G_1=39.8% O_2 in N_2. Compression at 30 fpm.
(2) Right knee pain radiating down to ankle at 37 min. Pain under knee increased and calf pain ceased at 39 min. Relief at 12.5 K on descent.
(3) Right knee pain for 1 min at 28 min. Recurred at 53 min and persisted to 57 min. Relief at 8.5K on descent.
(4) Right knee pain at 38 min. Relief at 13.5K on descent.

D_1 = 90 fsw, T_1 = 29.0 min (no flight; no symptoms)

Reference: NEDU V.53

Date	Subject #1	Subject #2
13 Apr 60	JAM	AVI
13	BRA	VAI
14	CAR	SIR
14	WIL	GWI
21	AND	LIN
27	JOS	ANG
5 May 60	MIC	PAR

D_1 = 90 fsw, T_1 = 128.5 min
D_1 = 30 fsw, T_2 = 5 min
D_3 = 20 fsw, T_3 = 36 min
D_4 = 10 fsw, T_4 = 74 min

Reference: NEDU V.53

Date	Subject	Control
2 June 60	ANG (2)	AND (1)
6	ZEI (3)	MAL (1)
8	AND (4)	AVI (1)
9	MAL (5)	ZEI (1)
13	AVI (6)	BUL (1) (7)

Notes:

(1) No flight.
(2) slight pain in left elbow and right knee at 13 min. Elbow pain increased. Pain gone at 9.5 K on descent. Pain recurred in p.m. Partial relief at 22 fsw on recompression. Treated on Table II.
(3) Right leg pain just below knee at 10 min. gone after 1 min. Right thigh and left below pain at 13 min. Pain gone at 10 K on descent.
(4) Pain in both arms at 9 K on ascent. Pain gone at 4 K on descent.
(5) Ankle on inside of right thigh and right shoulder close to neck at 9 min. gone after 2 min. Pain in both knees at 36 min.
(6) Pain in both wrists and right forearm at 1 min. Pain increasing at 3 min. Pain gone at 6.5 K on descent.
(7) Rash on chest and back 3 hrs post-dive. Left shoulder pain 3-5 hrs post-dive. Complete relief at 28 fsw on recompression. Treated on Table II.

D_1 = 110 fsw, T_1 = 28.5 min

Reference: NEDU V.53

Date	Subject #1	Subject #2
15 Apr 60	WIL (1)	JAM (1)
18	CAR (1)	SIR (1)
18	BRA (1)	JOS (1)
18	GWI (1)	VAI (1)
25	AND (1)	JOS (1)
27	AVI (1)	MAL (1)
28	SIR (2)	GWI (1)
28	WIL	JAM (1)
29	CAR (3)	JOS (1)
3 May 60	GWI (1) (4)	SIR (1)
4	WIL (5)	JON (1)
4	JOS (6)	AVI (1)
9	AVI (7)	VAI (1)
16	BRA (8)	CAR (1)
18	VAI (9)	AND (1)
31	AND (10)	BRA (1)

Notes:

(1) No flight.
(2) Shortness of breath and coughing at 13 min. Relieved on descent at 10 K.
(3) Left elbow pain at 31 min. Posterior arm pain at 32 min. Relieved on descent on surface.
(4) Headache following dive. No dive. No treatment.
(5) Rash on right shoulder for 6 min at 9 min. Completed 57 min at 18 K.
(6) Slight itch on right hip at 1 min. Completed 57 min at 18 K.
(7) Left shoulder pain, itching, and discoloration at 17 K on ascent. Burning pain and rash after ascent. Relief at 60 fsw on recompression. Treated on Table II.
(8) Left arm pain upon arrival at 18K. Pain spread to chest at 2 min. Pain relived at 8.5 K on descent.
(9) Right shoulder pain at 23 min. Increasing at 27 min. Relieved at 13 K on descent.
(10) Right shoulder pain at 7 K on ascent. Relief at 3.5 K on descent.

$D_1 = 118$ fsw, $T_1 = 58.5$ min
$D_2 = 30$ fsw, $T_2 = 9$ min
$D_3 = 20$ fsw, $T_3 = 23$ min
$D_4 = 10$ fsw, $T_4 = 52$ min

Reference: NEDU V.53

Date	Subject	Control
14 June 60	ANG (2)	JAM (1)
16	JOS (3)	ZEI (1)
20	JAM (4)	JOS (1)
21	MAL (5)	VAI (1)
22	ZEI (6)	NAQ (1)
27	VAI (7)	SIR (1)
28	ANG (8)	NAQ (1)

Notes:

(1) No flight.
(2) Left shoulder pain at 2 min. Increasing. Relieved at 14 K on descent.
(3) Left shoulder pain at 0.5 min. Relieved at 6.5 K on descent.
(4) Left knee pain at 8 min. Left chest pain at 10 min. Knee pain relieved at 10 K on descent. Residual chest pain at the surface.
(5) Pain left side of neck just below ear at 15 min. Left elbow pain at 18 min. Pains gone at 9.5 K on descent.
(6) Deep right shoulder pain at 17 min. gone at 10 K on descent.
(7) Left wrist pain at 8K on ascent. gone at 2 K on descent. Deep right shoulder pain 1-2 hrs post-flight. Complete relief at 50 fsw on recompression. Treated on Table II.
(8) Pain in both wrists at 17.5 K. Relieved at 10 K on descent.

$D_1 = 125$ fsw, $T_1 = 28.3$ min

Reference: NEDU V.53

Date	Subject #1	Subject #2
19 Apr 60	JAM (1)	WIL (1)
25	GWI (1)	AVI (1)
2 May 60	BRA (1) (2)	MIC (1)

Notes:

(1) No flight.
(2) Right arm pain (shoulder to elbow) < 3.5 hrs post-dive. Partial relief at 100 fsw on recompression. complete relief at 165 fsw. Treated on Table II.

$D_1 = 127$ fsw, $T_1 = 28$ min, $G_1 = 39.6\%$ O_2 in N_2

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
24 Mar 60	29	JOS (1)	VAI	P.42, NEDU V.55
25	30	CAR (2)	AVI	P.43, NEDU V.55; NEDU V.53, date 24 Mar
25	31	SIR (3)	LIN	P.44, NEDU V.55
28	32	JAM	WIL	P.45
28	33	GWI (4)	BRA	P.46

Notes:

(1) Itching at 2 min. Left elbow inkle at 8 min. Elbow worse at 11 min. Relief at 9.5 K on descent.
(2) Rash left pectoral region at 19 min. Rash and pain spreading to left shoulder and collar bone. Relief at 7 K on descent. Residual pain and fatigue.
(3) Knee ache for 2 min at 53 min. No other symptoms. completed 57 min at 18 K.
(4) Left knee pain at 22 min. Relief at 13 K on descent.

$D_1 = 130$ fsw, $T_1 = 58$ min
$D_2 = 30$ fsw, $T_2 = 9$ min
$D_3 = 20$ fsw, $T_3 = 23$ min
$D_4 = 10$ fsw, $T_4 = 52$ min

Reference: NEDU V.53

Date	Subject	Control
24 May 60	MAL (2)	JAM (1)
25	VAI (3)	JOS (1)
26	ZEI (4)	JAN (1)
1 June 60	ZUG (5)	NAQ (1)
7	NAQ (6)	BUL (1)
23	BUL (7)	AVI (1)

Notes:

(1) No flight.
(2) Itching in both knees at 9 min. Right elbow pain at 13 min. Left knee pain at 15 min (started as an inkle). Elbow pain cleared at 11 K on descent. Knee pain gone at 9 K.
(3) Right wrist pain at 6 K on ascent. Gone at 2 K on descent.
(4) Ascent to 18 K took 5 min. right wrist pain after 4 min. Terminated flight. No further comments.
(5) Right knee pain at 28 min. Complete relief at 1 K on descent.
(6) Rash on back at 12 K on ascent. Rash gone at 18 K. Left wrist pain at 4 min. Increased. Right hand pain at 5 min. Relieved at 9.5K on ascent.
(7) Itch and rash on back at 1 min. Left elbow pain at 2 min. Pain gone at 5 K on ascent. Elbow pain recurred after about 1 hr. Complete relief at 30 fsw on recompression. Treated on Table I.

