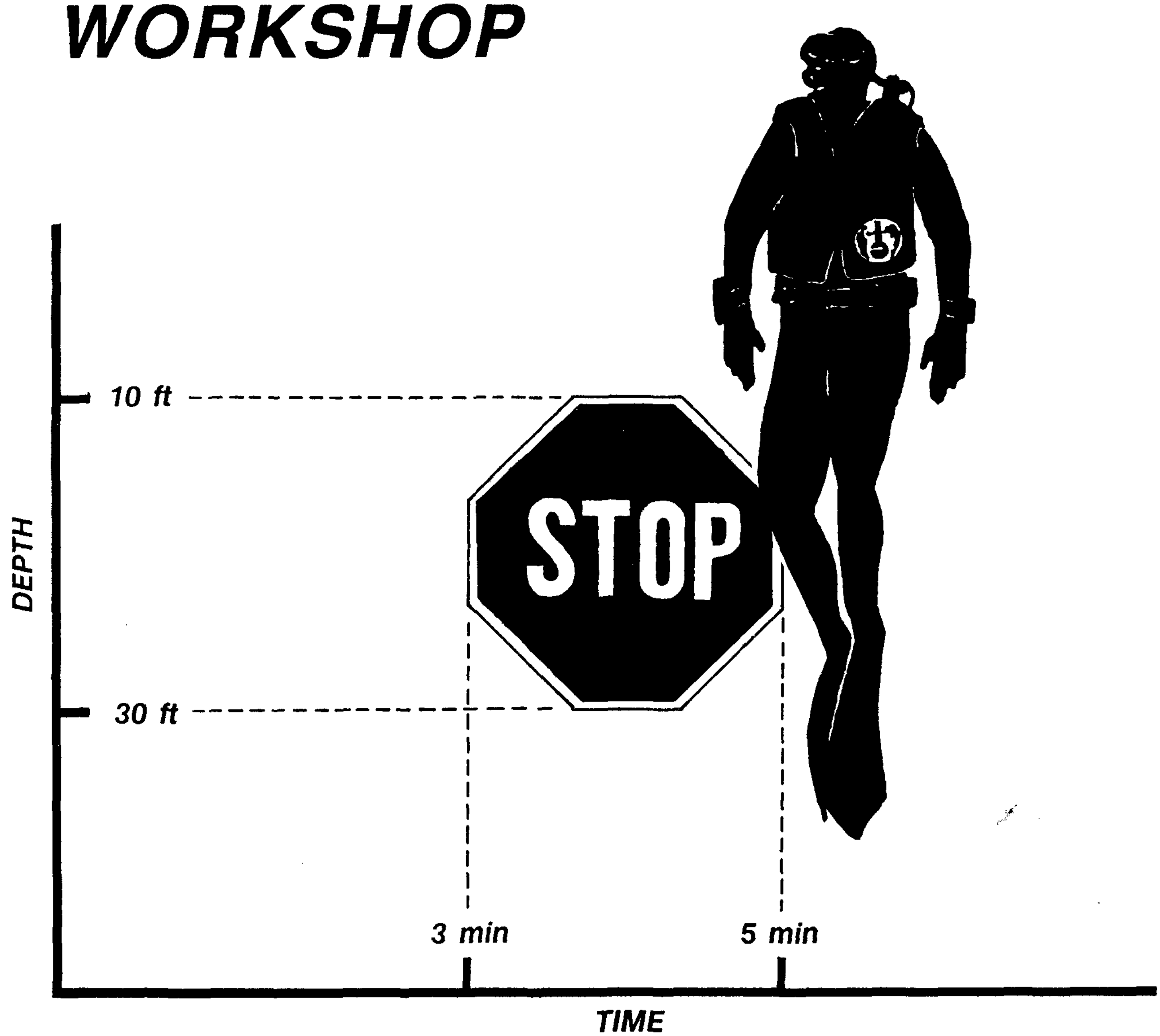
PROCEEDINGS OF

BIOMECHANICS OF SAFE ASCENTS WORKSHOP



AMERICAN ACADEMY OF UNDERWATER SCIENCES

September 25 - 27, 1989
Woods Hole, Massachusetts

Proceedings of the AAUS
Biomechanics of Safe Ascents Workshop
Michael A. Lang and Glen H. Egstrom, (Editors)

947 Newhall Street
Costa Mesa, CA 92627

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PROCEEDINGS OF
THE AMERICAN ACADEMY OF UNDERWATER SCIENCES

BIOMECHANICS OF SAFE ASCENTS WORKSHOP

WHOI / MBL
Woods Hole, Massachusetts

September 25 - 27, 1989

MICHAEL A. LANG

GLEN H. EGSTROM

Editors

American Academy of Underwater Sciences
947 Newhall Street, Costa Mesa, California 92627 U.S.A.

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Preface

The third major AAUS Workshop addresses the complexities of safe ascent rate. The information contained in this monograph is the result of the combined efforts of nearly fifty nationally recognized experts drawn from a variety of fields related to diving. The papers and discussions reflect some differences of opinion with regard to the options available to the diver when ascending from a dive. The message from these experts is, however, quite clear. There is a risk associated with ascending to the surface following a dive that can be minimized for the diver who will learn to exercise control over the buoyancy characteristics of the equipment in order to be able to make a stop 15-20 feet from the surface with ascent rates not in excess of 60 feet per minute. Once again, we are indebted to a group of dedicated professionals who gave of their time and energy to develop a position statement that represents the state of the art with regard to the understanding of the importance of controlling ascent rate. As a result of this workshop we have a clearer understanding of the known and the unknown that should provide guidance for our training programs and challenges for our researchers.

A very special thanks to our hosts Terry Rioux at the Woods Hole Oceanographic Institution and Anne Giblin at the Marine Biological Laboratory who provided an outstanding facility for the workshop and to Mike Lang who has pulled mightily on the oars to insure that the proceedings are not delayed on their path to the diving public.

Glen H. Egstrom, Ph.D.
President,
American Academy of Underwater Sciences

About AAUS

The American Academy of Underwater Sciences (AAUS) is a non-profit, self-regulating body dedicated to the establishment and maintenance of standards of practice for scientific diving. The AAUS is concerned with diving safety, state-of-the-art diving techniques, methodologies, and research diving expeditions. The Academy's goals are to promote the safety and welfare of its members who engage in underwater sciences. These goals include:

* To provide a national forum for the exchange of information in scientific diving;
* To advance the science and practice of scientific diving;
* To collect, review and distribute exposure, incident and accident statistics related to scientific diving;
* To promote just and uniform legislation relating to scientific diving;
* To facilitate the exchange of information on scientific diving practices among members;
* To engage in any or all activities which are in the general interest of the scientific diving community.

Organized in 1977 and incorporated in 1983, the AAUS is governed by a Board of Directors. An Advisory Board of past Board of Directors members provides continuity and a core of expertise to the Academy. Individual membership in AAUS is granted at the Member, Associate Member, and Student Member categories. Organizational membership is open to organizations currently engaged in scientific diving activities. Maintenance of membership is dependent on a continued commitment to the purposes and goals of the Academy, compliance with the reporting requirements and payment of current fees and dues.

* For the diving scientist, AAUS provides a forum to share information on diving research, methodologies and funding;
* For the diving officer, AAUS provides an information base of the latest standards of practice for training, equipment, diving procedures and managerial and regulatory experience.
* For the student, AAUS provides exposure to individuals, agencies and organizations with on-going programs in undersea research.

Scientific diving means diving performed solely as a necessary part of a scientific activity by employees whose sole purpose for diving is to perform scientific research tasks. Scientific diving does not include tasks associated with commercial diving such as: rigging heavy objects underwater, inspection of pipelines, construction, demolition, cutting or welding, or the use of explosives.

Scientific diving programs allow research diving teams to operate under the exemption from OSHA commercial diving regulations. This reduces the possibility of an OSHA fine and some concern regarding civil liability. Civil suits examine whether the "standards of practice of the community" have been met. Diving programs which conform to AAUS standards reflect the standard of practice of the scientific diving community and allow divers from different institutions to perform underwater research together. This reciprocity between programs is the product of years of experience, trust and cooperation between underwater scientists.

EXECUTIVE SUMMARY

The Biomechanics of Safe Ascents represents the combined effort of a group of selected experts in diving physics, physiology, equipment and training to address questions associated with diver ascent rates. There was consensus that there is a risk to the diver. In recent years the advent and increasingly wider use of dive computers, which require a variety of ascent rates, to assist divers in making safe ascents, has lead to a basic question. What is a safe and reasonable ascent rate?

The traditional ascent rate of 60 ft/min is based upon the United Sates Navy tables. Presentations by formulators of the original United States Navy tables indicate that this rate was a operational compromise between the fastest rate a hard-hat diver could be physically hauled to the surface, and the fastest rate a free swimming diver could swim to the surface. It also represented an ascent rate of 1 ft/min which could easily be calculated by the diver and surface tenders.

Dissolved and free gases within tissues do not behave in the same manner. Models indicate that bubble formation within tissues is initiated at micronuclei. The size and behavior of these bubbles is determined by the degree of saturation and the rate of ascent. A slow ascent rate has the advantage of maintaining the micronuclei under pressure, but has the disadvantage of slowing the diffusion of nitrogen from the tissue. The "staged" diver ascent - a relatively rapid ascent punctuated by stops at progressively shallower depths - approximates the ideal profile of a gradual but continuously decreasing pressure. The objective of such a protocol is to allow time for gasses to escape via the lungs and avoid supersaturated conditions which lead to the formation of bubbles in the blood or tissues. However, testing of human subjects has shown that dives conforming to U.S. Navy "no-decompression" limits produced bubble nuclei in all subjects after all dives. The occurrence of these "silent bubbles" was almost eliminated when divers stopped at depths of 20 to 10 feet for 1 to 2 minutes.

All of the data presented indicated that slower ascent rates decreased the likelihood of bubble formation and that a shallow stop for a short period of time significantly decreased the risk of pressure related injury.

Studies showed divers rarely ascend at rates as low as 60 ft/min. In practice, divers generally cannot recognize an ascent rate of 60 ft/min, and too frequently relied on equipment to replace adequate training in buoyancy control. The control of buoyancy is imperative in attaining and maintaining a predetermined rate of ascent. Tests of scuba divers with fully inflated buoyancy compensators showed rates of ascent ranging from 68 to 150 ft/min at depths of approximately 10 feet, and increased to a maximum of more than 250 ft/min in the last 4 feet of the ascent.

The technique of buoyancy control in wet suits or dry suits is exactly the same, that is proper weighting and the adding or expelling of air to remain in neutral trim. Training is required to reach and maintain a degree of proficiency. In dry suits an automatic exhaust valve located in the upper portion of the torso is recommended. In wet suits added emphasis must be placed on training the individual diver to recognize the importance of proper weighting and maintenance of control of buoyancy. In addition buoyancy compensators should be equipped with a rapid exhaust valve that can be activated in the horizontal swimming position.

In the examination of the records of hundreds of cases recompression treatment for pressure related injuries, approximately half were related to loss of buoyancy control. At present, it would appear that divers do not have adequate equipment or training to allow them to effectively monitor and control their ascent.

In summary, it has long been the position of the American Academy of Underwater Sciences that the ultimate responsibility of diver safety rest with the individual diver. Divers are encouraged to slow their ascents.

SAFE ASCENT RECOMMENDATIONS

1. Buoyancy compensation is a significant problem in the control of ascents.

2. Training in, and understanding of, proper ascent techniques is fundamental to safe diving practice.

3. Before certification, the diver is to demonstrate proper buoyancy, weighting and a controlled ascent, including a "hovering" stop.

4. Diver shall periodically review proper ascent techniques to maintain proficiency.

5. Ascent rates shall not exceed 60 fsw per minute.

6. A stop in the 10-30 fsw zone for 3-5 min is recommended on every dive.

7. When using a dive computer or tables, non-emergency ascents are to be at the rate specified for the system being used.

8. Each diver shall have instrumentation to monitor ascent rates.

9. Divers using dry suits shall have training in their use.

10. Dry suits shall have a hands-free exhaust valve.

11. BC's shall have a reliable rapid exhaust valve which can be operated in a horizontal swimming position.

12. A buoyancy compensator is required with dry suit use for ascent control and emergency flotation.

13. Breathing 100% oxygen above water is preferred to in-water air procedures for omitted decompression.

Acknowledgments
Michael A. Lang
Workshop Co-Chair
1989 AAUS Symposium Chair

I want to specifically thank a number of people right now. First, the speakers for preparing their presentations and sharing their knowledge and insight with the workshop. In addition, I extend an extra measure of appreciation to those speakers who provided me with a hard copy and floppy disk of their paper. It speeds up the compilation and editing of these workshop proceedings tremendously. We foresee a three months turn around time for this document, which should be available for distribution at the DEMA Trade Show in Orlando, Florida, January 18-21, 1990.

I also thank the participants for their useful input and discussions. Very special thanks goes to the scuba equipment manufacturers representatives: Dick Long (DUI), Bill Oliver (SeaQuest), Mark Walsh (Dacor Corp.), John Lewis (DC's: US Divers, Oceanic), Doug Toth (ScubaPro), Ron Coley (Suunto/SeaQuest), Bob Stinton (DUI), Karl Huggins (ORCA-Edge). These companies and individuals have been very supportive over the years of the AAUS efforts to increase diving safety. Thanks to Terry Rioux (WHOI) and Anne Giblin (MBL) for making the local arrangements.

Compiling these proceedings and transcribing and editing the recordings was a monumental, non-salaried effort. I wish to thank Maria, Michelle, Nicole and Sergio Lang for their patience and support, and understanding for the many hours spent away from them, locked up in the office. For this and other scientific diving projects, I very much appreciate the encouragement and support of Don Short, Bruce Wingerd and the SDSU Diving Control Board.

The following sponsors of the Biomechanics of Safe Ascents Workshop had the foresight and support, and contributed funds to make this meeting possible:

- The American Academy of Underwater Sciences
- Diving Equipment Manufacturer's Association
- National Oceanic and Atmospheric Administration

Finally, I thank Glen Egstrom, AAUS President and Workshop Co-Chair, for his efforts and thorough insight into the diving safety problems facing the diving community today.

WELCOMING ADDRESS

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On behalf of the American Academy of Underwater Sciences, I welcome you to Woods Hole, Massachusetts, the Woods Hole Oceanographic Institution, the Marine Biological Laboratory and the *Biomechanics of Safe Ascents Workshop*. This workshop is the third in the series of AAUS Diving Safety Workshops. The first workshop was held in November 1987 at the University of Washington, Seattle, and focused on cold water diving methods, equipment, physiology and specialized training considerations. The second workshop was convened in September 1988 at the USC Catalina Marine Science Center addressing dive computer procedures, guidelines for use and the underlying principles and algorithms. This year we aim to enhance our efforts to increase diving safety in general and specifically examine ascent rates: physics, physiology, training and equipment involved in bringing a diver to the surface.

The self-introduction of invited speakers, workshop participants, and their affiliations acquainted the workshop with the workshop attendees. A brief program overview was followed by administrative comments regarding workshop logistics and proceedings.

The following sponsoring agencies have made this workshop and the dissemination of the resulting information to the diving public possible:

- American Academy of Underwater Sciences (AAUS)
- Diving Equipment Manufacturers Association (DEMA)
- National Oceanic and Atmospheric Administration (NOAA).

BIOMECHANICS OF SAFE ASCENTS WORKSHOP INTRODUCTION

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It is really a pleasure to be here and once again see that the American Academy of Underwater Sciences was able to mount an effort to deal with a problem that is both timely and important. I am reminded of a couple of things that have happened in the past. One is a quote that has become somewhat famous and is attributed to Jim Stewart who, when observing about meetings of this sort said that frequently you get more information over a cold beer in the dark of night than you do from the deliberations of the day. I hope you recognize that this is not a workshop that is limited just to the structure of this particular program, but that hopefully we will have an opportunity for people with similar interests to be able to discuss these topics at length and with all candor. I am also reminded of another quote where an individual made the observation that he had never encountered a problem, however complicated, which, when viewed in the proper perspective, didn't become more complicated. I really think that is part of the problem of what we are running into, because when most of us in this room were trained as divers, life was really pretty simple. We had one set of dive tables to contend with and they came from the bible, the U.S. Navy Diving Manual. We had one ascent rate if you didn't read through the entire document too carefully. Reading more in-depth reveals that perhaps there were some considerations for some other ascent rates, but it was always "ASCEND NO FASTER THAN 60 FEET PER MINUTE", which was somehow equated with the small bubbles, smaller bubbles, smallest bubbles, or the person's best guess as to what that all amounted to.

One of the other things I believe we need to be aware of is an observation that was made by Einstein who said: "you should always try to make things as simple as possible, never simpler". Our major concern at this meeting is that when we start to put all of this information together, that we are, in fact, not only going to try to make it as simple as possible, but are also going to have readily aware that what we are doing is probably going to have a significant impact on what will take place within the instructional and possibly even the scuba equipment design communities as they are involved in our underwater activities.