$D_1 = 130$ fsw, $T_1 = 58.5$ min
$D_2 = 30$ fsw, $T_2 = 9$ min
$D_3 = 20$ fsw, $T_3 = 23$ min
$D_4 = 10$ fsw, $T_4 = 52$ min

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
9 Mar 60	17	JAM (1)	JAN	P.30, NEDU V.55; NEDU V.53, date 10 Mar
14	18	LIN (2)	VAI (3)	P.31, NEDU V.55
15	19	JOS (4)	MAL (5)	P.32
17	23	SIR (6)	PAR (7)	P.36
23	28	GWI (8)	SMI (9)	P.41

Notes:

(1) Left knee pain at 2 min. Relief at 5 K on descent.
(2) Right shoulder and forearm pain at 7.5K on ascent. Right wrist and left biceps pain at 13.5 K on ascent. Wrist and biceps relief at 8.5 K on decent. Shoulder and forearm relief at 5.5 K.
(3) Questionable inkles during afternoon.
(4) Right neck itch at 9 min. Right knee pain and weakness at 16 min. Relief at 8.5 K on descent.
(5) Inkles in right hip post-dive in afternoon.
(6) Left thigh pain and slight rash at 5 min. Relief at 8.5 K on descent.
(7) Mottled blue-red rash across lumbar region and right shoulder pain upon surfacing from dive. Relief at 30 fsw on recompression. Treated on Table II.
(8) Right upper arm rash and itching at 4 min. Right elbow and shoulder pain at 6 min. No relieved by descent. Relief at 25 fsw on recompression. Treated on Table II.
(9) Marked post-dive fatigue. Lasted 24 hrs.

D_1 = 146 fsw, T_1 = 58 min, G_1 = 28.2% O_2 in N_2
D_2 = 30 fsw, T_2 = 9 min, G_2 = 28.2% O_2 in N_2
D_3 = 20 fsw, T_3 = 23 min, G_3 = 28.2% O_2 in N_2
D_4 = 10 fsw, T_4 = 52 min, G_4 = 28.2% O_2 in N_2

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
24 Feb 60	7	LIN (1)	VAI (2)	P.19, NEDU V.55
25	8	JAM (3)	JAN (4)	P.20
29	9	JOS (5)	MAL (6)	P.21
1 Mar 60	10	SIR (7)	SMI (8)	P.22
2	11	GWI (9)	PAR (10)	P.23; No flight for GWI

Notes:

(1) Right shoulder pain at 13 K on ascent. Relief at 5.5 K on descent. Mild right elbow pain after 45 min on surface which lasted about 20 min. Extreme fatigue during evening.
(2) Left elbow pain, left hand pain, and left shoulder itch 5 min post-dive. Relief at 18 fsw on recompression. Treated on Table I. Recurrence overnight. Relief at 165 fsw on recompression. Treated on Table III.
(3) Gradually increasing pain in 5th intercostal space on left at 3 min. Left shoulder pain at 9 min. Partial relief at 12 K on descent. Complete relief at surface. Extreme fatigue.

(4) Extreme fatigue 3 hrs post-dive.
(5) Inkle in left wrist on reaching 18 K. Gone after 3 min. Returned after 2 min. Right knee pain after 7 min at 18 K. Relief of knee and wrist at 10.5 K on descent.
(6) Inkles and rash during evening. "Should have ha Rx."
(7) Backs of both hands numb at 17 K on ascent. Pain in right forearm after 2 min. Numbness gone at 16K on descent. Pain gone at 10.5 K. No residual on surface.
(8) Extreme fatigue and inkles during evening.
(9) Right elbow pain 30 min post-dive. No weakness or sensory loss. No flight. Pain relieved at 18 fsw on recompression. Treated on Table I.
(10) Woke up with right elbow pain 20 hrs post-dive. Relief at 28 fsw on recompression. Treated on Table II.

D_1 = 160 fsw, T_1 = 27.75 min, G_1 = Air
D_2 = 30 fsw, T_2 = 2 min, G_2 = Air
D_3 = 20 fsw, T_3 = 11 min, G_3 = Air
D_4 = 10 fsw, T_4 = 25 min, G_4 = Air

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
7 Mar 60	12	NIC (1)	LIN	P.25, NEDU V.55
7	13	AVI (2)	CAR	P.26
8	14	SIR (3)	KIE	P.27
8	15	WIL	GWI	P.28
9	16	BRA (4)	POW (5)	P.29

Notes:

(1) Dull pain in right shoulder at 17 K on ascent. Pain gone after 1 min at 18 K. Pain returned with weakness at 5 min. Increased and radiated to forearm. Rash at insertion of deltoid. Relief at 13.5 K on descent.
(2) Left elbow pain at 6 min. Left shoulder pain at 7 min. Shoulder relieved at 11 K on descent. Elbow relieved at 10.5 K.
(3) Right shoulder pain at 3 min. Pain relieved at 7 K on descent.
(4) Right shoulder pain at 17 K on ascent. Relieved at 13.5 K on descent.
(5) Rash at left anterior base of neck 45 min post-dive. Left shoulder pain 1 hr post-dive. No neurological symptoms. Relief at 90-100 fsw on recompression. Treated on Table II.

D_1 = 160 fsw, T_1 = 27.75 min, G_1 = Air

References: NEDU V.53; NEDU V.54

Date	Subject	No Flight Control	Comments
8 Feb 60	JOS (1)	GWI (2)	P.175 NEDU V.54
8	MAL (3)	WIL	P.176
9	SIR (4)	AND (5)	P.177
9	CAR (6)	AVI (7)	P.178
10	AVI (8)	SIR	P.179
10	WIL	JOS	P.180
11	GWI (9)	CAR	P.181
15	JAN (10)	LIN	P.182
15	AND (11)	MAL (12)	P.183
16	LIN (13)	JAN	P.184

Notes:

(1) Mild pain in right knee at 19 min. Became worse over next minute. Relief at 9 K on descent. slight residual pain on surface.
(2) Upon surfacing from dive, had weakness and slight pain in right arm which lasted for 10 min.
(3) Pain at 17 K on ascent in back, shoulder, and chest. Relieved at 7.5 K on descent.
(4) Right shoulder pain at 12 min. Relieved at 10 K on descent.
(5) Right shoulder pain 2 min post-dive. Relief at 25 fsw on recompression - treated on Table I.
(6) Mild flash of pain in right knee during surface interval at 35 min. Upon arrival at 18 K, pain in chest and neck. Relived at 7 K on descent.
(7) Fatigue and itching 5 min post-dive. Itch lasted about 10 min.
(8) Rash and burning pain in left shoulder and chest after 1 min at 18 K. Radiating down arm at 4 min. Transient right wrist pain at 7 min. Left leg pain at 9 min. Left leg weakness at 11 min. Chest pain relieved at 9 K on descent. Leg pain relieved at 7 K. Residual shoulder pain and rash on surface. Pain relieved at 13 fsw on recompression. Rash gone at 50 fsw. Treated on Table I.
(9) Right knee pain at 24 min. Radiating to ankle at 27 min. Relief at 5.5 K on descent. Rash on back and left knee after surfacing.
(10) Slight pain in left knee at 43 min. Descent at 49 min with persistent pain. Pain gone after 7 min on surface.
(11) Pain in right shoulder at 2 min. Increasing and radiating to chest at 6 min. Partial relief at 5.5 K on descent. Complete relief immediately after surfacing.
(12) Pain between neck and shoulder on right 13 min post-dive. Relived at 25 fsw on recompression. Treated on Table I.
(13) Right shoulder pain at 5 min lasted for 8 min. At 45 min, pain below left buttock radiating to knee and ankle. Relieved at 10K on descent.

D_1 = 170 fsw, T_1 = 12.67 min

Reference: NEDU V.53

Date	Subject	No Flight Control	Comments
20 Apr 60	VAI (2)	SIR (1)	D_2 = 10 fsw, T_2 = 5 min
27	AND (3)	CAR (1)	D_2 = 10 fsw, T_2 = 5 min
10 May 60	JOS (4)	MAL (1)	
10	JAN (5)	MAL (1)	
11	SIR	AND (1)	
12	WIL (1)	AVI (1)(6)	
17	GWI (7)	SIR (1)	
19	MAL (8)	JOS (1)	
20	AND (1) (9)	JAN (1)	
23	AVI (1) (10)	WIL (1)	
17 Jun 60	CAR (11)	WIL (1)	
24	WIL	CAR (1)	

Notes:

(1) No flight.
(2) Transient right arm pain at 45 min. Gone at 52 min. completed 57 min at 18 K.
(3) Right arm pain and numbness and rash 32 min post-dive. Relief at 56 fsw on recompression. Treated on Table II.
(4) Deep left foot pain at 30 min. Gone at 33 min. Extensive rash on left shoulder at 38 min. Rash gone at 7 K on descent.
(5) Slight rash and itch on left leg at 50 min. Still present on surface. Completed 57 min at 18 K.
(6) Left hip pain at 60 min post-dive. Complete relief at 110 fsw on recompression. Treated on Table II.
(7) Right arm rash and itching at 8 K on ascent. pain in left hip at 14 K. Pain and rash on right elbow on descent to sea level. Complete relief at 85 fsw on recompression. Treated on Table II.
(8) Slight pain in chest on arrival at 18 K. Both arms itching at 1 min. Pain in chest and under breast increasing at 4 min. Pain gone at 14 K on descent.
(9) Right shoulder pain, rash on back within 23 min post-dive. Complete relief at 25 fsw. Treated on Table II.
(10) Right shoulder burning pain and rash 9 min post-dive. Complete relief at 28 fsw on recompression. Treated on Table II.
(11) Left temple pain at 15 min. Gone at 9.5 K on descent.

D_1 = 170 fsw, T_1 = 12.75 min
D_2 = 10 fsw, T_2 = 4.74 min

References: NEDU V.53; NEDU V.54

Date	Dive #	Subject	Control	Comments
25 Jan 60	1	SIR (1)	JAM (1)	P.154, NEDU V.54
25	2	WLY (2)	WIL	P.156
26	3	JOS	AVI	P.158
26	4	MAL	AND	P.160
27	5	CAR (3)	TRI	P.162
27	6	AVI (4)	GWI	P.164, V.54; V.53

Date	Dive #	Subject	Control	Comments
				date 28 Jan
28	7	WLY (5)	TRI	P.166
28	8	WIL	JOS	P.168
27	9	--	SIR	P.170; Flight aborted due to regulator malfunction
1 Feb 60	10	TRI (6)	SMI	P.172
3	11	JAM	CAR	P.173
3	12	GWI (7)	MAL	P.174

Notes:

(1) T_1=7.5 min. Compression rate about 23 fpm. No symptoms.
(2) Left shoulder pain at 11 min. Left elbow pain at 13 min. Relief at 10.5 K on descent.
(3) Right shoulder pain moving towards left shoulder on arrival at 18 K. Pain moving into back at 2 min. complete relief at 6.5 K on descent.
(4) Slight wrist pain at 16 min lasted for 5 min. No further symptoms. Completed 57 min at 18 K.
(5) Abdominal pain at 13 min. Increased at 16 min. Dizziness and extreme weakness at 19 min. Descended. No further comment.
(6) Slight forearm pain at 10 min lasted for 2 min. Inkles all over body. Completed 57 min at 18 K.
(7) Right wrist, elbow, shoulder pain at 9 min. Arm numbness at 13 min. Relief at 11 K on descent.

D_1 = 179 fsw, T_1 = 27.5 min, G_1 = 28.2% O_2 in N_2
D_2 = 30 fsw, T_2 = 2 min, G_2 = 28.2% O_2 in N_2
D_3 = 20 fsw, T_3 = 11 min, G_3 = 28.2% O_2 in N_2
D_4 = 10 fsw, T_4 = 25 min, G_4 = 28.2% O_2 in N_2

References: NEDU V.53; NEDU V.54

Date	Dive #	Subject	Control	Comments
16 Feb 60	1	AND (1)	GWI (2)	P.11, NEDU V.55; V.53 date 17 Feb
18	3	SIR (3)	MAL	P.15, V.55
19	4	BRA (4)	POW (5)	P.16
23	5	WIL (6)	STE (7)	P.17
23	6	CAR (8)	AVI	P.18

Notes:

(1) Deep muscular pain in left shoulder on arrival at 18 K. Rash over right shoulder and chest at 4 min. Relief at 14 K on descent. Itching on surface.
(2) Inkles during evening. No treatment.
(3) Numbness along ulnar distribution of right arm on arrival at 18 K. Shooting pain in right arm at 3 min. Relief at 5.5 K on descent. No residuals.
(4) Right shoulder pain on ascent from 20 to 10 fsw during dive. Pain reoccurred 22 min post-dive. Relieved at 10 fsw on recompression. Treated on Table II.
(5) Right shoulder and upper arm pain 16 hrs post-dive. Relief at 50-60 fsw during compression. Residual tenderness in shoulder at 165 fsw. Treated on Table II.

(6) Right wrist pain at 12 min. Left ankle pain at 15 min. Ankle pain relived at 14 K on descent. Wrist pain relieved at 11.5 K.
(7) Numbness in left jaw with decreased sensation to pin prick at jaw and ear 3.5 hrs post-dive. Recompressed to 165 fsw. Relief after a few minutes. Treated on Table III.
(8) Deep left elbow pain at 3 min. Partial relief at 9.5 K on descent. Complete relief at 6.5 K.

$D_1 = 190$ fsw, $T_1 = 12.3$ min, $G_1 = 28.3\%$ O_2 in N_2
$D_2 = 10$ fsw, $T_2 = 4.73$ min, $G_2 = 28.3\%$ O_2 in N_2

References: NEDU V.53; NEDU V.55

Date	Dive #	Subject	Control	Comments
15 Mar 60	20	GWI (1)	AVI (2)	P.35, NEDU V.55
16	21	JAM (3)	BUL	P.33, V.55
16	22	WIL	CAR	P.34
18	24	JOS (4)	MAL (5)	P.37
21	25	SIR (6)	KIE	P.38
21	26	MAL (7)	BUL	P.39
22	27	AVI (8)	CAR	P.40

Notes:

(1) Both hands itched during surface interval. Itching and inkles at altitude. Left elbow pain and rash with a feeling of needle pricks at 13 min. Pain gone at 7 K on descent. Rash persisted for a few minutes at surface. About 20 min after surfacing, mild elbow pain with motion.
(2) Post-dive itching.
(3) Fatigue and itching at altitude. Completed 57 min at 18 K.
(4) Itching and rash post-dive. Transient, sharp left elbow pain after 7 min at altitude followed by several minutes of moving inkles. Left elbow pain at 10 min. Partial relief at 14 K on descent. Complete relief at 11 K. Inkles during the evening.
(5) Inkles during the evening.
(6) Left knee pain (medial aspect) after 46 min at altitude lasted for 6 min. completed 57 min at 18 K.
(7) Itching, rash, momentary headache, and fatigue while at 18 K. Completed 57 min. Left hip pain during the evening.
(8) Pain inside right elbow at 21 min. Left knee and elbow pain at 24 min. Completed 57 min at 18 K. Relief of left knee pain at 8.5 K on descent.

$D_1 = 75$ fsw, $T_1 = 28.5$ min, $G_1 = 20.3\%$ O_2 in N_2

References: NEDU V.53; NEDU V.54

Date	Dive #	Subject	Comments
12 Oct 59	40	AND (1)	P.212, NEDU V.54
12	41	BRA (2)	P.214
13	42	AVI	P.216
13	43	DIM	P.218
14	44	WHI (3)	P.220
14	45	GWI (4)	P.222
15	46	MIC (5)	P.224
15	47	HUD (6)	P.226

Date	Dive #	Subject	Comments
20	48	WIL	P.228
20	49	JOS (7)	P.230

Notes:

(1) Right shoulder rash and itch at 35 min. Spreading at 41 min. Transient pains in right shoulder lasted 5 min at 42 min. No further symptoms. completed 57 min at 18 K. No residuals.
(2) Right shoulder pain at 10 min. Increased at 12 min. Relief at 12 K on descent.
(3) Right lateral knee pain at 9 min. Left shoulder pain at 13 min. Relief at 14 K on descent. No residual.
(4) Mild left shoulder pain at 8 min. Spreading to left elbow at 16 min. Relief at 7.5 K on descent.
(5) Right shoulder pain at 2 min. Moderate to severe and spreading fast. Relief complete at 14 K on descent. No residual.
(6) Slight right hand pain at 23 min. Increased and spread up arm at 39 min. Relief complete at 15.5 K on descent. No residual.
(7) Right arm pain at 10 min. Increased with weakness. Complete relief at 13.5 K on descent. No residual.