These are not simple issues. Regarding this whole notion of ascent rates, if we could just belt out a number and walk away from it, we wouldn't have to have this kind of a workshop. What has taken place then is that we have been charged over the next two and a half days with trying to clarify the issues regarding the rate of ascent, in order to determine if it makes a difference if we come up faster, slower or at the rates of speed that divers are currently using. We are going to become familiar to a degree with the mechanics of bubble growth and formation, and how these processes act, in a manner that we have not been exposed to before. Most of us have some generic sense of what bubbles are and what they do, but, in fact, when looked at by the people who really have that particular insight, it is not a simple issue.

We also are going to be pressed to consider rationally the risk factors that are involved because this is certainly where the game is being played today. We, as a group of scientific divers and scientists who are interested in the issue of health and safety, are hard pressed to be able to objectify all of the kinds of risks that are involved in our particular sport. I think we do a better job than most, but in fact I believe that sometimes we have not, perhaps, paid as close attention as we should to some topics. To other notions we have paid too much attention because there is a significant body of myths that is operational. I hope that we can factor out some of the myths, so that we can go away from Woods Hole with a perspective that is going to be helpful to us all.

Basically, what we are charged to do is to try to quantify what we know and identify what we don't know so that we can start to make progress in that direction. We will, in this workshop, as I believe we did in the AAUS Dive Computer workshop last year, establish a state-of-the-art, if you will. In other words, at this point in time, this is what we know and understand and this is how we believe that it should be used in the best interests of our sport and our industry. Today we are going to have a rare opportunity to be able to get some historical perspective that I suspect could not be given by anyone other than Dr. Lanphier. We are going to have the opportunity to be able to get insight into the mechanics of bubbles, what they do and how they operate. We are going to be able to have discussions that will relate to the equipment issues that impinge on this particular type of phenomenon, as well as the training issues with which the majority of the people in this room are very concerned.

I do make the observation again that when most of us started diving, life was really simpler. I recall fondly the resistance that Jim Stewart had to adding any kind of flotation to a diver. If you needed flotation, you would blow in your sleeve and catch the bubble up in between your shoulder blades, which actually works just fine as long as you stay in the horizontal position. The question was: "What are the tradeoffs associated with this additional equipment that you wear and is buoyancy compensation really necessary?" We have gone through a period of being concerned only with the business at hand, and as a result, we now have gotten to the point where the envelope that the diver occupies in the water column has grown larger and larger. A good portion of that envelope is associated with a variety of gas containing equipment items (*i.e.* BC's, thermal protective suits, etc.) Within this problem area we have seen a growing concern for the kinds of problems that are going to be associated with ascent.

What I would also like to see come from this workshop is really an issue of some magnitude, which is: "What are the optimal ascent rates for people that are involved in our particular area of endeavor?" In other words, how fast should divers come up? "What are the tradeoffs if they come up at unacceptable rates of speed?" I believe that we are going to have a good deal of illumination in this area and for those of us who have been making some statements for years, we may have to change those as a result of the interface with facts.

I would like to finish this little portion of the exercise by saying that we all have the opprotunity to deal with this topic in a framework where we will not have made up our minds to the point where we are not willing to be confused by the facts because I believe that there is still significant confusion and misinformation operational in the field today. We are going to take two and a half days and hopefully some of the evenings to educate ourselves on ascent rate facts.

With that in mind, we have asked Dr. Lanphier if he would be willing to share with us some historical perspective and he was gracious enough to accept our invitation, so I would like to welcome as first speaker, the Rev. Ed Lanphier.

A HISTORICAL LOOK AT ASCENT

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In considering a question like Safe Ascent, part of the process is understanding "how we got to where we are". Having been in this field since 1951, I hope to shed some light on this question from my own recollections and other sources not widely available. For example, I was part of the small but representative group that chose 60 ft/min as the rate of ascent for the 1958 USN air decompression tables. Only recently, re-reading parts of Sir Robert Davis' rare but famous book, I learned that 60 ft/min had also been accepted long before.

Introduction

I believe that I am the second-oldest investigator still active in Diving Medicine and Underwater Physiology. That probably entitles me to tell sea stories and try to portray what diving was like back in the days when men were men. Here, however, I'll try hard to stick to relevant information.

The main reason I'm pleased and grateful for being part of this Workshop is that the work Dr. Charlie Lehner and I have done with sheep and goats has focused our concern on the risk of central nervous system (CNS) injury from decompression sickness (DCS). This risk appears to be greatest in relatively short, relatively deep dives - clearly prevalent in both sport diving and scientific diving. It seems very likely that the pattern of ascent holds the key to reducing the risk of CNS DCS. In fact, we are on the verge of starting a study on this topic. This Workshop should help us decide just where to begin and what sorts of procedure to investigate.

Ancient history

I haven't tried to go back beyond the early 1900's, but it is interesting to note that ascent procedure was being argued even then. Prof. J.S. Haldane [1], whom we revere for his fundamental work on decompression tables, had a worthy rival: an equally-notable physiologist who was also deeply interested in decompression, Sir Leonard Hill [2].

Hill seriously questioned Haldane's **stage decompression** concept - especially for longer exposures - and advocated **uniform decompression** - the "slow bleed" approach, which indeed has prevailed in caisson and tunnel work and - much more recently - in very deep diving. Also, we know now that Haldane was off base in supposing that freedom from symptoms meant freedom from bubbles. It has even been suggested that

Haldane's initial ascent produces bubbles that can slow the elimination of gas and cause problems later. We obviously need to keep an open mind.

Early practice

Sir Robert Davis' classic book, *Deep Diving and Submarine Operations* [3] details Royal Navy practices as of 1962 and before. The main thing I gleaned there is that the rate of ascent to the first stop should not exceed 60 ft/min. The concern seemed to be less with the rate of ascent itself than with the chance that the diver would miss his first decompression stop if he were coming up too fast.

A copy of the Royal Navy's *The Diving Manual* of 1943 [4] confirms this. It also has an excellent illustration of the contemporary hand-driven divers' air pump. The gauges on the front (one for each of two divers) are especially important since the reading is essentially equal to the diver's depth. The dive supervisor is instructed to consult the chart inside the pump cover to determine the gauge error, then use the gauge to determine the depth and rate of ascent.

The 1950's

I came on the scene at the Experimental Diving Unit (EDU) in 1951. At that time, it was located on the Anacostia River in the Washington, D.C. Navy Yard. Soon, and for some time thereafter, our "Bible" was a slender volume known as the Bureau of Ships *Diving Manual, NAVSHIPS 250-880*, issued in 1952 [5]. Ascent at "not over 25 ft/min" was firmly implanted there, and I have not been able to find out why that rate had been chosen - or when.

The 25 ft/min rate was naturally reflected in *Submarine Medicine Practice, NAVPERS 10838*, issued in 1949 [6], and it never occurred to us to question that when we produced a revised *Submarine Medicine Practice*, issued in 1956 [7].

In 1954, EDU had a most interesting visit by French naval officers from "GERS" (Groupe d'Etudes et de Recherches Sous-Marines de la Marine Nationale). Most of them had been associated with Cousteau. Later, one of these officers kindly sent me a copy of a fine little book that they had produced: *La Plongée*, published in 1955 [8].

Going through *La Plongée* in preparation for this Workshop, I found some interesting things concerning ascent. Allowing for my ability to translate, one statement was that the duration of ascent to the first stop is an element in decompression. Another was that divers with self-contained equipment are capable of ascending as rapidly as 60 meters/min - roughly 180 ft/min - but that as the surface or first stop is approached, this speed should be considerably reduced.

The section on ascent without stops presents depths and times resembling our "no-D" limits. (A curve of these depth/time limits elsewhere in the book suggests a maximum depth of 40 meters, where the allowable time is 15 min.). The text states that the diver should always take at least one minute to traverse the final 10 meters of ascent. If the dive was deeper than 40 meters, a short stop at 3 meters is indicated. "Negligence of these precautions in general tends toward illness."

The 1958 USN air tables

I remember one morning, probably in 1956 or 1957, when EDU personnel and a selected group from elsewhere met in a borrowed room in the nearby Naval Reserve Training building. The main topic concerned the proposed new *USN Diving Manual*; I'd been designated as editor of Part I; others were being consulted about suggested content, willingness to contribute, etc.

Decompression was definitely not the primary topic of discussion, but the main reason for having a new diving manual at that point was to put forth the new air decompression tables that Officer-in-Charge Maino des Granges and his merry band had been working on. In any case, the proposed rate of ascent in the new tables became a hot topic of discussion.

CDR Doug Fane, representing his West-coast Underwater Demolition Team, was adamant in saying that his frogmen couldn't possibly observe anything as slow as 25 ft/min. What they wanted was more like 100 ft/min - or even faster. The hard-hat types insisted that nothing of the sort would be practical for hauling up divers in suit and helmet.

Those involved in calculating the tables insisted that ascent was an important element in decompression and that two complete sets of schedules would have to be produced for different rates of ascent - and that doing so would be utterly impractical.

I'm quite sure nobody complicated matters further by asking for a variable rate. It was assumed that one constant rate would apply between the bottom and surface or the first stop.

In that setting, the two sides decided to compromise on 60 ft/min. That had the merit of being one foot per second, and it seemed possible for a hard-hat diver to be hauled up that rapidly and for a scuba diver to come up that slowly. Anyhow, the group decided on 60 ft/min, and the calculations proceeded on that basis.

I doubt that Doug Fane or anybody else realized quite how slow 60 ft/min would seem in practice. I suspect that Doug figured that coming up a little faster wouldn't really hurt . . . and the hard-hat contingent probably thought that coming up slower than 60 ft/min wouldn't matter much, either.

In any event, the calculator - presumably Dr. Bob Workman at that stage - concluded that variations from 60 ft/min could make a real difference under some circumstances - a difference sufficient to warrant some rules. I seem to recall that, as editor, I had to squeeze those rules into the new Manual [9] in as intelligible a form as possible. I did my best, but I never got to the point where I could remember them from one day to the next myself.

The basic ideas were that if a diver tarried close to the bottom, he would take up enough extra gas to require more time in decompression. On the other hand, if he came up too rapidly, he would miss some of the decompression time that ascent at 60 ft/min would have afforded. Adjustments were to be made accordingly.

In the current (1985) *USN Diving Manual* [10], the rules are basically the same; but they are presented with examples that seem to help considerably in getting the ideas across.

I'll assume that most of you are familiar with more recent developments concerning ascent, so this concludes my excursion into history.

Current implications

It will be both interesting and beneficial to hear what the participants in this Workshop believe and suggest concerning ascent. Basically, I'm most impressed by the lack of solid experimental data on this subject. We must try hard to avoid "determining the truth by voting on it in the absence of information" and setting up new procedures just because they sound good.

At the same time, the need for better ascent procedures seems urgent, and there are things that surely can't hurt and might be of some help - like a stop at 30 ft or less on ascent.

To my knowledge, only Dr. Lehner and I have actual plans for looking into this matter experimentally, and we will be doing so in sheep. This allows us to be more provocative than with human subjects, but our conclusions will have to be checked cautiously in humans. We hope that others will be able to undertake experimentation that will supplement and check what we can do.

References

[1] Boycott, A.E., G.C.C. Damant and J.S. Haldane. 1908. The prevention of compressed air illness. J. Hyg. Camb. 8: 342-443.

[2] L. Hill. 1912. Caisson sickness and the physiology of work in compressed air. London: Edward Arnold.

[3] R.H. Davis. 1962. Deep diving and submarine operations. Seventh Edition. London: The Saint Catherine Press.

[4] Admiralty (Gunnery Branch). 1943. The diving manual, B.R. 155/1943. London: Her Majesty's Stationery Office.

[5] US Navy Department (Bureau of Ships). 1952. Diving Manual, NAVSHIPS 250-880. Washington: Superintendent of Documents.

[6] US Navy Department (Bureau of Personnel). 1949. Submarine Medicine Practice, NAVPERS 10838. Washington: Bureau of Naval Personnel.

[7] US Navy Department (Bureau of Medicine and Surgery). 1956. Submarine Medicine Practice. Washington: Bureau of Personnel - Superintendent of Documents.

[8] Marine Nationale (Groupe D'Etudes et de Recherches Sous-Marines). 1955. La Plongée. Paris: Arthaud.

[9] US Navy Department (Bureau of Ships). 1959. US Navy Diving Manual. Washington: Superintendent of Documents.

[10] Navy Department. 1985. US Navy Diving Manual, NAVSEA 0994-LP-001-9010. Volume 1 Air Diving, Revision 1. Washington: Superintendent of Documents.

INTRODUCTORY SESSION DISCUSSION

Discussion Leader: Glen H. Egstrom

Hugh Van Liew asked if there was evidence from the tunnel work that the "slow bleed" really did work better than the stage decompression? Ed Lanphier responded that he really couldn't answer that.

The next question inquired if there was a relationship of ascent rates and procedures in preventing bone necrosis at deeper depths/times? Ed Lanphier answered that Eric Kindwall would say that we didn't have procedures that would work for higher pressures or longer exposures to really prevent bone necrosis. Furthermore, Hills had some data on comparative approaches to decompression that he found quite convincing, but did not have time to analyze those.

John Lewis wondered whether there was any testing that supported the Navy procedures for omitted decompression. Ed Lanphier couldn't remember, it was too long ago. "That is one disadvantage of being so old. I like to talk about my favorite vehicle, which is a 22 year old camper van. Everything that could possibly happen to a Dodge van has happened to *Moby*, but the problem is that I can't remember what a particular noise actually meant, so it doesn't help a lot to have known him for so long".

Mike Emmerman asked if when the 60 fpm ascent rate came up, whether it was 25 fpm or 180 fpm and if there was any discussion or real data to determine whether it could have been 300 fpm or 5 fpm? Ed Lanphier didn't think so. The approach to reality came in the actual calculations where all they could say was that it made a difference what rate of ascent they assumed. The rate of ascent we adopted, 60 ft/min, was part of all of the Navy table testing that was done and we never really questioned whether that was a particular problem or not.

Bill Hamilton noted that from the way Ed Lanphier described it, the 60 fpm ascent rate was for operational reasons, rather than for optimal decompression. Ed Lanphier: Yes, surely. If we had chosen something that sounded very fine from a physiological standpoint but it wouldn't work for either scuba divers or hardhat divers, it wouldn't have made a difference. But I think it is very important to understand that these things did not come down from heaven.

David Yount stated that it seemed like the only implications from the theoretician's point of view were that you'd have to add more or less time onto the stages. It wasn't that there was anything intrinsically wrong with the faster ascent or slower ascent. Ed Lanphier Well, we would have had misgivings about coming up much faster than 60 fpm, I think. David Yount rephrased: What I'm getting at is if the theoretician takes the ascent rate into account in calculating the tensions in these different tissues, then there is a particular reason. Ed Lanphier: As far as the theoretician can see, there isn't any particular reason, I think, especially since we were following Haldane in those days and at that point we really did not know. It took Spencer, quite a few years later, with his bubble detection to convince us that freedom from symptoms did not mean freedom from bubbles. It is hard to realize that this is fairly recent information.

Ed Lanphier was asked to recall what kind of a repetitive schedule the Navy was testing. His response was that the schedules that were fairly well tested were in the diving manual. "One thing a lot of people don't realize was the bind we were in for not doing as many exposures we would have liked. We just didn't have the manpower or the time to do it as thoroughly as we would have liked".

Is there a myth around that the Navy tables were tested with only one, possibly two repetitive schedules? Ed Lanphier: I think that might be true because that was the main sort of thing that the Navy itself was concerned about, not about people diving time after time, day after day.

Hugh Van Liew pointed out that when the tables were set up, there was a tremendous bias to be thinking about tissues and whether or not the gas was washing into them or out of them, and there wasn't any thought at all about bubbles. Ed Lanphier: That is correct, because we thought that if we did it right, there wouldn't be any bubbles. Now we know that they are probably there, at least in some of the schedules.

Phil Sharkey: Did some of the foreign systems develop similarly, with different ascent rates applying to different tables which occurred in the same era, maybe also in an arbitrary fashion? Ed Lanphier: I think you can almost bet on it. I don't have proof, but how else could it have been done?