$D_1 = 90$ fsw, $T_1 = 28$ min, $G_1 = 20.5\%$ O_2 in He

References: NEDU V.53; NEDU V.54

Date	Dive #	Subject	Comments
29 Sept 59	31	AND (1)	P.192, NEDU V.54. Surface interval was 15 min not 45 min
30	32	BRA (2)	P.194. Surface interval was 15 min not 45 min
1 Oct 59	33	DIM (3)	P.196
1	34	AVI (4)	P.198
5	35	GWI (5)	P.200
5	36	GUD (6)	P.202. No flight.
6	37	JOS (7)	P.204. No flight.
7	37	WHI (8)	P206; Incorrect dive #. No flight.
7	38	MIC (9)	P.208
8	39	WIL (10)	P.210
21	50	AND (1)	P.232
21	51	BRA (12)	P.234

Notes:

(1) Very slight burning pain in chest at 8 K on ascent. Gone after switch to O_2 at 10 K. Itch on buttocks at 16 min. slight pain in stomach at 17 min. Increased to moderate and spread upwards towards chest. On descent to surface, complained of difficult breathing and sensations in throat. Relief at surface but pain returned. Relief at 75 fsw on recompression. Treated on Table II. No recurrences.
(2) Slight pain or burning in chest at 8 K on ascent. Pain relieved by 2 min of O_2 at 8 K. Ascent from 8 K to 18 K in 3 min. Slight chest pain after 6 min at 18 K. Gone in 2 min. Pain in right groin and

thigh at 13 min increasing with weakness. Relief at 8 K on descent. Dizzy on surface with slight right leg weakness. Complete relief at 15 fsw on recompression. Treated on Table II.

(3) Slight right knee pain at 37 min. Increased to moderate and spread down calf at 39 min. complete relief at 6 K on descent. No residual.
(4) Mild burning in right wrist at 17 min for several minutes. Came and went. Left hand pain at 34 min for 2 min. Left foot and armpit pain at 43 min. Remained until descent at 57 min. No residual.
(5) Strong inkle in right arm at 42 min Gone after 5 min. Completed 57 min at 18 K. No residual.
(6) Chest pain 17 min post-dive. Pain relived at 35 fsw on recompression. Treated on Table I.
(7) Right shoulder pain 21 min post-dive. Pain relived at 35 fsw on recompression. Treated on Table I.
(8) Left shoulder inkle 14 min post-dive. Increasing and spreading. Relied at 20 fsw on recompression. Treated on Table I.
(9) Left shoulder pain at 4 min. Increasing and spreading down arm. Relief at 16.5 K on descent.
(10) Right shoulder inkle at 22 min. Gone in 2 min. completed 57 min at 18 K without further symptoms.
(11) Left wrist pain at 15 min. Spreading and increasing to moderate. Relief at 10.5 K on descent. No residual.
(12) Left shoulder pain at 2 min. Increasing with rash. Relief at 13 K on descent.

Edel et al (1969)

This study conducted experiments from which to derive rules for flying in commercial aircraft after no-stop diving with compressed air. All exposures were conducted in dry chambers. Condition 2 was tested with and without work during the dive. It is of interest that resting subjects developed itching at altitude while working subjects did not itch.

Subjects

Name	Age	Height	Weight
EB	51	70 in	174 lbs
PE	39	66 in	131 lbs
JC	44	71 in	155 lbs
MC	21	71 in	150 lbs
VV	49	68 in	177 lbs
ES	42	69 in	145 lbs
FB	28	69 in	192 lbs
RR	22	73 in	170 lbs
BH	35	73 in	170 lbs
BM	31	72 in	148 lbs
DD	30	72 in	200 lbs

Workload
Subjects were at rest unless otherwise noted

A. Pull 70 lb elastic one foot 300 times during 15 min dive or lift 40 lb weight 1.5 feet 200 times. Some subjects did more work. Workload was determined to maintain heart rates at above 120 bpm.

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	Missing	Air	
D	T	Air	A
Decompression	Missing	Air	
0 fsw	SI	Air	
Ascent	1,000 ft/min	Air	
8,000 ft	112 min	Air	
Ascent	1,000 ft/min	Air	
16,000 ft	5 min	Air	
Descent	Missing	Air	
0 fsw	--	Air	

Condition #1: D = 120 fsw, T = 15 min

SI = 5 min

- 4 subjects completed the profile without symptoms
- 1 subject (name missing) had pain at 16,000 ft

SI = 30 min

- 5 subjects (PE, EB, EB, BH, FB) completed the profile without symptoms

Condition #2: D = 40 fsw, T = 200 min, no work

SI = 5 min

- JC and PE completed the profile without symptoms
- MC developed pain after 20 min at 8,000 ft. The pain regressed during the 112 min at 8,000 ft. Further decompression to 10,000 ft caused the pain to return, and the subject was recompresse to ground level. He had residual soreness for 24 hrs.
- VV developed pain upon arrival at 11,000 ft
- BH developed pain upon arrival at 14,000 ft. He had residual soreness for 24 hrs.
- EB had pain upon arrival at 16,000 ft
- All subjects had itching at altitude

SI = 30 min

- PE, JC, and BH completed the profile without symptoms.
- EB had pain at 16,000 ft
- 3 subjects had itching at altitude

SI = 1 hr

- JC and BH completed the profile without symptoms
- PE had pain on arrival at 16,000 ft. Residual pain next a.m.
- EB, who did not report pain at altitude, had residual pain in right knee at sea level
- 3 subjects had itching at altitude

SI = 2 hr

- JC, BH, and EB completed the profile without symptoms
- PE had pain on arrival at 16,000 ft
- 4 subjects had itching at altitude

SI = 3 hrs

- 6 subjects (EB, PE, JC, BH, MC, BM) completed the profile without symptoms
- 1 subject had itching at altitude

Condition #2: D = 40 fsw, T = 200 min, Workload A

SI = 5 min

- 5 subjects (PE, EB, BH, JC, FB) completed the profile without symptoms
- DD developed left elbow pain after 20 min at 8,000 ft but pain disappeared while at altitude. Just prior to further ascent he developed wrist pain and after ascent to 14,000 ft had to be recompressed to ground level.
- No subjects had itching at altitude

SI = 30 min

- PE and EB completed the profile without symptoms

Condition 3: D = 33 fsw, T = 24 hrs

SI = 2 hr

- PE developed severe pain in his left knee upon decompression to 8,000 ft. and was recompressed to ground level. The pain recurred within 4 hrs and persisted for 12 hrs before spontaneously subsiding.
- EB developed fleeting pain in both knees upon ascent to 8,000 ft but developed severe knee pain at 11,000 ft which required recompression to ground level.

SI = 5 hrs

- PE developed right knee pain at 4 hrs during the surface interval. The pain intensified upon further decompression to 5,000 ft. The subject was recompressed to ground level, but experienced little relief. The pain resolved with treatment on Table 5.
- EB developed right knee pain at 8,000 ft which disappeared in 1 hour. The pain increased during decompression to 11,000 ft and forced descent to ground level.

D = 30 fsw, T = 24 hrs, SI = 2 hrs

- BH and JC had no definable symptoms during the surface interval but both developed severe pain in the knees upon decompression to 8,000 ft. One was recompressed to ground level after 4 min and the other after 29 mins. Both subjects had recurrences within 3 hrs and were treated successfully on a Table 5.

Edel (1970)

The purpose of this study was to determine the interaction of repetitive hyperbaric exposures during simulated weightlessness training of astronauts and subsequent altitude exposure during air travel. The subject population is not described. All exposures were conducted in a dry chamber.

Workloads

Subjects were at rest unless otherwise indicated.

A. Lifted a 40 lb weight 1.5 ft from floor at regular intervals (240 times) during the 2 hrs at pressure.
B. Lifted a 5 lb weight 1.5 ft from the floor 240 times during the first 15 mins of altitude exposure in Series A and C and most of B.

Pressure Profile - Series A

Pressure	Time or Rate	Gas	Workload
Compression	47 fpm	Air	
47 fsw	120 min	Air	A
Decompression	24 fpm	Air	
0 fsw	SI	FO2	
Ascent	Missing	Air	
10,000 ft	120 min	Air	B
Descent	Missing	Air	
0 fsw	--	Air	

Results

SI = 30 min, F02 = Air
- 4 subjects completed profile with no incident.

SI = 2.5 hrs, F02 - Air
- 6 subjects completed profile with no incident

SI = 4 hrs, F02 = Air for 2 hrs and O2 for 2 hrs
- 6 subjects completed profile with no incident

Pressure Profile - Series B

Pressure	Time or Rate	Gas	Workload
Compression	47 fpm	Air	
47 fsw	120 min	Air	A
Decompression	24 fpm	Air	
0 fsw	180 min	Air	
Compression	47 fpm	Air	
47 fsw	120 min	Air	
Decompression	24 fpm	Air	
0 fsw	SI	F02	
Ascent	Missing	Air	
10,000 ft	120 min	Air	B
Descent	Missing	Air	
0 fsw	--	Air	

Results

SI = 5 hrs on air with no work at altitude
- 2 subjects completed profile with no incidents

SI = 4 hrs on air with no work at altitude
- 2 subjects completed profile with no incidents

SI = 4 hrs on air with Workload B
- 2 subjects developed pain within 30 mins at 10,000 ft. One had pain in the knees, the other had shoulder pain. Severe pain after 10 mins forced descent to ground level where subjects were symptom-free.

SI = 2 hrs on air and 2 hrs on oxygen by mask. Workload A at altitude.
- 10 subjects, no incidents

Pressure Profile - Series C

Pressure	Time or Rate	Gas	Workload
Compression	47 fpm	Air	
47 fsw	120 min	Air	A
Decompression	24 fpm	Air	
0 fsw	180 min	Air	
Compression	47 fpm	Air	
47 fsw	120 min	Air	A
Decompression	24 fpm	Air	
0 fsw	15 hrs	Air	
Compression	47 fpm	Air	
47 fsw	120 min	Air	A
Decompression	24 fpm	Air	
0 fsw	180 min	Air	
Compression	47 fpm	Air	
47 fsw	120 min	Air	A
Decompression	24 fpm	Air	
0 fsw	SI	FO2	
Ascent	Missing	Air	
A1	120 min	Note(a)	
Ascent	Note(b)	Note(a)	
A2	10 min	Note(a)	
Descent	Missing	Missing	
0 fsw		Air	

Note(a) - Air at 10,000 ft or less
- Oxygen above 15,000 ft.
- Between 10,000 ft and 15,000 ft, chamber air was breathed when the PIO2 was 110 mmHg or higher. Below this level, the subjects breathed 100% oxygen by mask (exhausting into the chamber) until the PIO2 rose above 110 mmHg.

Note(b) - Rate of ascent 5,000-10,000 ft/min.

Results

Series C-1 - (aborted after the second dive)
- 1 subject completed second dive without symptoms
- 1 subject noticed pain in right elbow 8 hrs after surfacing from second dive. Pain increased during next 7 hrs. slight relief on 02 at 60 fsw. Complete relief after 20 min on air at 165 fsw. Table 6A completed successfully.

Series C-2
SI = 5 hrs, F02 = Air, A1 = 10,000 ft, A2 = 20,000 ft
- 2 subjects completed the profile without symptoms
- 1 subject felt slight discomfort in right knee during decompression from 10,000 ft which became painful by 17,500 ft. Recompressed after 1 min at 17,500 ft. Symptoms relieved during descent.
- 1 subject developed pain in both shoulders at 17,500 ft. Recompressed after 1 min at 17,500 ft. Symptoms relieved during descent.

Series C-3
SI = 2 hrs, F02 = 02, A1 = 10,000 ft, A2 = 20,000 ft
- 3 subjects completed the profile without symptoms

- 1 subject noted pain in his right knee at 20,000 ft which increased in severity during 10 min. The symptoms resolved during recompression.

Series C-4
SI = 5 hrs, FIO2 = Air for 3 hrs and O2 for 2 hrs
A1 = 12,000 ft, A2 = 25,000 ft

- 3 subjects completed the profile without symptoms
- 1 subject had symptoms in his right thigh shortly after arrival at 25,000 ft. The pain increased while at 25,000 ft and resolved during descent to ground level.

Series C-5
SI = 5 hrs, F02 = Air for 3 hrs and 02 for 2 hrs
A1 = 15,000 ft, A2 = 25,000 ft

- 1 subject had right knee pain upon arrival at 15,000 ft which increased over 30 mins but disappeared during the next 90 mins. The pain recurred during decompression to 18,000 ft and became worse upon arrival at 20,000 ft. Symptoms resolved during descent.
- 1 subject developed pain during ascent from 15,000 to 20,000 ft. Symptoms resolved during descent.
- 1 subject had pain in both knees on arrival at 15,000 ft. The right knee pain increased over 5 min but disappeared during the rest of the time at 15,000 ft. The left knee pain increased during the first 90 min at 15,000 ft and remained constant for the remaining time at 15,000 ft. The pain disappeared during descent from 15,000 ft.
- 1 subject reported right thigh pain upon arrival at 15,000 ft. The intensity increased during the first hour and remained constant during the 2nd hour. Recompressed to ground level for companion's DCS and returned to altitude. Symptoms recurred at 20,000 ft and became worse at 25,000 ft where flight was terminated after 1 min. Symptoms cleared during descent.

Balldin and Borgstrom (1976)

This study evaluated the use precordial Doppler bubble detection at altitude. A hyperbaric exposure prior to the flight was used in 4 of 16 experiments. There were 5 male subjects between the ages of 23 and 27. The subjects rested during all exposures. There was an interval of at least 1 week between exposures. Each exposure was followed by a prophylactic hyperbaric oxygen period of 60 mins at 2.2 ATA. Any precordial bubbles remaining from the altitude exposure cleared after a few minutes at 2.2 ATA.

Profile 1

Pressure	Time or Rate	Gas
Ascent	Rate	02
Alt	120 min	02
Descent	~ 4,000 m/min	02
0 fsw	< 1 min	Air
2.2 ATA	45-60 min	O2

Results

Rate = 4,000 m/min, Alt = 8,000 m

- 5 subjects (ML, BL, MC, OH, GJ) completed profile without incident

Rate = 9,000 m/min, Alt = 9,000 m

- 4 subjects (BL, MC, OH, GJ) completed profile without incident
- ML had left arm pain after 12 min at altitude. The pain disappeared after 40 min at altitude

Rate = 5,750 m/min, Alt - 11,500 m

- 3 subjects (MC, OH, GJ) completed the profile without incident
- ML reported left arm pain after 27 min at altitude. The pain disappeared at 120 min during descent.
- BL reported left knee pain after 95 mins at altitude. Pain was relived during descent at 99 min.

Profile 2

Pressure	Time or Rate	Gas
Compression	1-2 min	Air
2 ATA	T	Air
Decompression	~ 1 min	Air
1 ATA	< 1 min	Air
Ascent	5,750 m/min	02
11,500 m	120 min	02
Descent	~ 4,000 m/min	02
1 ATA	< 1 min	Air
2.2 ATA	45-60 min	O2

Results

T = 30 min

- GJ completed profile without incident
- MC reported left wrist pain at 29 mins. Pain was relived upon descent at 35 min.
- OH reported right ankle pain at 30 mins. Pain was relieved upon descent at 35 min.

T = 45 min

- GJ reported left shoulder pain at 28 mins. Pain was relieved upon descent at 49 mins.

Balldin (1978)

This study investigated the influence of long surface intervals (12-24 hrs) on the incidence of DCS and precordial bubbles at the maximum cabin altitude (9,000 m) expected in fighter aircraft. There were 5 male subjects (pilots or divers) with a mean age or 32.4 yrs (range 27-37), height 180.6 cm (range 165-188 cm), and weight 76.4 kg (range 68-90 kg). Decompression sickness was confirmed by the disappearance of symptoms upon descent from altitude. Pain disappeared at 8,500 -6,000 m on descent.

Subjects

Name	Age	Height	Weight
CS	35	181 cm	72 kg
LP	34	165 cm	68 kg
BL	27	182 cm	74 kg
JO	37	188 cm	78 kg
BJ	29	187 cm	90 kg

Workloads

Subjects were at rest unless otherwise noted.

A. 75 watts of leg exercise on a dry bicycle ergometer for 2 mins of every 4 mins to simulate a swimming diver.

B. Pull a handle with a 6.6 kp force a distance of 0.75 m once per minute to simulate pilot activity.

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	TR	Air	
D	T	Air	A
Decompression	18 m/min	Air	
0 fsw	SI	Air	
Ascent	4,500 m/min	02	
9,000 m	120 min	02	B
Descent	~ 4000 m/min	02	
0 fsw	< 5 min	Air	
2.2 ATA	45-60 min	O2	

Results

D = T = TR = 0 (control flight)
- 4 subjects (LP, BL, JO, BJ) completed profile without incident.
- CS developed left hand pain after 75 min. The pain was vague and uncertain and almost disappeared while at 9,000 m.