Hugh Van Liew wondered if there was any information from non-written systems like the Polynesian divers that don't have tables but seem to be doing things right by experience? Ed Lanphier: I think David Yount is the best one to field that question. Hugh Van Liew: I wonder if primitive people who are diving successfully would favor a rapid ascent or a slow ascent? David Yount: They would go rapid. Ed Lanphier said that when you stopped to think about it, coming up at a specific, relatively slow rate like 60 fpm, which is relatively slow as far as he was concerned, it is extremely difficult. "How are you going to spend reliably and accurately 5 minutes at 10 feet unless you have a line with weight and float and can hang onto it and sit there. Of course, the dive computers help that now and if you have a good buoyancy compensator and are expert in using it, maybe you can, but it is still so much more difficult than just coming up". Glen Egstrom added that he had the opportunity to do some research with some of the Polynesian divers and it would be his observation that they come up slower if they're carrying a heavy load and faster if they are not. But the issue there, he believes, is that we don't know how many of those people were getting significant amounts of decompression sickness. In Polynesia, they have a malady called Taravana, which, as far as we could determine, really is acute decompression sickness from coming up too fast from depths in excess of 50 meters. Their bottom times are singularly short, but they make these rapid excursions to and from the bottom with working times on the bottom of maybe 50 seconds. Hugh Van Liew: So, that is breathhold diving which really is a different ball game. Ed Lanphier: Not totally. Glen Egstrom: I wonder if it is from the point of view of ongassing and bubble formation Hugh Van Liew: They have a terrible problem of getting oxygen into their lungs. Ed Lanphier summarized that the kind of diving they do was very clearly on the verge where breathhold diving can cause decompression sickness.

Glen Egstrom: Remember Paulev? Ed Lanphier: "I sure do". He was a Dane who took a submarine crew up to the escape tank in Bergen, Norway, for training and in that setting, he and several others developed what almost had to be decompression sickness and they responded to recompression. They wrote an article for the Journal of Applied Physiology, describing this whole thing. I was called in as a referee editor. I recognized this paper as an extremely important first. It was the first time that decompression sickness from breathhold diving had ever been reported. I assisted in rewriting the paper, it was published and is one of the monuments of decompression literature. Glen Egstrom added that the side issue to that was that Paulev described this experiment at the international physiological conference in 1965 in Tokyo and his observation was that they were making 30m drops into the tank and didn't seem to be having any kind of a problem. Finally, they were getting so tired they couldn't make it to the bottom and back up any more, so for the last dives of the series they were only getting down to about 20m. Everything seemed to be alright, he got out of the tank, started to walk, collapsed, lost bladder, bowl, etc. They rushed him to a chamber for treatment.

David Yount: One of the points you made was the "slow bleed". I'd like to make a remark about that. On a typical exposure, if you had only one tissue that was activated, then the ascent produces a certain delta p which is just barely enough not to produce any bubbles. In the one tissue, at one time constant, the ideal way to surface is a straight line, as you would get in a saturation dive. The saturation dive is characterized by one tissue because it is so long. Only the longest tissue comes into play. If you have two tissues, that would mean two different time constants where the first part of the dive is controlled by the fast tissue and the second part is controlled by the slower tissue. What really happens is you don't have a bunch of discrete tissues like ten different tissue compartments, but really have a continuum of tissues and if you modeled it that way, you would have a smooth curve. That is the slow bleed. The slow bleed is really the best way to surface if you have an operational way of doing that, which you usually don't. Bill Hamilton commented that if you're doing this on a saturation, you're only operating in the last compartment and you do get a straight ascent. David Yount concurred. On a saturation dive where you have a continuous range of tissues, the step function, versus straight ascent, is only an operational artifact. It's only that way because it's hard in practice get the straight line. The slow bleed really is the way to do it if you have control.

Ed Lanphier: One other thing to mention is that Ed Thalmann, in his calculations for the Navy, came up with the idea that once you had bubbles in more than one tissue, then the picture changed, and you ended up with a straight line. Bill Hamilton: Decompression is not necessarily a straight line, it's the outgassing. Ed Lanphier: It's the basic assumption that you no longer deal with an exponential curve. John Lewis: That presumes that the delta p (pressure change) is acceptable. David Yount: As you approach the surface when you're doing this, it's holding delta p constant. As long as you hold a fixed delta p in decompression, you're keeping the bubble number constant, or you're controlling the bubble volume. It's really delta p, it's not the ratio. John Lewis: You still have a ratio that's greater than it should be at depth, than on the surface. Bill Hamilton: In some cases the tolerable delta p expands as you go deeper, or it shrinks as you get towards the surface. John Lewis: The larger tension is not acceptable, and I think that's perfectly logical.

Ed Lanphier: If I had said more about things we know are wrong with Haldane's concept, I would have emphasized the fact that this 2:1 ratio, while pretty true in shallower diving, does not hold when you go deeper. That is absolutely obvious. It is somewhere in between delta p and the ratio. The ratios have to be more conservative than 2:1 as you go deeper, but the delta p that you can get away with apparently gets a little bigger. David Yount: Basically, the delta p is the threshold for bubble formation. It is determined by the radius of the nucleus and the radius is connected to the delta p.

Glen Egstrom: I want to thank Dr. Lanphier for getting us off to a flying start.

PHASE DYNAMICS IN DIVING

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Dissolved and free gases do not behave the same way in tissue under pressure, and their interaction is complex. Differences are highlighted, particularly with respect to time scales, gradients, and transport. Impacts of free phases on diving are described, contrasting increased off-gassing pressures, slower ascent rates, safety stops, and reduced repetitive exposures as consistent practical measures within traditional models (limited supersaturation) which can be played off against buildup of dissolved gas. Simple computations illustrate the points. Using critical volumes as trigger points lies between classical supersaturation models (tables and meters) and nucleation-modern bubble models, that is, a realistic limit point divorced from nucleation and stabilization for convenience. Such limit points can be substituted for matrices of critical tensions (M-values) in table or meter algorithms. Based on main concern of phase growth, we suggest that 60 ft/min ascent rates be retained for nominal exposures, and that safety stops at 15-20 feet for 3-5 minutes are warranted, with stop time added to bottom time when using tables. The USN tables are the reference point.

Introduction

Diving sectors (military, sport, scientific, commercial) employ a modified supersaturation algorithm [1-11], often termed multi-tissue (different perfusion-dominated compartments) or M-value (critical tissue tensions), and therein an issue [12-31] has always been an incomplete treatment of gas dynamics. Concerns encompass all activity when recent investigations [26-29] conclude that living tissues are persistent storehouses of growth-excitable gas nuclei of sub-micron size, though problems surface more fully in repetitive cases. When supersaturation models do not address free phases, they are not optimal, nor global. As part fix-up, one might incorporate free phase limiters to make them more predictive when extended outside tested ranges, though full blown nucleation-bubble models appear preferable. Safety stops and slower ascent rates are other alternatives, along with reduced no-decompression time limits and critical tensions. We examine some possibilities, focusing on critical volumes, ascent rates, and safety stops, with a convenient program (DECOMP) [20], offering various combinations of gas transport models (perfusion-limited, diffusion-limited, both) and critical limiters (tissue tension, separated gas fraction, free-dissolved gradient, bubble number). Results are compared with the standard predictions of the multi-tissue algorithm. Safety stops and slower ascent rates in the context of the supersaturation model are consistent with free phase limiters, though perhaps less natural. For the future, we suggest that bubble models offer optimal bases for tables and meters, and that testing and further development are warranted.

Some regard safety stops, slower ascent rates, and increased off-gassing pressures as consistent treatment practices for separated (free) gas phases, particularly near the surface where reduced pressure enhances growth. Nucleation theory and experiment tell us that on any given dive (compression-decompression), families of stabilized micronuclei larger than a critical minimum size are always excited into bubble growth, so we must pay attention to free phase development throughout the dive. Bubble growth criteria automatically address both issues, via allowable pressure gradients, and are more realistic, unlike critical gas tensions which the chemists tell us are ill-defined. We might think about replacing M-values with bubble criteria instead of patching time limits, ascent rates, and safety stops.

Testing is central to diving, and much testing of bounce (single), no-decompression diving has transpired. Repetitive and multi-day exposures can neither claim, nor reap, the same benefits, and application of the algorithm in the latter cases has witnessed higher bends statistics than in the former one. Reasons appear tractable. The multi-tissue approach is a dissolved gas model, and so long as the bulk of tissue gas remains in the dissolved state, the more correct and useful such an approach will prove. But as increasing proportion of free phases grow, by direct excitation of critical micronuclei or more gradual bubble coalescing transitions, the multi-tissue algorithm can lose predictive capability. Invariably, such conditions attend diving activity extrapolated outside model and test ranges, sometimes as a surprise.

The establishment and evolution of gas phases, and possible bubble troubles, involves a number of distinct, yet overlapping, steps:

1) nucleation and stabilization (free phase inception);
2) supersaturation (dissolved phase buildup);
3) excitation and growth (free-dissolved phase interaction);
4) coalescence (bubble aggregation);
5) deformation and occlusion (tissue damage and pain).

In the past, much attention has focused on supersaturation. Recent studies have shed much light on nucleation and excitation. Bubble aggregation and tissue damage are difficult to quantify in any model, and remain more obscure. Complete elucidation of the interplay is presently asking too much. Yet, the development and implementation of better computational models is necessary to eliminate problems re-echoed in workshops, reports, meter disclaimers, publications, and even a very slanted segment of 20/20 on ABC last winter.

History and background

Origins of diving regimens at sea level are traced to a supersaturation model proposed by the eminent English physiologist, John Scott Haldane [1]. Observing that goats, saturated to depths of 165 feet of sea water (fsw), did not develop decompression sickness if subsequent decompression was limited to half the ambient pressure, Haldane constructed schedules that limited the critical saturation ratio to 1.58 in each of five hypothetical tissue compartments. The tissue compartments were characterized by their half-life, τ, that is, the time required for the compartment to half, or double, existent nitrogen. The five original tissue compartments (5, 10, 20, 40, 75 minutes) were employed in diving calculations for fifty years. Later, in performing deep dives and expanding table ranges, workers, in particular the USN, advocated the use of six tissues (5, 10, 20, 40, 80, 120 minutes) in constructing diving tables, with each tissue compartment having its very own critical pressure (M-value).

Changes to the basic format were driven by increasing diving activity. New compartments and M-values were added as existing schedules failed extrapolations. Today, many slower compartments have been proposed in applications, with variable decompression ratios at 10 ft increments producing many degrees of freedom (fit parameters) to characterize the data. Yet, slower tissue compartments do not necessarily give the model proper physical signatures. While the concern is free phase growth and the hope is that slower compartments with smaller M-values will prevent growth, that hope is not physically realistic from different vantage points. Yet, though the M-value approach may not prevent bubble growth, it can represent an adequate treatment table for separated, but still asymptomatic, gas [2,8,23]. In such circumstance, treatment (elimination) of free phases tends to take place at shallower depths with present diving practice. Then, as elimination becomes less efficient with decreasing pressure, safety stops and slower ascent rates, tending to increase average pressure, appear qualitatively wiser practices. Further on, quantification will be presented.

Certainly, any algorithm can be piecewise safe over tested ranges, but not always globally. Some implementations, as pointed out by Weathersby [7], may not be statistically rigorous, relying on much too small a set of exposure data to confidently predict outcome. Models not strongly correlated with tests can promulgate wide variation in predictive capability. Similarly, models can often interpolate within data, while failing to extrapolate outside the data. And then we must modify procedures to accommodate the extrapolation. A good point in question is the repetitive use of the USN tables. It is now clear [24, 25] that single, no-decompression dives, followed possibly by one more repetitive dive, form the test basis of the no-decompression parts of the schedules. Yet, we observe that multiple repetitive dives permitted by the tables incur higher bends statistics, particularly in the deeper categories. This results from both model shortcomings and less reliable statistics. Adequate testing of any algorithm is always requisite, that is, descent rate, exposure profile, ascent rate, surface interval, and repetitive loading.

Supersaturation model and dissolved phase dynamics

Multi-tissue computational algorithms are ultimately based on assumptions of limited supersaturation in tissues, with gas exchange controlled by blood flow rates (perfusion) in assumed homogeneous media. Tissue is first separated into intravascular (blood) and extravascular (tissue) regions for modeling. Blood containing dissolved inert and metabolic gases passes through the intravascular zone, providing both initial and boundary conditions for subsequent gas transport throughout the extravascular zone. Arterial blood tensions equilibrate rapidly with alveolar partial pressures, and venous tensions then equilibrate with arterial tensions at a somewhat slower rate. Tissue tensions fall somewhere between arterial and venous tensions during equilibration.

Exchange of inert gas by random molecular motion across regions of varying concentration is driven by the gradient, that is, the difference between the arterial blood tension, p_a, and the instantaneous tissue tension, p. That behavior can be modeled in time, t, by mathematical classes of exponential response functions, bounded by p_a and the initial value of p, denoted p_i. These multi-tissue functions are easily accessed with hand calculators, taking a very simple form, where λ is the tissue decay constant,

$$p = p_a + (p_i - p_a) \exp(-\lambda t),$$

$$\lambda = \frac{\ln 2}{\tau} \qquad (1)$$

Ten compartments with 2.5, 5, 10, 20, 40, 80, 120, 240, 360, and sometimes 480 minute half-lives, τ, are routinely employed in application, and half-lives are assumed to be independent of pressure. A one-to-one correspondence between the ten compartments and specific anatomical entities is neither established, nor implied.

For very large values of τ, tissue uptake and elimination of inert gas is relatively slow according to the response function. For small values of τ, inert gas uptake and elimination proceed much more rapidly. An important assumption built into the supersaturation model requires intercellular diffusion of inert gas to occur rapidly compared to time scales of τ, so as to not significantly limit, nor effect, the gradients driving gas exchange. The only controlling factor is assumed to be the perfusion rate. To maximize the rate of uptake or elimination of dissolved gases, the gradient, simply the difference between instantaneous tissue tension and ambient pressure, is maximized. Historically, maximization gives rise to a long (first) pull to the surface. Maximization of the gradient, however, must never permit gas buildup above empirical limits.

Fits to the exposure data, mainly for no-decompression diving, limit degrees of compartment supersaturation by critical values, M, having a typical modern range, $122 \leq M \leq 36$ fsw, notably of American origin. Critical gradient criteria require differences between the tissue tension and ambient pressure, P, to remain less than another critical trigger point, L. Gradient criteria can be linked to laboratory tests while critical tensions are empirical and not well defined. In decompressed gel experiments, Strauss [19] suggested that $L \approx 14$ fsw, for all pressure. Even in the early times of Haldane, Hill [9] opted for a fixed gradient near 24 fsw under nominal loadings as a realistic constraint. Thermodynamic tables [8] and recent bubble formation-regeneration tables [18] employ variants of L effectively.

Critical gradients are more easily linked to bubble mechanics than critical tensions, but critical tensions enjoy widespread popularity in diving applications. Yet, τ and M are not fundamental. Sets of half-lives and critical tensions evolved from self-consistent application of Equation (1) to sets of exposure data, that is, trial and error bootstrapping of model equations to observed exposure time limits. Newer compilations ultimately extend older ones in like manner. For instance, the sets of critical tensions, M, detailed by Workman [4] and Bühlmann [3] for arbitrary compartments at depth, as well as the later compilations of Schreiner [5] and Spencer [6], along with the response function, are popular realizations of the algorithm. The Workman (USN) critical tensions are plotted in Figure 1 as a function of ambient pressure for a chosen set of tissue half-lives. They are linearily increasing functions of pressure, and were tested at sea level ($P = 33$ fsw).

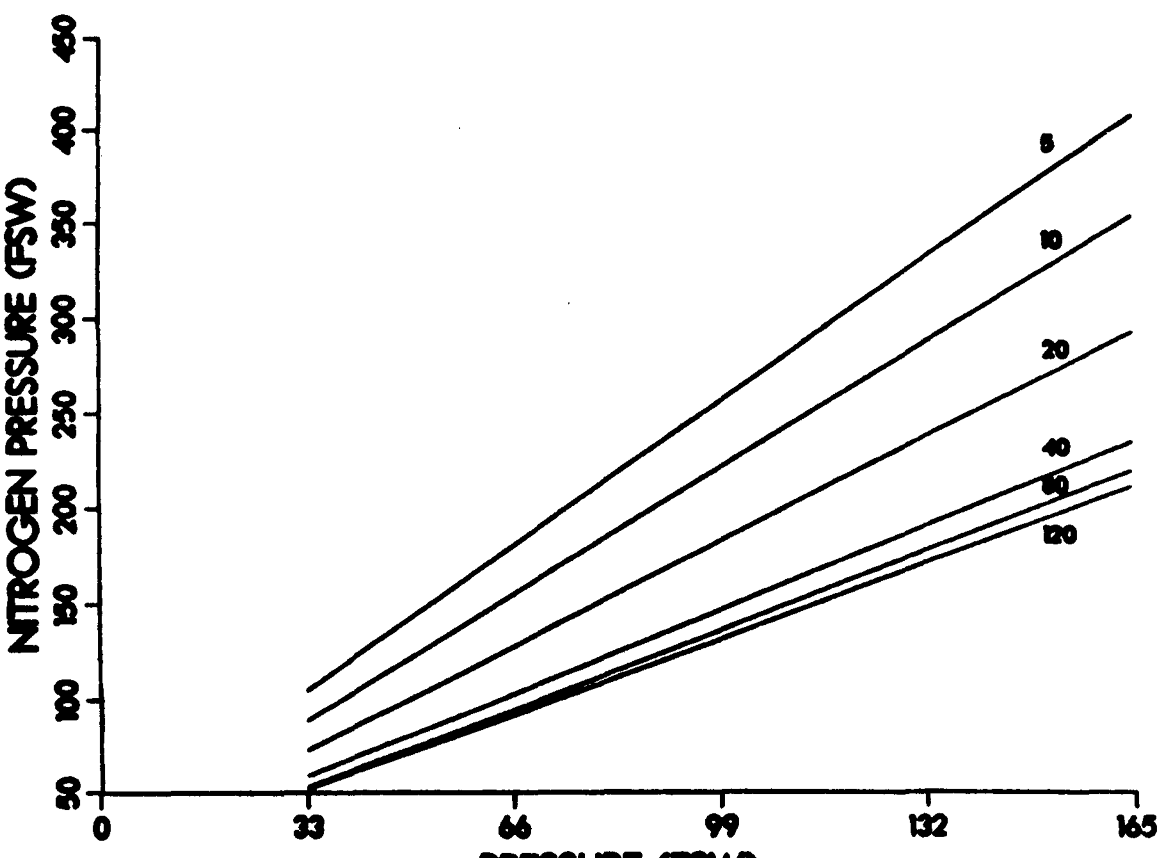
Bühlmann, [3] and Bell and Borgwardt [10] extended (tested) the critical tensions at altitude ($P < 33$ fsw). The extension has not only been a study in itself, but also a reflection of the limitations of sea level compilations. Wienke [16] proposed exponential extrapolations of M-values back through zero absolute pressure, an intuitively conservative scheme. However, proposed extrapolations of critical parameters require testing, and altitude is no exception. Such is also the case for deep exposures. Based on reductions in Venous Gas Emboli (VGE) counts in select exposures, Spencer [6] and Pilmanis [32] pioneered a modern trend to reduce no-decompression time limits, and subsequent M-values extracted from them. These welcome conservative procedures must reduce bends incidence statistics, but central model issues remain.