D = 39 m, T = 10 min

SI = 12 hrs
- 3 subjects (LP, BL, BJ) completed the profile without incident.
- CS noted right upper arm pain at 14 mins. Pain was relieved upon descent at 15 min.
- JO noted right wrist pain at 22 min. Pain relieved upon descent at 33 min.

SI = 18 hrs
- LP completed the profile without incident.
- CS noted left hand pain at 55 mins. Pain relieved on descent at 62 mins.
- BL noted left upper arm pain after 14 mins. Relieved upon descent at 21 mins.
- JO noted right and left shoulder pain at 36 mins. Relieved on descent at 44 mins.
- BJ had left knee pain at 75 min. Pain relived on descent at 81 min.

SI = 24 hrs
- LP, BL, BJ completed profile without incident.
- LP had right shoulder pain at 70 mins, but symptoms were vague and uncertain and almost disappeared while at 9,000 m
- JO had left shoulder pain at 63 mins. Relieved on descent at 90 mins,.

D = 15 msw (2.5 ATA), T = 100 min

SI = 12 hrs
- LP, BL, BJ completed profile without incident.
- CS had left wrist pain at 14 mins. Relieved on descent at 22 mins.
- JO had left knee and right shoulder pain at 6 min. Relieved on descent at 8 mins.

SI = 18 hrs
- LP, BL, BJ completed profile with no incident.
- CS had left finger pain at 23 mins. Relieved on descent at 34 mins.
- JO had right hip pain at 39 mins. Relieved on descent at 48 mins.

SI = 24 hrs
- LP, BL completed profile with no incident.
- CS had foot pain at 70 min. Pain vague and uncertain and almost disappeared while at 9,000 m.
- JO had left knee pain at 23 mins. Relieved on descent at 28 mins.
- BJ had incipient chokes at 90 mins. Relieved on descent at 100 min.

Balldin (1979)

This study investigated the use of oxygen in the surface interval after diving to reduce the incidence of DCS and precordial bubbles during subsequent flight at the maximum expected fighter aircraft cabin altitude. There were 3 male subjects of ages 29, 35, and 38 years. all exposures were made in dry chambers. No flying or diving was allowed for one week prior to the experiments. Altitude exposure was followed by prophylactic hyperbaric oxygen at 2.2 ATA for 1 hour.

Subjects

Name	Age	Height	Weight
JO	38	188 cm	78 kg
BJ	29	187 cm	90 kg
CS	35	181 cm	72 kg

Workload

Subjects were at rest unless otherwise noted.

A. 75 watts of leg exercise for 2 of every 4 mins on a bicycle ergometer.
B. Pulled a handle 0.75 m with 6.6 kp force once per minute.

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	R	Air	
D	T	Air	A
Decompression	18 msw/min	Air	
745-759 torr	12 hrs	F02	
Ascent	4,500 m/min	02	
9,000 m	120 min	02	B
Descent	~ 4,000 m/min	02	
0 msw	< 5 min	Air	
2.2 ATA	60 min	02	

R = 13-19.5 msw/min, D = 39 msw, T = 10 min
FIO2 = Air for 12 hrs
- 1 subject (BJ) completed the profile without symptoms
- 1 subject (JO) developed right wrist pain after 22 min at 9,000 m. Pain resolved at 33 min upon descent.
- 1 subject (CS) developed upper right arm pain after 14 mins at 9,000 m. Pain resolved at 15 min upon descent.

FIO2 = Air for 10 hr. 55 mins, 02 for 1 hr, Air for 5 min
- 2 subjects completed the profile without symptoms.
- 1 subject (JO) developed left shoulder pain after 100 min at 9,000 m. Pain resolved at 110 min upon descent.

R = 7.5-15 msw/min, D = 15 msw, T = 100 min
FO2 = Air for 12 hrs
- 1 subject (BJ) completed the profile without symptoms
- 1 subject (JO) developed pain in his left knee and right shoulder after 6 mins at 9,000 m. Pain resolved at 8 min on descent.

- 1 subject (CS) developed pain in his left wrist after 14 mins at 9,000 ft. Pain resolved at 22 mins on descent.

FO2 = Air for 10 hr. 55 mins, 02 for 1 hr, Air for 5 mins

- 2 subjects completed the profile without symptoms.
- 1 subject (JO) developed left knee pain after 10 mins at 9,000 m. Pain resolved at 13 mins on descent.

Balldin (1980)

The objective of this study was to investigate the risks of flying at commercial aircraft cabin pressures after diving. Ten subjects participated in exposure which were separated by an interval of at least one week. All subjects received prophylactic hyperbaric oxygen at 2.2 ATA for 30-45 mins after the altitude exposure.

Workloads

Subjects were at rest unless otherwise noted.

A. Intermittent leg exercise on a bicycle ergometer. 75 watts of work for 2 min followed by 2 min of rest.
B. Arm exercise by pulling a handle with 6.6 kp, a distance of 0.75 m once per minute.

Subjects

Name	Age	Height	Weight
MS	25	170 cm	69 kg
TL	28	173 cm	72 kg
JE	30	188 cm	82 kg
LF	37	174 cm	70 kg
CR	45	176 cm	69 kg
IL	36	174 cm	68 kg
ES	33	172 cm	60 kg
PE	33	180 cm	74 kg
UL	22	179 cm	74 kg
JO	39	188 cm	78 kg

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	2-3 min for D=39 msw 1-2 min for D=15 msw	Air	
D	10 min for D=39 msw 100 min for D=15 msw	Air	A
Decompression	18 m/min	Air	
0 msw	3 hrs	Air	
Ascent	3,000 m/min	Air	
ALT	2 hrs	Air	B
Descent	Missing	Air	
Compression	~/min	02	
220 kPa	30 min	02	
Decompression	~/min	02	
0 msw	< 5 min	Air	
2.2 ATA	30-45 min	02	

Results

D = 15 msw
  ALT = 3,000 m
    - All 10 subjects completed profile without incident
  ALT = 2,000 m
    - JE, IL, ES, PE, and UL completed profile without incident.
    - CR had a vague feeling of dull discomfort in right elbow after 5-15 min. It gradually declined and vanished after about 100 min.
  ALT = 1,000 m
    - JE and IL completed profile without incident.
    - CR had the same symptoms as described above.

D = 39 msw
  ALT = 3,000 m
    - All 10 subjects completed profile without incident.
  ALT = 2,000 m
    - CR and IL completed profile without incident.
  ALT = 1,000 m
    - CR completed profile without incident.

Balldin and Sporrong (1980)

This study investigated the effects of vibration on the appearance of venous gas emboli during hypobaric exposure after hyperbaric exposure. There were no DCS incidents, and vibration did not significantly affect the appearance of venous gas emboli. the subjects were 10 male scuba divers between 18 and 38 years old (mean 28 ± 7 years). Mean height and weight were 184 ± 7 cm and 79 ± 10 kg.

Workload

Subjects were at rest unless otherwise noted.

A. Intermittent leg exercise on a bicycle ergometer. 75 watts of work for 2 min followed by 2 min of rest.

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression		Air	
15 msw	100 min	Air	A
Decompression		Air	
0 msw		Air	
Ascent		Air	
3,000 m	120 min	Air	
Descent		Air	
0 msw		Air	
200 kPa	30 min	02	

Results
- All 10 subjects completed the exposure without symptoms.

Bassett (1982)

The object of this study was to test the predicted exposure limits for no-stop dives which were immediately followed by altitude exposure. Some individual exposures were aborted earlier than planned because of precordial doppler bubble grades at altitudes that were felt to be excessively high. Two Flying After Diving (FAD) profiles were tested: FAD-I and FAD-II. There were at least 7 days between exposures for a given subject. All studies were conducted in a dry chamber at room temperatures. There were 59 male subjects with a mean age of 26.6 (SD - 6.4, range - 18-48) and mean percent body fat of 16.2% (SD = 5.1, range - 7.3-29.4%).

Workloads

Subjects were at rest unless otherwise noted.

A. Moderate step-test exercise for about half the exposure period except for the 1440 min saturation exposure.
B. Five minutes of each 30 mins stepping in place activity.

Subjects

Name	Age	Height (cm)	Weight (kg)	% BF
A5	40	185	75.1	11.8
A7	36	182	79.3	19.6
N12	43	173	81.8	28.5
N16	30	182	83.3	16.7
A9	33	188	85.4	12.9
N14	24	170	76.4	15.1
A13	23	174	68.5	17.9
AF17	24	183	72.6	12.4
AF19	20	187	75.6	13.7
AF20	31	176	88.4	18.4
N18	21	176	81.2	15.1
A15	48	173	78.3	24.8
AF2	27	177	83.7	17.4
N5	35	177	84.9	29.4
N6	36	180	85.7	23.0
A11	36	176	85.9	23.5
A12	38	172	770.3	21.5
AF13	28	187	76.3	11.9
AF15	23	181	79.9	14.3
N19	21	169	81.4	17.9
21	28	184	73.0	12.1
19	40	187	85.3	24.5
5	33	189	101.7	21.2
1	35	193	107.7	23.6
3	23	173	80.8	20.6
4	30	181	69.3	15.0
6	42	190	83.2	16.9
10	30	172	84.5	23.1
17	22	174	70.5	16.0
20	46	174	85.1	26.5

Name	Age	Height (cm)	Weight (kg)	% BF
22	45	184	73.7	9.4
26	38	184	86.6	22.1
28	33	176	68.7	16.8

Pressure Profile

Pressure	Time or Rate	Gas	Workload
Compression	60 fpm	Air	
D	T	Air	A
Decompression	60 fpm	Air	
0 fsw	1 min	Air	
Ascent	2,500 ft/min	Air	
A1	240 min	Air	B
Ascent	4,000 ft/min	Note(a)	
A2	60 min	Note(a)	
Descent	4,000 ft/min	Note(a)	
0 fsw	--	Air	

Notes : (a) Diluter-demand oxygen equipment. FI02 missing.

FAD-I Results (A1 = 10,000 ft, A2 = 16,000 ft)

D = 10.8 fsw, T = 1440 mins
- 17 subjects completed profile without incident.
- 2 subjects (AF19, AF20) descended after 240 mins at 10,000 feet due to VGE
- 1 subject (A5) developed left arm and shoulder pain after 22 mins at 16,000 feet. Flight aborted at 25 mins. Relief at 6,000 on descent.

D = 40 fsw, T = 34 min
- 16 subjects completed profile without incident.
- 1 subject (A13) descended after 240 min at 10,000 feet due to VGE.
- 1 subject (N12) reported left knee pain after 35 mins at 16,000 feet. Flight aborted at 45 mins. Relief at 10,000 feet on descent.

D = 60 fsw, T = 20 min
- 16 subjects completed profile without incident.
- 1 subject (A9) descended after 240 min at 10,000 feet due to VGE
- 1 subject (A7) reported pain in right leg above knee upon reaching 16,000 feet. Flight aborted after 7 mins at 16,000 ft. Pain relieved at 13,000 ft on descent.

D = 80 fsw, T = 14 min
- 12 subjects completed profile without incident
- 1 subject (A9) descended after 120 min at 10,000 ft due to VGE.
- 1 subject (N14) descended after 240 mins at 10,000 ft due to VGE.
- 1 subject (AF17) descended after 25 mins at 16,000 ft due to VGE.
- 1 subject (N16) developed pain in right thigh after 80 mins and pain in right knee at 90 mins at 10,000 ft. flight aborted at 90 mins. Pain relieved at 6,000 ft on descent.

D = 100 fsw, T = 14 mins
- 17 subjects completed profile without incident.
- 1 subject (N12) reported left knee pain after 50 mins at 16,000 ft. Pain relieved at 13,000 ft on descent.

D = 130 fsw, T = 7 mins
- 20 subjects completed profile without incident.

FAD-II Results (A1 = 8,500 ft, A2 = 14,250 ft)

D = 60 fsw, T = 20 mins
- 16 subjects completed profile without incident.
- 1 subject (5) descended after 23 mins at 14,250 ft due to VGE
- 1 subject (21) reported pain in left upper quadrant of chest along ribs after 25 mins at 14,250 ft. Relieved by 100% oxygen at ground level.

D = 80 fsw, T = 14 mins
- 19 subjects completed profile without incident.

D = 100 fsw, T = 10 mins
- 19 subjects completed profile without incident.
- 1 subject (19) descended after 15 mins at 14,250 ft due to VGE.

Buehlmann

Most of the dives which follow are previously unpublished in complete form.. Descent and ascent rates are 10 - 12 msw/min for the chamber dives. Descent times are included in the bottom time. During chamber dives, the subjects exercised on a bicycle ergometer. The breathing gas was air unless otherwise noted. The chamber temperature was 20-22°C and the workload 80 watts. Different subjects (both male and female were used for all dives. The chamber dives were conducted during 1971-1985 and the real dives during 1985-1986.

Chamber Dives. Series A

Depth (msw)	Time (min)	DCS/ Dives	Comments
30	73		Code AA-73.2
8	5		
7	5		
5	10		
3	35	1/16	Skin bends
41	80		Code AA-80
15	4		
12	11		
9	19		
6	33		
3	71	0/19	
30	320		Code AA-320.2
12	18		
10	25		
9	35		
7	50		
6	75		
5	100		
4	120		
2	120		
1	125	2/18	Mild knee pain 2-3 hrs post-dive. Gone 2-3 hrs. No therapy.
30	320		Code AO-320.2
15	5		O2
12	15		O2
9	25		O2
6	35		O2
3	90	1/19	02. Mild knee pain 2-3 hrs post-dive. Gone 2-3 hrs. No therapy.
20	300		50% 02-50% N2
3	1	0/21	Code NO-300 Water immersion
30	45		21% 02-79% He
30	75		Air
			Code CO-120.2
15	5		02
10	10		02
6	10		02
3	10	0/16	02
30	150		21% O2/79% He
30	150		Air
			Code CO-300.2
15	5		02
10	30		02
6	45		02
3	50	0/18	02

Chamber Dives. Series B.

Depth or Altitude	Time (min)	DCS/ Dives	Comments
41 msw	20		Code AA-20
6	3		
3	5		
0	40	0/16	
4,400 m	120	5/16	Itching & red spots. Disappeared at altitude
41 msw	30		Code AA-30
9	3		
6	5		
3	15		
0	40	0/16	
3,400 m	120	2/16	Itching & red spots. Disappeared at altitude
30 msw	120		Code AA-120
9	22		
6	38		
3	50		
0	60	1/16	Mild pain disappeared at altitude
1,450 m	120	6/16	
30 msw	120		Code A0-120
12	5		
9	29		
6	15		
3	7		
2,000 m	120	2/15	Mild knee pain. Disappeared at altitude.
20 msw	15		Code AA-60 St
26	15		
32	15		
38	15		
9	4		
6	13		
3	30		
0	40	0/16	
2,700 m	120	0/16	

Chamber Dives. Series B. (cont'd)

Depth or Altitude	Time (min)	DCS/ Dives	Comments
20 msw	20		Code AA-65 St
26	15		
20	15		
35	15		
6	7		
3	26		
0	60	0/16	
3,250 m	120	0/16	
31 msw	120		79% He-21% 02
15	10		02 Code BO-120
12	15		02
9	15		02
6	20		02
3	20		02
2,200 m	120	0/15	
42 msw	30		Code AA-30-2
12	3		
11	3		
9	5		
7	5		
5	5		
3	15		
1	20		
1,150 m	45	0/12	
3,200 m	180	0/12	
32 msw	60		Code AA-60.2
10	6		
7	6		
4	30		
1	38		
1,150 m	74	0/12	
3,200 m	120	0/12	
32 msw	120		Code AA-120.2
11	4		
9	10		
7	15		
5	20		
3	50		
1	75		
1,150 m	200	0/15	
3,200 m	180	1/15	Mild leg pain disappeared while at 3,200 m
0.967 BAR	5 days		AA-Sat
0.460 BAR	180 min	0/16	Workload at 0.46 BAR (6,200 m) was 125-200 watts.