Figure 1. Critical Tensions (M-Values).

Critical tensions are fitted linear functions of pressure, obviously increasing with ambient pressure. Faster compartments permit greater amounts of dissolved nitrogen, slower compartments less. During any dive, tensions in compartments must stay below the depicted curves in this modified Haldane approach. Wienke reduced them to an approximate form (fsw),

$$M = 152.7\ \tau^{-1/4} + 3.25\ \tau^{-1/4}\ d,$$

for depth d (ft). Dividing M-values by ambient pressure, P, yields the critical ratios, R. Extensions of the curves to altitude (P < 33 fsw) have been effected linearily and exponentially. In the linear case, the zero pressure intercepts are positive, while in the exponential case the intercepts are zero. Thus, in the former case, critical ratios become unbounded at zero ambient pressure, while in the latter case, they remain finite. These trigger points are artifacts of data fitting, and not necessarily physically tractable. Any set of no-decompression time limits can be plugged into Eq. (1) and ensuing sets of tensions for compartments can be scanned for maximum values (M-values) across all depths and half-lives.



Bubble model and free gas phase dynamics

Blood rich, well-perfused, aqueous tissues are usually thought to be fast (small τ), while blood poorer, scarcely-perfused, lipid tissues are thought to be slow (large τ). As reflected in Figure 1, critical tensions are larger for faster tissues and increased pressures. The range is linear within tissue compartments. In the field, fast compartments control deep, short exposures, while slower tissue compartments contend with shallower, prolonged exposures. Additionally, near surfacing M-values are principal concerns, yet, as such, are somewhat shortsighted, probably contributing to ascent rate and safety stop concerns, among others. Algorithms tracking both dissolved and free phases offer broader perspectives and wider alternatives. Tracking the interplay of component gas phases throughout the dive automatically determines ascent rates and possible stops in modern bubble models, but with some changes from classical procedures. Free and dissolved gas dynamics differ.

Since differences between free phase and ambient pressures increase with depth, the gradient for free phase elimination also increases with depth, directly opposite to the dissolved phase elimination gradient which decreases with depth. Then, changes in operational procedures become necessary for optimality. Impacts of this on decompression diving can be seen clearly in Figure 2, which contrasts supersaturation staging (USN and RN) against thermodynamic staging according to vintage Hills [8]. Similar profiles are seen in bubble models, such as the varying permeability approach [18]. Considerations of growth invariably require deeper staging procedures than supersaturation methods. Though not as dramatic, similar constraints remain operative in no-decompression exposures. The reason is linked to the interaction of free and dissolved phases in bubbles and tissue, as summarized in Figures 3 and 4.

Internal pressures in bubbles exceed ambient pressures by amounts equal to the effective surface tensions of the bubbles, as seen in Figure 3. To eliminate bubbles or reduce growth, increasing ambient pressure is requisite not only to restrict size, but also to drive the gas by diffusion out of the bubble and across the tissue-bubble interface, as depicted in Figure 4. The shorter the desired time of elimination, the greater must be the ambient pressure. Experiments conducted in decompressed gels, notably by Yount and Strauss [12, 19], Kunkle and Beckman [15], and others, bear testimony to this fact. Figure 5 contrasts experimental bubble dissolution time as a function of ambient overpressure for various small bubbles. The smaller the bubble, the shorter the dissolution time. Here, implication for diving is rather simple. In the presence of even threshold amounts of free phases, increased pressure is prudent. With any pressure, the length of time required to dissolve bubbles of 250 micron diameter is significantly shorter than that required to dissolve larger bubbles. Immediate recompression within less than 5 minutes is adequate treatment for bubbles less than 100 microns in diameter, and forms the basis for Hawaiian emergency in-water recompression procedures [22]. Such facts prop arguments for safety stops when conventional tables are pushed to limits, timewise or repetitively.

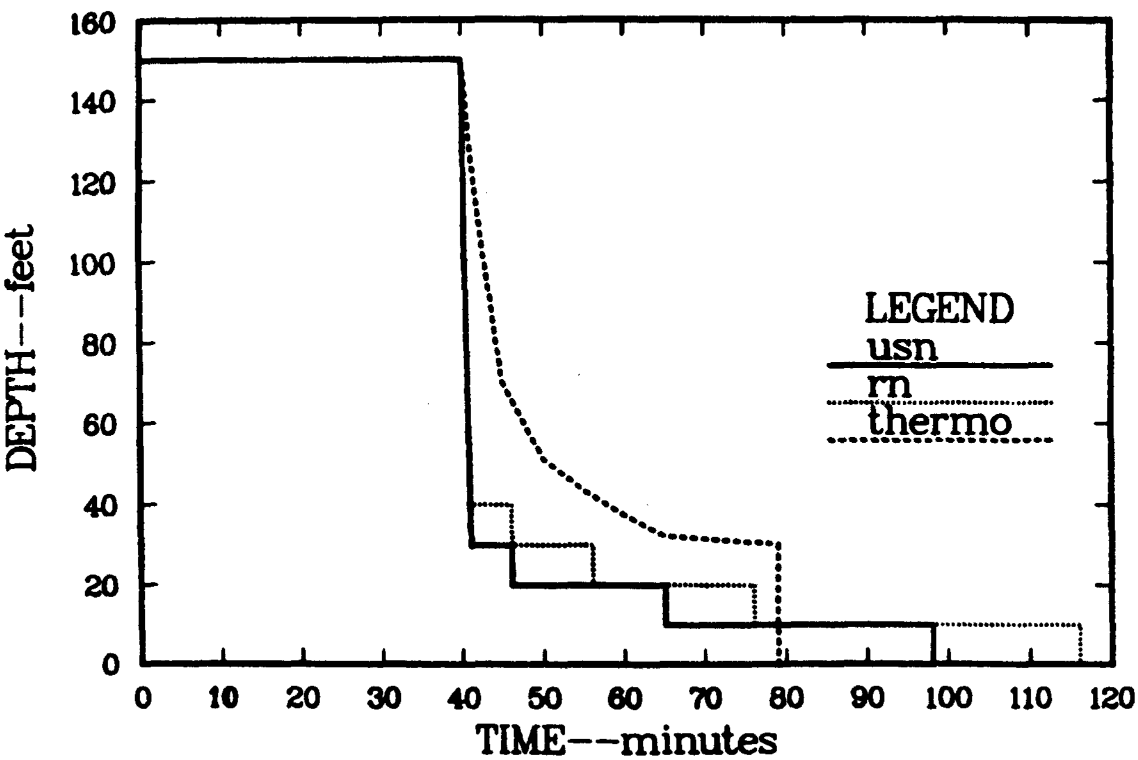
There are other concerns with the presence of free phases in tissue. Use of just a supersaturation gradient to quantify elimination is not correct, because the free phase pressure is not the tissue tension, p. A split gradient [16] fractioning dissolved and free phases, is advisable. As recently discussed by Van Liew [30], the relative composition of gases in bubbles can also change upon decompression. Similarly, if inert breathing mixtures are changed, existing bubbles can grow or shrink, depending on relative gas solubilities and diffusivities [33]. Operational diving then becomes a complicated playoff against dominant phases.

Figure 2. Phase And Supersaturation Decompression Profiles

Decompression profiles for a dive to 150 ft for 40 minutes are depicted according to supersaturation and critical phase formats. The supersaturation schedules (USN and RN) obviously differ from the phase format (thermo). Such differences are generic to bubble models versus critical tension models and involve:

1. more time spent deeper to minimize bubble excitation and growth, and maximize the driving force to eliminate free phases, followed by;
2. possible drop out at 20-30 fsw to dump asymptomatic free gas, if phase separation has been minimized by the overall ascent procedure.

In supersaturation formats, stops in the 10 to 30 ft range are thought to represent the treatment portion of the diving schedule. Computational analyses, some tests, and experiments have validated features of phase models, while work needs to continue on such approaches. Models extending biophysics can hopefully provide additional insights and optimal formats.



A free phase in tissue introduces another dimension to gas exchange models. But as a critical indicator, the free phase volume is noteworthy since it can be linked systematically to the mechanics of bubble formation, growth, and elimination, as probed in experiments and corroborated by theory. Bubbles, which are unstable, are thought to grow from stable, micron size, gas nuclei which resist collapse due to elastic skins of surface-activated molecules (surfactants), or possibly reduction in surface tension at tissue interfaces. Families of these micronuclei persist, varying in size and surfactant content. Large pressures (somewhere near 10 atm) are necessary to crush them. Micro-nuclei are small enough to pass through the pulmonary filters, yet dense enough not to float to the surfaces of their environments, with which they are in both hydrostatic (pressure) and diffusion (gas flow) equilibrium. According to Figures 3 and 4, when nuclei are stabilized, and not activated to growth or contraction by external pressure changes, the skin (surfactant) tension offsets both the Laplacian (film) tension and any mechanical help from surrounding tissue ($\gamma = 0$). Then all pressures and gas tensions are equal. However, on decompression, the seed pockets are surrounded by dissolved gases at high tension and can subsequently grow (bubbles) as surrounding gas diffuses into them. The rate, $\dot{r}$, at which bubbles of radius, r, grow (or contract) can be approximated,

$$\dot{r} = \frac{\partial r}{\partial t} = \frac{1}{r}\frac{DS}{C}\left[p_t - P - \frac{2\gamma}{r}\right] , \qquad (2)$$

with D the diffusivity, S the solubility, C the concentration, γ the effective surface tension of the bubble, p_t the total tissue tension, and P the usual ambient pressure. At some later point, a critical volume of separated gas is established and symptoms of decompression sickness become increasingly probable. On compression, the micronuclei are crunched down to smaller sizes across families, apparently stabilizing at a new reduced size. Bubbles are also crunched by increasing pressure because of Boyle's law, and then additionally shrink if gas diffuses out of them. As bubbles get smaller and smaller, they possibly re-stabilize as micronuclei.

Figure 3. Pressure Balance.

The total gas pressure, P_t, within a bubble equals the sum of ambient pressure, P, plus effective surface tension, $2\gamma/r$, according to,

$$P_t = P + \frac{2\gamma}{r} ,$$

$$P_t = P_{O_2} + P_{N_2} + P_{H_2O} + P_{CO_2} .$$

At small radii, surface tension effects are large, while at large radii effects of surface tension vanish. Effective surface tension is the difference between Laplacian (thin film) tension and skin (surfactant) tension. Stabilized nuclei exhibit zero effective surface tension, so that total gas pressures and tensions are equal. When nuclei are destabilized (bubbles), any gradients between free and dissolved gas phases will drive the system to different configurations, that is, expansion or contraction, until a new equilibrium is established.

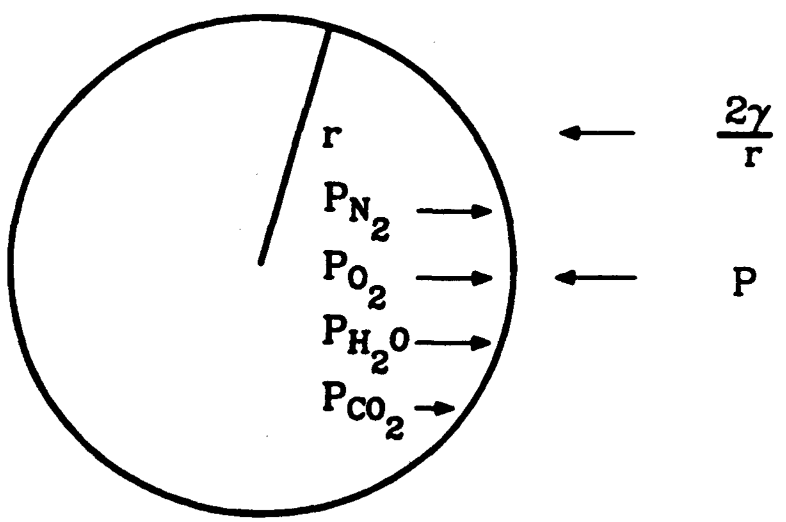


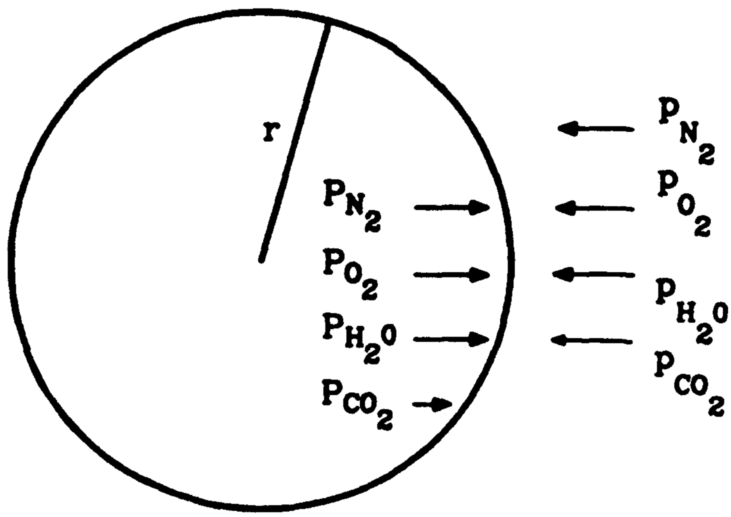
Figure 4. Gas Diffusion

A bubble in hydrostatic equilibrium will grow or contract, depending on its size and any relative gradients between free gas in the bubble and dissolved gas in tissue. Gradients are inward if tensions exceed bubble gas pressures, and outward if free gas pressures exceed tensions. A critical radius, r_c, separates growing from contracting bubbles for a given set of pressures. The critical radius depends on the total tension, p_t, ambient pressure, P, and effective surface tension, γ,

$$r_c = \frac{2\gamma}{p_t - P} ,$$

$$p_t = p_{N_2} + p_{O_2} + p_{H_2O} + p_{CO_2} ,$$

where growth occurs for $r > r_c$, and contraction for $r < r_c$. Some stabilized gas micronuclei in the body can always be excited into growth by pressure changes (compression-decompression).