Chamber Dives. Series C (Repetitive).
Ref: Buehlmann (1987)

Depth (msw)	Time (min)	DCS/ Dives	Comments
41	3		Code AA-13 Rpt.1
41-0	3.9		Ascent time
0	120	0/12	
41	60		
12	8		
9	15		
6	27		
3	51	2/12	Skin bends
35	18		Code AA-18 Rpt.1
35-0	3.3		Ascent time
0	30	0/12	
35	22		
3	13	1/12	Skin bends
32	20		Code AA-20 Rpt.1
32-0	3.0		Ascent time
0	10	0/15	
32	24		
6	2		
3	17		
0	20	0/15	
32	15		
3	15	2/15	Skin bends
44	35		Code AA-35 Rpt.1
12	2		
9	5		
6	11		
3	26		
0	90	0/20	
38	26		
6	3		
3	15		
0	90	0/20	
41	25		
6	4		
3	19	0/20	
44	37		Code AA-37 Rpt1
12	3		
9	5		
6	12		

Chamber Dives. Series C (Repetitive).(cont'd)
Ref: Buehlmann (1987

Depth (msw)	Time (min)	DCS/ Dives	Comments
3	28		
0	90	0/9	
38	25		
6	3		
3	12		
0	80	1/9	Skin bends
41	40		
12	2		
9	5		
6	17		
3	40	0/4	
41	40		Code AA-40 Rpt.1
12	2		
9	5		
6	13		
3	27		
0	120	0/24	
41	33		
12	2		
9	4		
6	6		
3	27	1/24	Significant shoulder and trunk pain 40 min post-dive. HBO treatment.

Chamber Dives. Series D.

Depth or Altitude	Time (min)	DCS/ Dives	Comments
37 msw	15		Code AA-15 Rpt.1
5	3		
3	4		
1	5		
1,000 m	8		
3,200 m	40	0/12	
37 msw	30		
11	5		
9	5		
7	5		
3	20		
1	20		
1,150 m	50		
3,200 m	120	0/12	
38 msw	20		Code AA-20.2 Rpt
7	5		
4	5		
2	5		
0	7		
2,600 m	45	0/12	
37 msw	25		
11	5		
9	5		
7	5		
5	5		
3	20		
1,150 m	50		
3,200 m	120	0/12	
37 msw	25		Code AA-25.2 Rpt
7	5		
3	7		
1	10		
1,150 m	29	0/11	
3,200 m	45		
37 msw	22		
5	5		
3	5		
1	8		
1,150 m	20		
3,200 m	180	0/11	

Chamber Dives. Series E.
Ref.: Buehlmann (1988)

Depth (msw)	Time (min)	DCS/ Dives	Comments
30	73		Code AA-73.1
8	5		
7	5		
5	10		
3	18	5/12	Skin bends
30	320		Code AA-320.1
12	18		
10	25		
9	35		
7	50		
6	75		
5	100		
4	120		
2	100	9/18	Knee or shoulder pain 1-3 hrs post-dive. Mild pain in 7 cases disappeared without treatment. Significant pain in 2

Chamber Dives. Series E.(cont'd)
Ref.: Buehlmann (1988)

Depth (msw)	Time (min)	DCS/ Dives	Comments
			cases treated by HBO
30	320		Code A0-320.1
15	5		O2
12	15		O2
9	25		O2
6	35		O2
3	75	5/16	O2 Post-dive pains. Mild pain in 7 cases. Significant pain in 3 cases treated with HBO
30	45		21% 02-79% He
30	75		Air Code CO-120.1
15	5		02
10	10		02
6	7		02
3	5	5/6	02
30	150		Air Code CO-300.1
15	5		02
10	30		02
6	45		02
3	30	2/4	02. Mild pains post-dive disappeared in 60 min
30	120		Code A0-120.1
12	5		02
9	20		02
6	10		02
3	2	3/8	02. Skin bends
30	150		Code AA-550.2
11	5		
9	30		
6	60		
3	70	4/12	Mild pain in knees or legs 1-3 hrs post-dive. No Rx.

Actual Dives at Altitude

F1. Lake Titicaca (3,800 m; 0.633 BAR)

No-stop dives made in 1987 by 17 British divers (Capt. M. Moody, Royal Marines, expedition leader) who were adapted (equilibrated) at altitude before diving began. All dives were on air. There were no incidents of decompression sickness.

Depth (mfw)	Time (min)	DCS/ Dives
9	204	0/40
12	88	0/32
15	76	0/38
18	43	0/6
21	28	0/41
24	18	0/25
30	12	0/14
36	9	0/11
39	8	0/3

F2. Lake di Lucendro, Switzerland (2,130 m; 0.783 BAR)

All dives were on air. The divers ascended from 500 to 2,130 m in 1-2 hrs and remained at 2,130 m for at least 2 hrs before diving. After surfacing, they remained at 2,130 m for 2 - 3 hours

Depth (mfw)	Time (min)	DCS/ Dives
15	30	
2	1	0/3
24	7	
2	1	0/2
27	17	
2	1	0/3
30	16	
4	5	
2	9	0/3
32	15	
2	1	0/4
33	18	
2	1	0/3
36	16	
2	4	0/6

F3. Lake Silvaplana, Switzerland (1,800 m; 0815 BAR)

All dives were on air. The divers remained at 1,800 m for 2 hrs before diving. After surfacing, the divers remained at 1,800 m for 2 - 3 hours.

Depth (mfw)	Time (min)	DCS/ Dives
16	50	
2	5	0/3
20	30	
2	1	0/2
24	23	
2	1	0/4
27	17	
2	1	0/10
27	35	
4	2	
2	13	0/4
30	16	
2	1	0/1
30	20	
2	4	0/15
30	25	
4	2	
2	6	0/12
30	30	
6	1	
4	4	
2	11	0/4
32	15	
2	1	0/3
43	20	
4	2	

Depth (mfw)	Time (min)	DCS/ Dives
2	5	0/6
33	13	
2	1	0/6
35	20	
6	3	
4	5	
2	12	0/2
36	16	
2	1	0/4
36	20	
4	4	
2	6	0/6
39	9	
2	1	0/2
39	15	
4	2	
2	4	0/4
39	18	
6	2	
4	3	
2	6	0/4
39	20	
2	4	0/2
42	21	
9	3	
6	3	
4	5	
2	14	0/5
48	10	
6	3	
2	7	0/2
48	18	
9	4	
6	3	
4	4	
2	14	0/2
47	10	
4	1	
2	4	0/2
51	15	
9	2	
6	3	
4	4	
2	10	0/4
53	10	
6	1	
4	3	
2	4	0/2

F4. Lake di Lucendro, Switzerland, 1988 (2,130 m; 0.783 BAR)

All dives on air. Subjects remained at 2,130 m for 2 - 3 hours before diving. Subjects were 13 men and 2 women.

Depth (mfw)	Time (min)	DCS/ Dives
17	15	
2	1	0/2
32	10	
2	1	0/4
41	11	
2	1	0/2
42	14	
2	2	0/3
42	8	
2	1	0/2
43	15	
2	2	0/2

F5. Lake Muttsee, Switzerland, 1988 (2,450 m; 0.747 BAR)

Repetitive air diving. Subjects (48 male, 11 women) equilibrated at 2,450 m for 18 hours before diving.

Depth (mfw)	Time (min)	DCS/ Dives
39	15	
4	2	

2	6	
Depth (mfw)	Time (min)	DCS/ Dives
0	215	0/2
33	18	
4	2	
2	4	0/2
39	21	
4	2	
2	4	
0	190	0/2
33	18	
2	2	0/2
33	21	
2	3	
0	254	0/3
45	13	
6	2	
4	4	
2	4	0/3
39	18	
4	2	
2	3	
0	246	0/2
45	10	
4	1	
2	3	0/2
42	18	
6	2	
4	3	
2	4	
0	246	0/2
48	10	
6	1	
4	1	
2	2	0/2
45	15	
4	2	
2	3	
0	246	
39	12	
4	2	
2	3	0/4
45	18	
6	2	
4	4	
2	4	
0	277	0/4
42	13	
4	3	
2	4	0/2
51	15	
6	2	
4	3	
2	4	
0	202	0/2
57	8	
6	2	
4	3	
2	3	0/2
57	12	
6	2	
4	3	
2	3	
0	210	0/2
60	11	
9	4	
6	3	
4	4	
2	8	0/2
60	15	
9	4	
6	3	
4	4	
2	8	
0	180	0/2
60	8	
9	1	
6	2	
4	3	
2	4	0/2
39	25	
6	3	
4	5	
2	7	
0	103	0/6
33	25	
4	3	
2	5	4/5