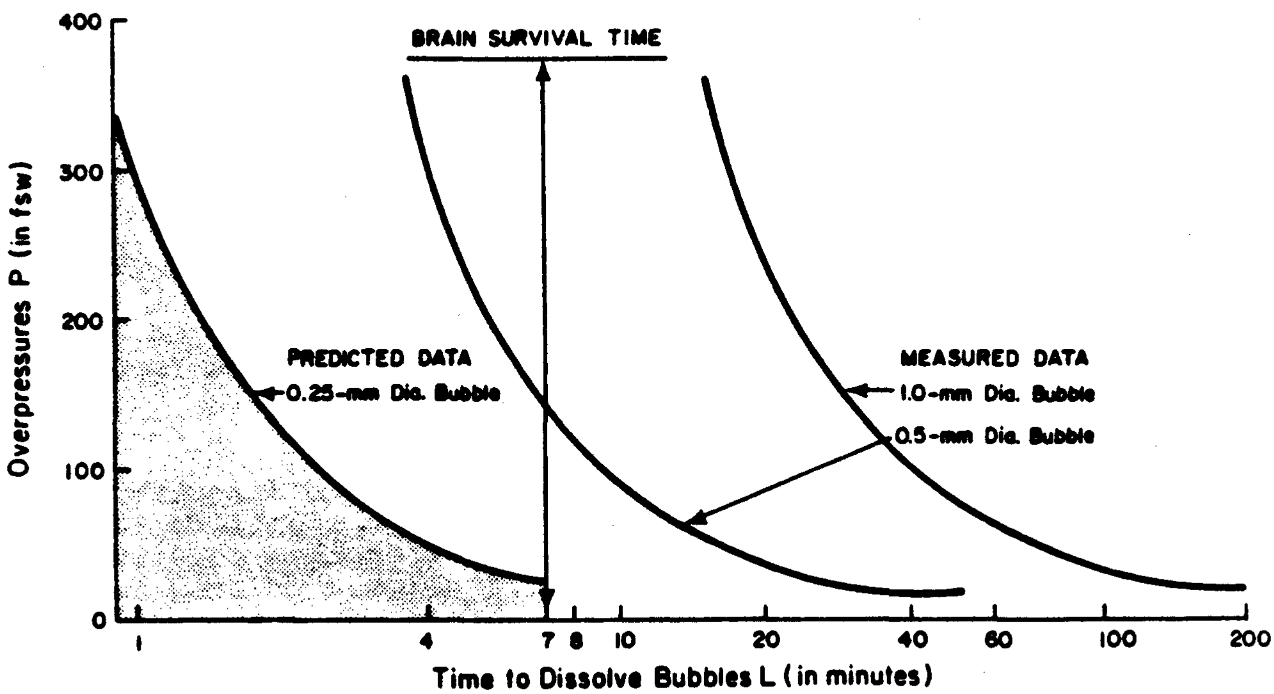
Nucleation theory is consistent with a number of diving observations [15, 19, 31]. Divers significantly increase tolerance against bubble formation, and therefore decompression sickness, by following three simple practices:

1) make the first dive a deep, short (crush) dive, thereby constricting the micronuclei down to a smaller, safer size;
2) make succeeding dives progressively more shallow, thus diving within the crush limits of the first dive and minimizing excitation of smaller micronuclei;
3) make frequent dives (like every other day), thus depleting the number of micronuclei available to form troublesome bubbles.

An underlying point can be made here. If nucleation sites are extinguished, reduced in number, or ill-disposed to excitation, bubble formation and risk are commensurately reduced. Regeneration times for classes of micronuclei are estimated [18, 26] to be near a week, underscoring physiological adaptation [15, 31] to recurring pressure environments. The mechanics of nucleation, stabilization, and bubble growth are fairly complex, with stabilization mechanisms for micronuclei only having been recently elucidated [26-29]. Source and generation mechanisms before stabilization are not well understood. Some candidates include cosmic radiation and charged particles, dissolved gases in fluids we drink, lymph draining tissues into veins, collisional coalescence, blood turbulence and vorticity, exercise, the stomach, and the thin air-blood endothelium in the lungs. Once formed, micronuclei apparently stabilize very rapidly with surfactant material [27, 28]. Passing through the pulmonary filters of the lungs, only sub-micron sizes survive.

Figure 5. Dissolution Times For Graded Bubbles

Bubbles develop and grow over longer time scales than nuclear stabilization. Yet, the rapid dissolution of bubbles in decompressed saturated gelatin (and the body proper) requires immediate and adequate repressurization. The absolute length of time required to dissolve bubbles with given overpressure is directly proportional to the size of the bubble. Obviously, the smaller the bubble, the shorter the time needed to dissolve that bubble at any overpressure. The bubbles studied in this experiment by Kunkle and Beckman grew to approximately 1mm in 5 hrs, starting from stabilized micronuclei. Such experiments have provided vital information, and confirmation of nucleation and bubble theories.



Introducing phase mechanics into decompression theory enhances our basic understanding, while maybe pushing numerical perseverance a little. Such perhaps is reason for slow integration into working algorithms. Testing and costs are important other reasons. Meter implementation appears timely, along the following lines.

Critical volumes versus critical tensions

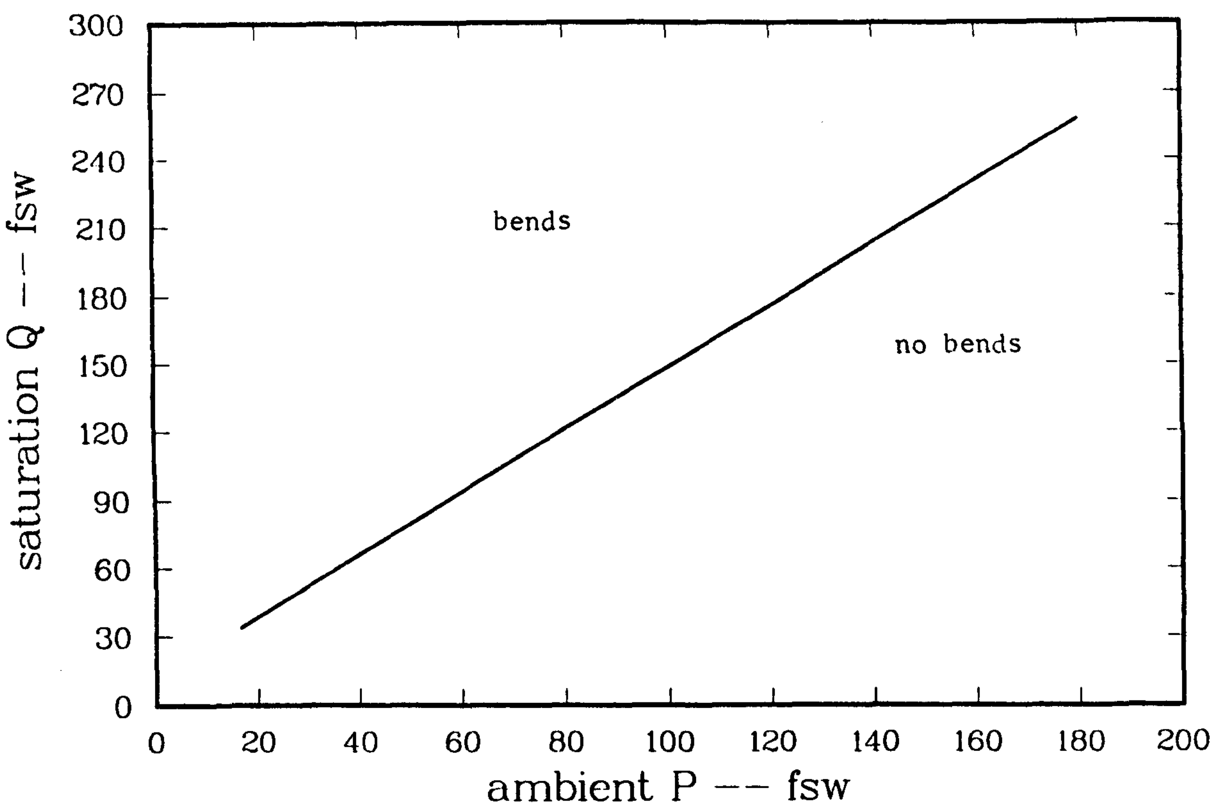
In elegant experiments, Crocker [21] exposed goats to compressed air at one absolute pressure, Q, for 12 hours (saturation) and then decompressed the animals to another absolute pressure, P, for several hours, checking for bends development. A few days later, the same animals were exposed to the same pressure, Q, and decompressed to slightly higher or lower pressure, P, until a distribution of P, separating bends from no-bends points, was generated. The whole titration was then repeated for a new series of Q. Repetitive exposures are, of course, not included in the titration. Analyzing this data and others, Hills [8] proposed a complete separation of bends from no-bends points via a linear relationship between Q and P, redrawn in Figure 6 for the appropriate range, $0 < P < 200$ fsw. Similar type constraint curves are demonstrable for saturation diving at great depth [34]. Over comparable pressure range, an exact one-to-one correspondence between the M-values in Figure 1 and the titration curve is not demonstrable. At most, only one correlation could be established anyway. Certainly, all linear representations of M-values must be broadly consistent with the titration trend of the experiment. Ambiguity arises, of course, because tissue compartments are assigned different critical tensions by design, and must differ from the curve. Actually, the original Haldane assignment of the same critical tension to all compartments is consistent with the titration line. With this in mind, it is worthwhile to now consider a more realistic trigger point for the bends, the critical volume.

Figure 6. Decompression titration

For simple bends (Type I and II), decompression titrations have been performed. A linear relationship between the saturation pressure, Q, and permissible decompression, P, has been established over a range of exposures to depths less than 300 ft. While predictions of M-value models are close to the curve, only one compartment can match the curve. Models employing critical volumes recover the features (slope and intercept). The line is of the approximate form (fsw),

$$Q = 1.37\ P + 11.01,$$

according to Hills, Hennessy and Hempleman, and Yount and Hoffman. Beyond 300 fsw the relationship becomes curvilinear. The original Haldane assignment of the same critical tension to all compartments is consistent with the titration experiment. One notes, however, that repetitive exposures are not cases in point here. Similar profiles apply to very deep saturation diving.



Hennessy and Hempleman [13] first established a linear titration curve for the data assuming that the same critical volume of released gas provokes mild attacks of decompression sickness. Their analyses also offer explanations for changes in signs and symptoms which follow changes in the nature of the exposure to pressure. Such findings question and press dissolved gas approaches. While the titration experiment is compatible with broad trends, it is clear that dissolved gas limiters, such as M-values, are often not the best critical flags. Indicators such as the volume fraction of free gas phases are not only more natural, but are also more strongly correlated with experiments. Computational algorithms, such as those suggested by Hills [8] and Hennessy [2] described by Wienke [16, 17] and, particularly, proposed by Yount [26-29] in coupling observed numbers of micronuclei in decompressed media to critical volumes, offer basic alternatives to the matrix of M-values. Fewer arbitrary parameters also attend those treatments. Some regard the zero-supersaturation approach of Behnke [11] whereby the inherent unsaturation is allowed to limit supersaturation on ascent, as the classical predecessor to phase algorithms. The interesting empirical practices of Hawaiian and Australian diving fishermen [22, 23] suggest a working cognizance of phase dynamics, and developed over many years of trial-and-error experimentation, albeit, with considerable trauma. Present diving practices, correlated with critical tensions, appear riskier [24, 25] under increasing exposure time and pressure loading.

Denoting the separated gas fraction per unit volume of tissue, χ, and the solubility, S, as before, Hennessy and Hempleman [13] deduced for saturation exposures,

$$\frac{\chi}{S} = .397 , \tag{3}$$

from the titration curve (Figure 6).For lipid tissue, S = .069, while for aqueous tissue, S = .012. The ratio broadly represents a trigger point for bends, and can be employed in simple calculations to contrast effects against critical tensions. Under worst case conditions of zero gas elimination, the amount of free gas phase can be assumed to be the difference between the original amount in solution before a pressure excursion, and the amount remaining in solution. In terms of the above, this requires that,

$$\chi P_{N_2} = S \left[p - P_{N_2} \right] , \tag{4}$$

with PN_2 the free (nitrogen) partial pressure, which can be estimated in models.[8, 11, 17]. Not important to discussion here, PN_2 increases roughly with the ambient pressure, P. For given p, χ, and S, Eq. (4) limits ascents through PN_2, leading to deeper staging, as already seen in Figure 2. It appears to have some interesting implications for repetitve diving, particularly when compared to M-value approaches, and we hope to report results of calculations soon. The quantity, p - PN_2, acts as a critical gradient, L, though not constant.

Surfacing tensions will change with safety stops and slower ascent rates. The faster compartments will respond more quickly than the slower ones, and the relative change in tissue tensions will be greater in faster compartments. Similarly, bubbles will grow if conditions favor their expansion on ascent. Fast ascent rates (decreased average pressure) can maximize their growth rate, while slower ascents and safety stops (increased average pressure) can support their dissolution. Bubble growth and dissolved gas buildup compete. Table 1 contrasts relative changes in surfacing critical tensions, $\Delta M_o / M_o$, critical volumes, $\Delta\chi_o / \chi_o$, and bubble radii, $\Delta r_o / r_o$, for a dive to 120 feet for 12 minutes against the same dive with a stop at 15 feet for 3 minutes. Equations (1), (2), and (4) are employed, assuming an initial bubble radius of 1 micron, and an ascent rate of 60 ft/min. Clearly, relative effects are greater on free phase triggers than critical tensions. Calculations are typical for bounce exposures in the 40-150 feet range.

Table 1. Relative Decrease In Critical Parameters After Safety Stop

τ (*min*) half-life	critical tension relative change	critical volume relative change	bubble radius relative change
5	.21	.34	.68
10	.11	.24	.39
20	.06	.11	.24
40	.02	.08	.18
80	-.01	-.03	.02
120	-.02	-.04	-.01

If stop time is added to bottom time, exposures in Table 1 will exhibit higher tensions, as seen in Table 2, contrasting tensions after the safety stop with an actual dive to 120 feet for 15 minutes. Big differences occur in the fastest compartments, but the procedure is conservative. A small table penalty in the slowest compartment, incurred by adding stop time to bottom time, is offset by free phase reduction after the stop.

Table 2. Comparative Surfacing Tissue Tensions

τ (*min*) half-life	surfacing tension (*fsw*) 120 *ft*/15 min	surfacing tension (*fsw*) 120 *ft*/12 min/15 *ft*/3 min
5	101.5	77.0
10	87.5	73.0
20	66.9	59.0
40	49.9	45.7
80	39.0	36.9
120	34.9	33.5

Suggestions

The computational issues of dual phases, bubble formation, growth, and elimination are seen to be outside traditional framework, but get folded into specifications in terms of M-values. Very slow tissue compartments with small M-values can be treatment compartments, tracking both free and dissolved gas exchange in poorly perfused regions. Attempts to track free phases within patently dissolved phase models are not optimal, but still can be mocked up to be more consistent with phase dynamics.

One approach is to slow ascent rates and/or introduce safety stops strategically. As far as net gas exchange is concerned, most combinations of stops and rates can be equated to almost any other set at given pressure, so there is always some leeway. Growth minimization and free phase elimination favor slow ascents, but very slow ascent rates are difficult maneuvers at best, and most divers pay lip service to 60 ft/min. Additionally, ascent rates of 60 ft/min are part of tested schedules. Therefore, we suggest maintaining the present rate of 60 ft/min, while introducing safety stops instead.

Based on results similar to Table 1, a safety stop for 3 minutes at 15 feet is recommended, with the stop time added to bottom time. Such procedure helps to restrict bubble growth, while having relatively small impact on buildup in the slow tissue compartments. A stop at 15 feet for 3 minutes is roughly equivalent to more than halving the standard ascent rate at depths in excess of 120 ft. Adding the stop time to bottom time is conservative, without much penalty. Procedures such as this, as well as reduced no-decompression time limits, appear beneficial in repetitive cases, and we are checking possibilities more completely. A safety stop near 15 ft is easier than 10 ft in adverse water conditions, such as surge and surface disturbances.

At altitude, the same procedures are suggested, with depths, ascent rates, and stops scaled [16, 20] by correction factors, α

$$\alpha = \exp(-.038119z)\ , \qquad (5)$$

for z measured in multiples of 1000 ft, when using the USN tables, or any set for which M-values need extrapolation at reduced ambient pressure. Tables with M-values fitted to altitude data [3, 10] have their own rules.

Summary

We presently do not possess a totally first-principles decompression theory, but we suspect shortcomings of approaches and how to enhance their effective implementation. In the case of the multi-tissue algorithm, there are two problem areas, free phase dynamics and bends trigger points. Fundamentally, tissue tensions are not the same as gas pressures in bubbles and elimination gradients for dissolved phases are not the same as gradients for free phases. Alone, M-value trigger points cannot optimally address the most probable cause of decompression sickness (Type I and II) symptomatic phase levels. With increased exposure, one deduces lower tolerance levels to free phases. With successively deeper profiles, one expects to excite greater numbers of micronuclei into troublesome growth, exceeding body capacity for elimination. These considerations appear at the root of higher bends statistics for divers embarking on multi-day, repetitive, and multi-level excursions, in that order of decreasing risk.[24, 25]. Bounce (non-repetitive) dives appear relatively risk free these days, especially algorithms employing reduced time limits ostensibly restricting growth. And the presence of only small proportions of free phases bootstraps any supersaturation treatment. Overall, such issues might best be left to nucleation and bubble models. Safety stops and slower ascent rates are useful, and correlate in principle with bubble models. Further reduction in no-decompression time limits appears a zero-sum game between safety and optimality.

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Bibliography

[1] Boycott A.E., G.C.C. Damant and J.S. Haldane. 1908. The Prevention Of Compressed-Air Illness. J. Hyg. 8: 342-443.

[2] Hennessy, T.R. 1974. The Interaction Of Diffusion And Perfusion In Homogeneous Tissue. Bull. Math. Biol. 36: 505-527.

[3] Bühlmann, A.A. 1984. Decompression/Decompression Sickness, Berlin: Springer-Verlag.

[4] Workman, R.D. 1965. Calculation Of Decompression Schedules For Nitrogen-Oxygen And Helium-Oxygen Dives, USN Experimental Diving Unit Research Report, NEDU 6-65, Washington, D.C.

[5] Schreiner, H.R. and P.L. Kelley. 1971. A Pragmatic View Of Decompression, Proc. Fourth Symp. Underwater Physiol. New York: Academic Press : 205-219.

[6] Spencer, M.P. 1976. Decompression Limits For Compressed Air Determined By Ultrasonically Detected Blood Bubbles. J. Appl. Physiol. 40: 229-235.

[7] Weathersby, P.K., L.D. Homer, and E.T. Flynn. 1984. On The Likelihood Of Decompression Sickness. J. Appl. Physiol. 57: 815-825.

[8] Hills, B.A. 1977. Decompression Sickness, New York: John Wiley And Sons Inc.

[9] Hempleman, H.V. 1957. Further Basic Facts On Decompression Sickness. Investigation Into The Decompression Tables, Medical Research Council Report, UPS 168, London.

[10] Bell, R.L. and R.E. Borgwardt. 1976. The Theory Of High Altitude Correction To The US Navy Standard Decompression Tables: I. The Cross Corrections, Undersea Biomed. Res. 3: 1-23.

[11] Behnke, A.R. 1967. The Isobaric Oxygen Window Principle Of Decompression, Trans. Third Annual Conf. Marine Tech. Soc., Washington, D.C: Marine Technology Society: 213-228.

[12] Yount, D.E. and R.H. Strauss. 1976. Bubble Formation In Gelatin: A Model For Decompression Sickness. J. Appl. Phys. 47: 5081-5089.

[13] Hennessy, T.R. and H.V. Hempleman.1977. An Examination Of The Critical Released Gas Concept In Decompression Sickness, Proc. Roy. Soc. London (B) 197: 299-313.

[14] Epstein, P.S. and M.S. Plesset.1950. On The Stability Of Gas Bubbles In Liquid-Gas Solutions. J. Chem. Phys. 18: 1505-1509.

[15] Kunkle, T.D. and E.L. Beckman.1983. Bubble Dissolution Physics And The Treatment Of Decompression Sickness. Med. Phys. 10: 184-190.

[16] Wienke, B.R. 1987. Computational Decompression Models. Int. J. Bio-Med. Comp. 21: 205-221.

[17] Wienke, B.R. 1989. Tissue Gas Exchange Models And Decompression Computations: A Review. Undersea Biomed. Res. 16: 53-89.

[18] Yount, D.E. and D.C. Hoffman. 1986. On The Use Of A Bubble Formation Model To Calculate Diving Tables. Aviat. Space Environ. Med. 57: 149-156.

[19] Strauss, R.H. 1974. Bubble Formation In Gelatin: Implications For Prevention Of Decompression Sickness. Undersea Biomed. Res. 1: 169-174.

[20] Wienke, B.R. 1986. DECOMP: Computational Package For Nitrogen Transport Modeling In Tissues. Comp. Phys. Comm. 40: 327-336.

[21] Crocker, W.E., F.C. Goodenough and W.M. Davidson. 1951. Investigation Into The Decompression Tables: Progress Report On The First Series Of Human Exposures. Medical Research Council Report, UPS 118, London.

[22] Farm, F.P., E.M. Hayashi and E.L.Beckman. 1986. Diving And Decompression Sickness Treatment Practices Among Hawaii's Diving Fisherman", University of Hawaii Sea Grant Report UNIHI-SEAGRANT-TP-86-01, Honolulu.

[23] LeMessurier, D.H. and B.A. Hills.1965. Decompression Sickness: A Study Of Diving Techniques In The Torres Strait. Hvaldradets Skrifter 48: 54-84.

[24] Lang M.A. and R.W. Hamilton (Eds.). 1989. Proceedings Of The American Academy Of Underwater Sciences Dive Computer Workshop", University Of Southern California Sea Grant Publication, USCSG-TR-01-89, Los Angeles, CA.

[25] Vann, R.D., J. Dovenbarger, C. Wachholz and P.B. Bennett. 1989. Decompression Sickness In Dive Computer And Table Use. DAN Newsletter 3-6.

[26] Yount, D.E. 1982. On The Evolution, Generation, And Regeneration Of Gas Cavitation Nuclei. J. Acoust. Soc. 71: 1473-1481.

[27] Yount D.E., C.M. Yeung and F.W. Ingle. 1979. Determination Of The Radii Of Gas Cavitation Nuclei By Filtering Gelatin. J. Acoust. Soc. Am. 65: 1440-1450.

[28] Yount, D.E. 1979. Skins Of Varying Permeability: A Stabilization Mechanism For Gas Cavitation Nuclei. J. Acoust. Soc. Am. 65: 1431-1439.

[29] Yount, D.E. 1981. Application Of A Bubble Formation Model To Decompression Sickness In Fingerling Salmon. Undersea Biomed. Res. 8: 199-208.

[30] Van Liew, H.D. 1989. Readjustment Of O_2, CO_2, and H_2O In Bubbles After A Decompression. Undersea Biomed. Res. 16: 32.

[31] Walder, D.N. 1968. Adaptation To Decompression Sickness In Caisson Work. Biometeor. 11: 350-359.

[32] Pilmanis, A.A. 1976. Intravenous Gas Emboli In Man After Compressed Air Ocean Diving. Office Of Naval Research Contract Report, N00014-67-A-0269-0026, Washington, D.C.

[33] Hyldegaard, O. and J. Madsen. 1989. Influence Of Heliox, Oxygen, And N_2O - O_2 Breathing On N_2 Bubbles In Adipose Tissue. Undersea Biomed. Res. 185-194.

[34] Thalmann, E.D. 1989. Testing Of Revised Unlimited-Duration Upward Excursions During Helium-Oxygen Saturation Dives. Undersea Biomed. Res. 16: 195-218.

THE PHYSICS OF BUBBLE FORMATION: IMPLICATIONS FOR SAFE ASCENT RATES IN DIVERS

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A typical decompression schedule for divers consists of a series of relatively rapid ascents interspersed with appropriate safety stops at progressively shallower depths. This is a convenient way of approximating, in practical situations, a theoretically more ideal profile, which would be a smooth curve describing a gradual but continuous pressure reduction. The objective of such a profile or schedule is to allow time for gas dissolved in the body to exit through the lung, thereby avoiding excessive supersaturation, the formation of bubbles in blood or tissue, and the onset of decompression sickness. In the past, attention has been focused mainly on the stops, their depths, and their durations; and the ascent rates between stops varied widely from one set of tables to another with no apparent justification. This paper focuses on the rate of ascent between safety stops and addresses the question of whether there are any limits on that rate that can be deduced from a theory of decompression sickness based on the physics of bubble formation.

Introduction

The topic of this workshop is the biomechanics of safe ascents. The particular issue examined in this paper is whether there are any limits on ascent rates that can be deduced from a theory of decompression sickness based on the physics of bubble formation. To lay a proper foundation for such an inquiry, the paper begins with some observations about decompression sickness. These are followed by a discussion of bubble nucleation and a description of the use of a bubble formation model to calculate diving tables. Finally, with this foundation and all of this scaffolding in place, the more specific subject of ascent rates is addressed.

Decompression Sickness

Decompression sickness is caused by a reduction in ambient pressure which results in supersaturation and the formation of gas bubbles in blood or tissue. This well-known disease, often called "the bends," is associated with such modern-day activities as deep-sea diving, working in pressurized tunnels and caissons, flying at high altitudes in unpressurized aircraft, and EVA excursions from spacecraft.

A striking feature of decompression sickness is that almost any body part, organ, or fluid can be affected, including skin, muscle, brain and nervous tissue, the vitreous humor of the eye, tendon sheath, and bone. Medical signs and symptoms range from itching and mild tingling sensations to crippling bone necrosis, permanent paralysis, and death. There are cases in which bubbles have been found in a diver who died more than 30 days after surfacing. Similarly, bone necrosis can show up months or even years after a single exposure, and often there is no other indication of hyperbaric stress.

Evidently, decompression sickness is a syndrome, rather than a single sign or symptom. It is also a series of events, rather than a single incident. In spite of this complexity and variability, safe decompression can usually be achieved. The key is to reduce the ambient pressure gradually, allowing sufficient time for gas elimination. The word "safe" really means "relatively safe," implying, for example, that the incidence rate for decompression sickness is on the order of 1% of less. The expression "gas elimination" refers to the transport of dissolved gas from blood and tissue to the lung, where it can be expired before bubble formation occurs.

Previous strategies for decompressing humans have been based mainly on trial-and-error informed by past mistakes as well as by a set of unsupported algorithms and assumptions, some of which are now known to be wrong (Yount, 1978).

Given the shortcomings of the standard model, it is appropriate to consider a new theory based on verifiable physical principles and especially on the physics of bubble formation.

Bubble Nucleation

Ordinary samples of sea water, tap water, or even distilled water form visible bubbles when subjected to tensile, ultrasonic, or supersaturation pressures as small as 1 atm. This is several orders of magnitude below the theoretical tensile strength of pure water, and it implies that cavitation must be initiated by processes other than modest changes in pressure and the random motion of water and gas molecules.

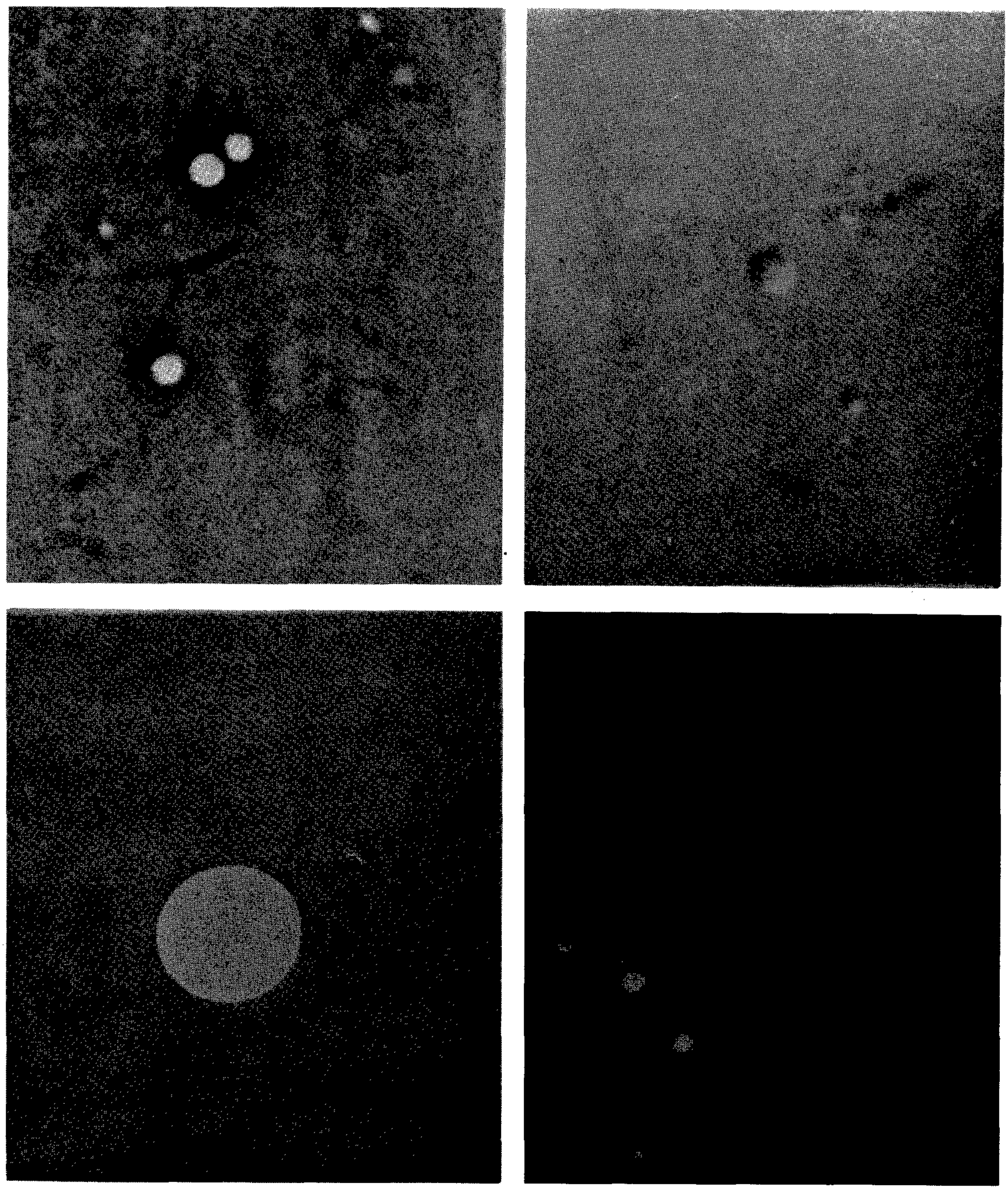
Numerous experiments have demonstrated that thresholds for bubble formation can be significantly raised by degassing or by a preliminary application of static pressure. These are specific tests for gas nuclei, and it is therefore evident that the precocious onset of cavitation in water and in aqueous media generally must be due mainly to the presence of such nuclei, even though their origins and the mechanisms stabilizing them are still poorly understood.

The existence of stable gas nuclei is at first rather surprising. Gas phases larger than 1 micron in radius should float to the surface of a standing liquid, whereas smaller ones should dissolve within a few seconds due to surface tension. The various proposals for coping with this dilemma are critically reviewed in an earlier paper (Yount, 1979b), and a new model, called the varying-permeability or VP model, is introduced.

The essence of the VP model is that cavitation nuclei consist of spherical gas phases small enough to remain in solution and strong enough to resist collapse, their mechanical compression strength being provided by an elastic skin or membrane composed of surface-active molecules. VP skins are ordinarily permeable to gas, but they can become impermeable if the ambient pressure is increased rapidly by a sufficiently large amount, typically exceeding 8 atm.

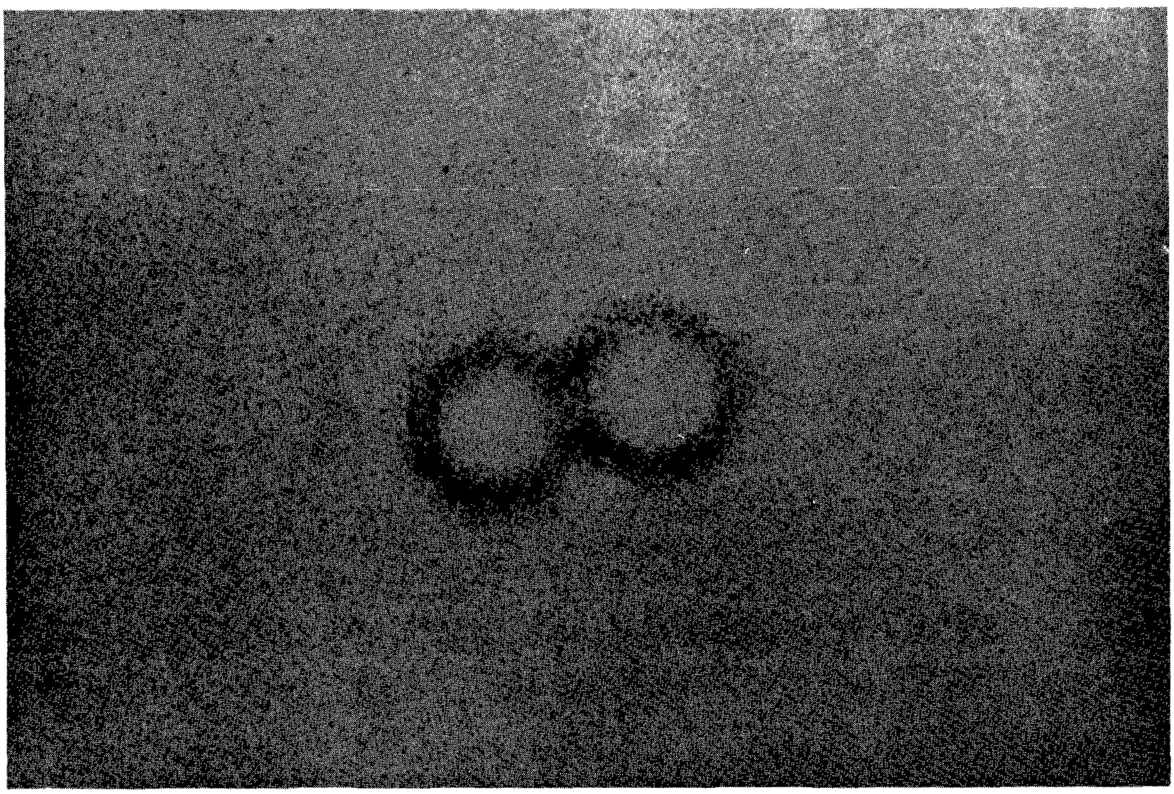
Fig. 1 is a photomontage of microbubble nuclei found in agarose gelatin (Yount *et al.*, 1984). Moving clockwise from upper left are phase-contrast, Nomarsky or interference-contrast, dark field, and transmission electron micrographs. The largest nuclei in each case have radii on the order of 1 micron. The structures identified as nuclei with phase-contrast and Nomarsky optics resemble ordinary gas bubbles. In the Nomarsky micrographs, the shadowing of the nuclei is opposite that of the surrounding gelatin, implying that nuclei are spherical cavities rather than solid or liquid inclusions.

Fig. 1. Candidate nuclei found in agarose gelatin. Moving clockwise from upper left are phase-contrast, Nomarsky, dark-field, and transmission electron micrographs.



Near the center of the phase-contrast micrograph in the montage are two osculating nuclei, that is, two nuclei that are just barely touching and appear to be spherical in shape at the point of contact. Fig. 2 shows a similar binary nucleus photographed in distilled water with ordinary bright-field illumination (Yount *et al.*, 1984).

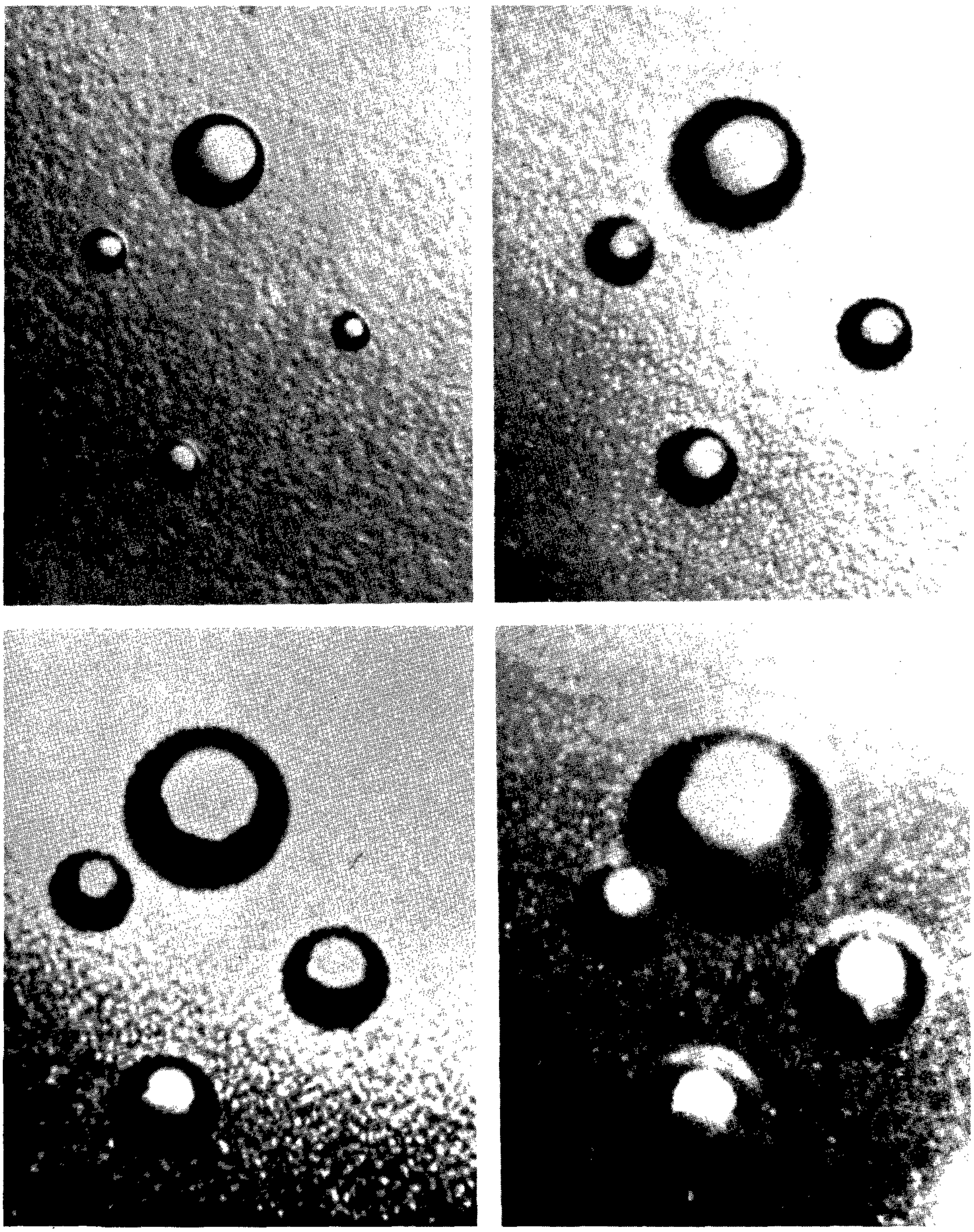
Fig. 2. Two osculating nuclei photographed in distilled water with ordinary bright-field illumination. The larger member of this stable binary has a radius of 1.5 microns.



The facts that there are binary nuclei in nature and that binary nuclei are stable provide further evidence that individual nuclei are enclosed in gas-permeable skins. The idea is that permeable skins allow each nucleus to reach diffusion equilibrium with the gas dissolved in the surrounding liquid. Since both members of a binary configuration are in diffusion equilibrium with the same liquid, they are in diffusion equilibrium with one another and retain their gas contents and relative size. This situation does not hold for binary soap bubbles in air, where it is well-known that the smaller member of the pair will lose its gas to the larger. The fact that nuclei occur in distilled water suggests that they probably can be found in almost any aqueous medium including blood and tissue.

Fig. 3 shows four microbubbles injected into blood plasma (Yount, 1988). The largest radius in the first micrograph is about 5 microns. Moving left to right and top to bottom, the pressures are 1.0, 0.75, 0.5, and 0.25 atm abs. If these microbubbles were not stabilized by some mechanism, presumably by a skin of surface-active molecules, they would have dissolved within a few seconds. It is an important feature of the VP model that a given nucleus can reach equilibrium at different pressures and that a given pressure can support nuclei having widely different radii.

Fig. 3. Four microbubbles injected into blood. The largest radius in the first micrograph is 5 microns. The respective pressures are 1.0, 0.75, 0.5, and 0.25 atm abs.



Theoretical curves are calculated in the VP model by tracking the changes in nuclear radius that are caused by increases or decreases in ambient pressure. This is facilitated by the "ordering hypothesis" which states that nuclei are neither created nor extinguished by a pressure schedule and the initial ordering according to size is preserved. It follows that each bubble count is determined by the properties of a single critical nucleus since all nuclei with larger than critical radii will form bubbles and all those with smaller than critical radii will not. Obviously one of the properties of a VP nucleus is its radius; another is the crumbling compression of its skin.

Typical results of a bubble counting experiment carried out in supersaturated gelatin are shown in Fig. 4 (Yount *et al.*, 1979). The test schedule illustrates how the supersaturation pressure $p_{ss} = p_s - p_f$ and crushing pressure $p_{crush} = p_m - p_o$ are defined in terms of the initial pressure p_o, the maximum pressure and supersaturation pressure $p_m = p_s$, and the final pressure p_f. The impermeability threshold $(p^* - p_o)$ is that value of p_{crush} beyond which the nuclear skin becomes effectively impermeable to gas; this is regarded as another property of the nucleus, yielding a total of three nuclear parameters altogether.

The experimental points in Fig. 4 were determined by finding combinations of p_{ss} and p_{crush} that give a fixed bubble number: N = 0.1, 1.0, 10, 30, 100, and 200 per 0.4 ml sample. The dashed lines were calculated from the VP model. Below the impermeability threshold, the lines are straight with a slope determined primarily by the crumbling compression and with an intercept determined primarily by the radius. At higher crushing pressures where the nuclear skins are impermeable to gas, the pressure inside the nucleus increases as the volume decreases. This makes the nucleus more resistant to further crushing and thereby reduces the slope in a manner rigorously determined by Boyle's law.

Calculating Diving Tables

In the earliest applications of the VP model to decompression sickness (Yount, 1979a, Yount, 1981), one additional assumption was made, namely, that isopleths of constant bubble number N are also lines of constant physiological stress. This idea is tested in Fig. 5 (Yount, 1981) using data from a paper by D'Aoust *et al.* (1980). The new variable $P_i = p_m$ is just p_{crush} displaced by p_o = 1 atm abs to the right, and $P_i - P_f$ is the pressure reduction and hence the supersaturation p_{ss}. Since the pressure excursions are entirely within the permeable region of the VP model, the individual dive scores map out another family of straight lines. Comparison with Fig. 4 suggests that for saturation dives at least, there is a close correlation between physiological outcome and bubble number, as was originally assumed.

An *in vivo* test of the VP model in the impermeable region is shown in Fig. 6 (Yount, 1979a; Yount and Lally, 1980), where ED-50 is the pressure reduction required to produce signs of decompression sickness in 50% of the subject rats (Berghage *et al.*, 1976; Berghage and McCracken, 1979a; Berghage and McCracken, 1979b). In this case, the permeable region extends up to an exposure pressure of about 10 atm abs (p_{crush} = 9 atm), and the VP model continues to provide an excellent description of the rat data all the way out to 40 atm abs. Similar comparisons have been made with decompression results for humans, and although the data for humans are sparse and highly variable, the agreement with the VP model appears to be satisfactory (Yount, 1979a).

Can it be that diving tables are just protocols for producing a constant bubble number in divers? The answer is no. Fig. 7 illustrates what goes wrong (Yount and

Hoffman, 1986). Shown here are the US Navy (1977) and Royal Naval Physiological Laboratory (1968) no-stop decompressions along with various practical observations - combinations of depth and bottom time which yield no symptoms or only the mildest symptoms - compiled by Leitch and Barnard (1982). When one tries to describe these "data" with a line that yields a constant bubble number, the result is always too flat.

Fig. 4. Supersaturation pressure p_{ss} versus the initial crushing pressure p_{crush} for various numbers of bubbles N per sample. Dashed lines were calculated from the VP model.

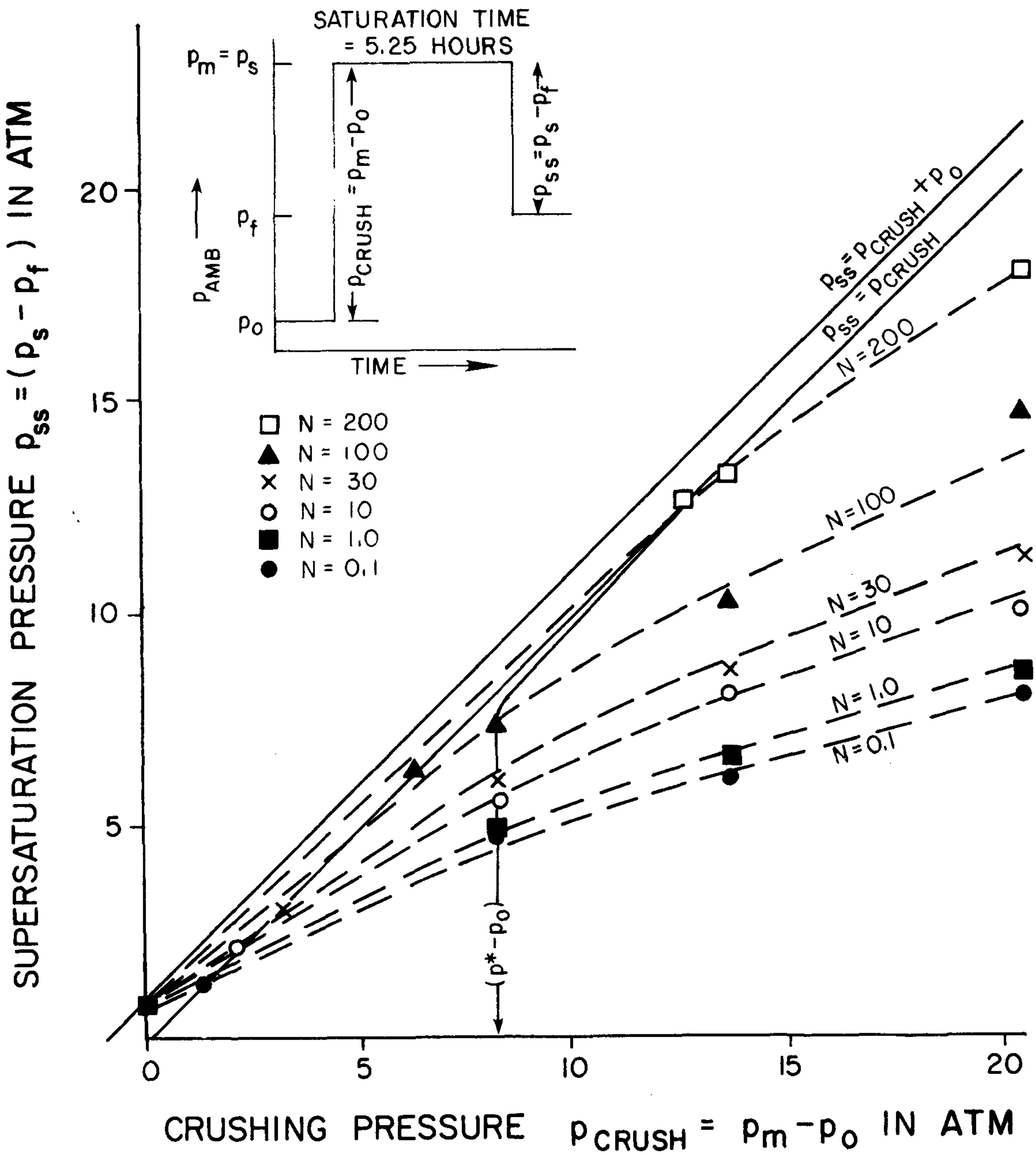
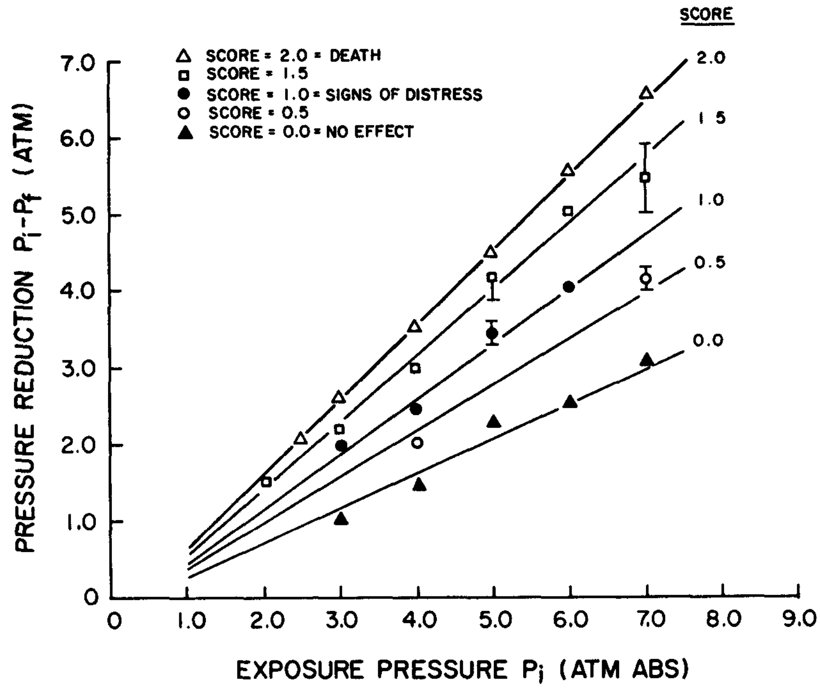


Fig. 5. Limits of pressure reduction $P_i - P_f$ versus exposure pressure P_i for various dive scores in fingerling salmon. The solid lines were calculated from the VP model.



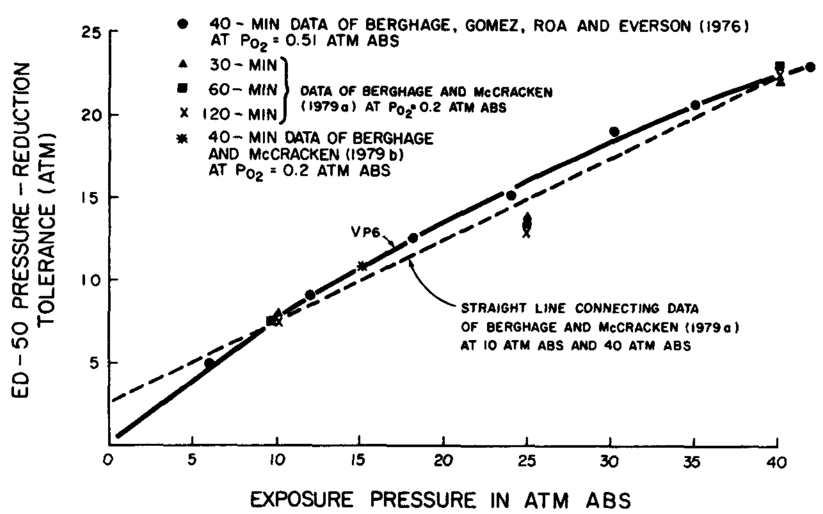
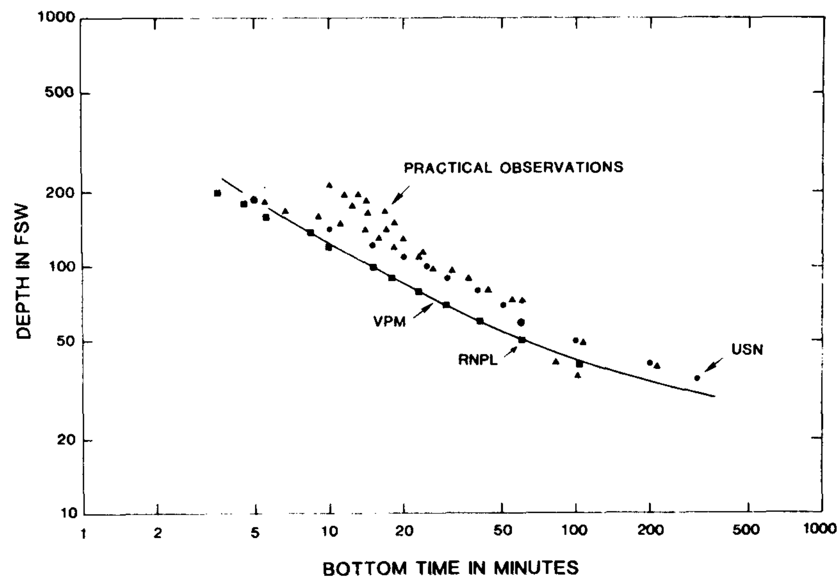


Fig. 6. Compilation of pressure-reduction tolerances versus exposure pressure for albino rats. The solid line was calculated with the VP model.

The inescapable conclusion of this study (Yount and Hoffman, 1986) is that more bubbles actually form on the shorter dives. The naive hypothesis of constant bubble number must therefore be abandoned if the entire range of diving experience is to be described by a single "global theory." A plausible alternative is to assume instead that the total volume of released gas is constant for a given level of risk (Yount and Hoffman, 1986). Since the shorter dives yield more bubbles for a shorter time, the same critical volume of gas is released as on the longer dives. The curve labeled VPM in Fig. 7 is based on the critical volume hypothesis and describes the no-stop data very well.

Fig. 7. Comparison of VPM, USN, and RNPL no-stop decompressions with various practical observations. Over the entire range, the VPM curve gives useful lower bound.



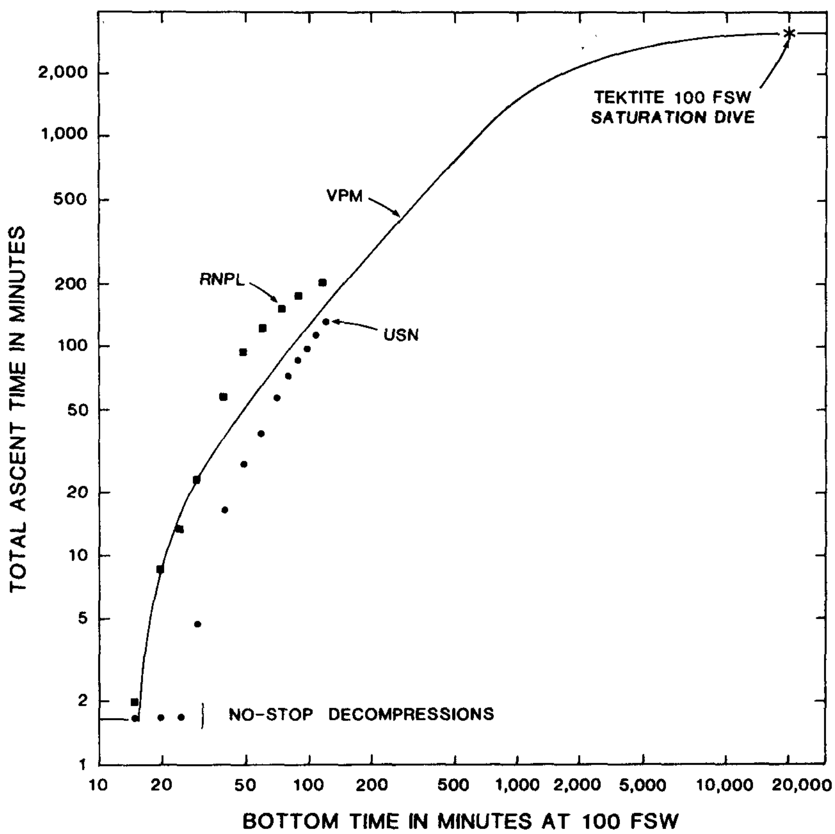
A novel feature of this application of the critical volume hypothesis is the assumption that bubbles present in the venous blood are efficiently trapped and dissipated as free gas by the lung (Butler and Hills, 1979). Meanwhile, dissolved gas in the tissue is continuously coming out of solution. Because gas is simultaneously leaving and entering the gas bubble phase, the term "dynamic critical volume hypothesis" has been used (Yount and Hoffman, 1986).

Global theories have the advantage that they can be tested globally, that is, by bringing to bear the full statistical weight of all of the diving lore available, including other tables. Global testing also takes advantage of the principle of leverage; effects which would be difficult to detect over a small range of depths, durations, or dive situations may become quite pronounced when that range is large.

Perhaps the best example of the principle of leverage is the no-stop decompressions already shown in Fig. 7; when all of these data are examined at once, it becomes quite obvious that the hypothesis of constant bubble number is not universally applicable. As a second example, the total ascent times versus bottom times at 100 fsw for VPM (Yount and Hoffman, 1986), U.S. Navy (1977), Royal Naval Physiological Laboratory (1968), and TEKTITE (Beckman and Smith, 1972) decompression tables are plotted in Fig. 8.

What can be deduced from Fig. 8 is that decompression sickness involves a wide range of tissue half-times. At the low end of the scale, there may be situations such as skin bends, where the controlling half-times are as short as 1 min. To describe the high end, however, half-times as long as 720 min may be required. A complete set of half-times from 1 to 720 min is therefore used in this application of the VP model (Yount and Hoffman 1986).

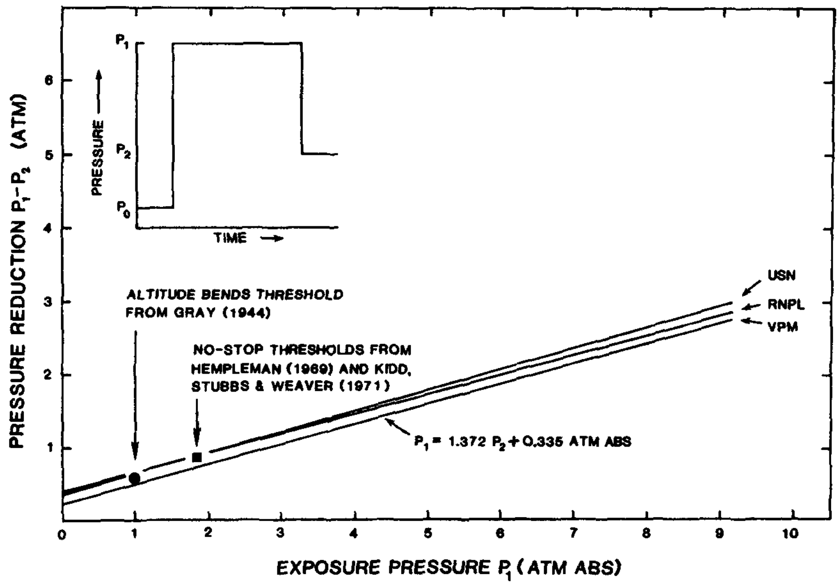
Fig. 8. Total ascent times versus bottom times at 100 fsw for VPM, USN, RNPL, and TEKTITE decompression tables. A single VPM curve connects no-stop and saturation dives.



It should be remembered that the original hypothesis of constant bubble number did work well in certain rudimentary cases, cases which have been referred to as the "nucleation limit" or as the "nucleation regime" (Yount and Hoffman, 1986). This raises the question of whether the new "critical volume hypothesis" can also describe these special situations. The answer is illustrated in Fig. 9, which is a graph of the allowed pressure reduction $P_1 - P_2$ versus exposure pressure P_1 for U.S. Navy (1977), Royal Naval Physiological Laboratory (1968), and VPM (Yount and Hoffman 1986) air diving tables. For exposures of long duration, the actual number of supercritical nuclei N_{actual} is not allowed to exceed N_{safe}, the number determined by the constant bubble number hypothesis. The result is a line of constant bubble number, that is, a straight line which is characteristic of the permeable region of the VP model.

The predictions of the VP model plotted in Fig. 9 are also compared with the altitude bends threshold measured by Gray (1944) and with the no-stop thresholds for arbitrarily long bottom times measured by Hempleman (1969) and by Kidd, Stubbs, and Weaver (1971). The VPM straight line falls within the "safe" region just below these firm experimental limits. By contrast, the USN and RNPL tables lie in the "unsafe" region just above. This illustrates again the difference between a local table-by-table empirical approach and the global method. In the global method, altitude bends and decompression sickness are regarded as aspects of the same phenomenon, and both must therefore be described by the same set of parameter values.

Fig. 9. Allowed pressure reduction $P_1 - P_2$ versus exposure pressure P_1 for USN, RNPL, and VPM air tables. In this case, VPM yields a line of constant bubble number.



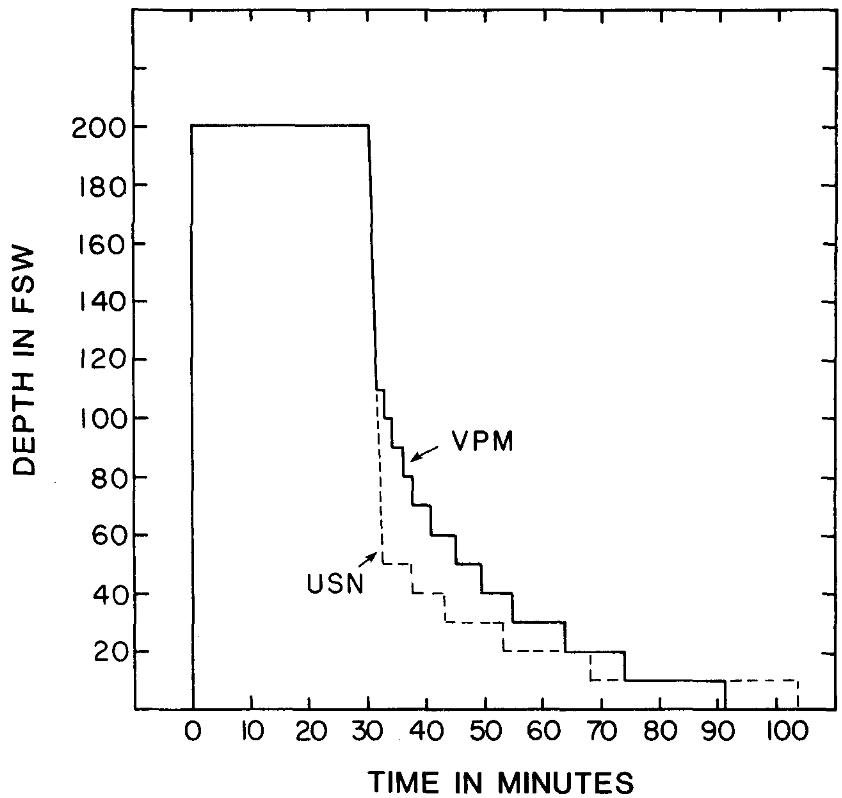
The statistical leverage made possible by the global method can now be visualized by imagining that the straight lines in Fig. 9 are simple levers subjected to an appropriate force at each data point. The better the statistics, the stronger the force. But it also helps to have leverage, and that is another reason why the altitude bends threshold at one end of the lever (Gray, 1944) is so very important. From a phenomenological point of view, the VP model merely explains why the line is straight; but this is a useful contribution because it imparts to the lever a theoretical "stiffness" that it would not have in an ad hoc parameterization.

Ascent Rate

In calculating diving tables with the VP model, it was assumed, following the U.S. Navy (1977), that descent and ascent rates are 60 fsw per min. As illustrated in Fig. 10 (Yount and Hoffman, 1986), the 3.33 min required to reach 200 fsw is counted as part of the bottom time, and the various times required to ascend are attributed to the subsequent depth. The main difference in these tables is the deeper first stop for VPM, 130 fsw versus 60 fsw for USN. It is believed on the basis of VP model calculations (Yount and Hoffman,

1986) that the longer "first-pull" of conventional tables results in a larger supersaturation, a larger bubble number, and ultimately, in a larger maximum volume of released gas.

Fig. 10. VPM and USN profiles for a 60-min dive to 200 fsw. The longer "first pull" of conventional tables results in a larger supersaturation and a larger volume of released gas.



Whereas most decompression schedules, including the one shown in Fig. 10, involve a range of tissue half-times, the theoretically optimum profile for a saturation dive is determined by a single tissue type, which is the slowest tissue in the decompression model. This ideal profile (Yount and Strauss, 1976) is remarkably simple and consists of only two phases: a first-pull which yields a fixed bubble number and a straight-line trajectory that begins at the end of the first-pull and decreases with constant slope. In the VP model, the bubble number for a saturation dive never exceeds N_{safe}, and the constant slope is calculated from the single controlling tissue half-time and the initial radius and crumbling compression of the critical nucleus.

For decompressions which are controlled by two tissue half-times, the first pull is followed by two successive straight lines having different slopes determined, respectively, by the two half-times. Generalizing to a continuous range of half-times, one obtains a smooth curve with a slope that decreases gradually as the longer half-times come into play. It is this smooth curve which, for practical reasons, is generated by a finite set of discrete half-times and is approximated by the more common staged decompression, such as that shown in Fig. 10.

Focusing now on the ascent rate used between stages as well as on the first pull, one can now address the question of whether there are any limits on that rate which can be determined from the VP model. To a first approximation, the answer is no. Providing the degree of supersaturation never exceeds the level imposed by the dynamic critical volume hypothesis, it makes very little difference how rapidly that level is achieved. This conclusion, which applies only to decompression sickness per se and not to other possible manifestations of decompression, such as arterial air embolism, pulmonary barotrauma, and inner ear problems, is consistent with the fact that rates of ascent as slow as 20 ft/min and as fast as 510 ft/min have been reported at this workshop.

Taking a closer look, one can say that ascent rates slower than 20 ft/min would begin to add significantly to the overall decompression time, perhaps contributing a slight margin of safety to tables that are presumably already safe. If the ascent rate becomes too rapid, on the other hand, unusually short tissue half-times would come into play.

Whereas applications of the VP model (Yount and Hoffman, 1986) have assumed a complete set of half-times from 1 to 720 min and an ascent rate of 60 ft/min, the 1 min half-time is never actually used. If the ascent rate were significantly faster than 60 ft/min, the 1 min half-time would be excited and eventually even shorter half-times would have to be taken into account. What this implies physiologically is that tissues with exceedingly short half-times, such as skin, lung, and brain, would be at risk.

In summary, it is expected on the basis of VP model calculations that a wide range of ascent rates can be used safely, especially if the times required for ascent are properly taken into account. This conclusion applies only to decompression sickness per se, which suggests that in practical situations the maximum rate of ascent is limited by other manifestations of decompression, such as arterial air embolism, pulmonary barotrauma, and inner ear problems. There is no apparent limit to the minimum rate of ascent.

Literature Cited

Beckman, E.L. and E.M. Smith. 1972. Tektite II: Medical supervision of the Scientists In The Sea. Texas Reports Biol. Med. 30: 155-169.

Berghage, T.E., J.S. Gomes, C.E. Roa and T.R. Everson. 1976. Pressure reduction limits for rats following steady state exposures between 6 and 60 ATA. Undersea Biomed. Res. 3: 261-272.

Berghage, T.E. and T.M. McCracken. 1979a. The use of oxygen for optimizing decompression. Undersea Biomed. Res. 6: 231-239.

Berghage, T.E. and T.M. McCracken. 1979b. Equivalent air depth: fact or fiction. Undersea Biomed. Res. 6: 379-384.

Butler, B.D. and B.A. Hills. 1979. The lung as a filter for microbubbles. J. Appl. Physiol. 47: 537-543.

D'Aoust, B.G., L. Stayton and L.S. Smith. 1980. Separation of basic parameters of decompression using fingerling salmon. Undersea Biomed. Res. 7: 199-209.

Gray, J.S. 1944. Aeroembolism induced by exercise in cadets at 23,000 feet. Committee on Aviation Medicine Report 260. United States National Research Council, Washington, D.C.

Hempleman, H.V. 1969. British decompression theory and practice. *In:* Bennett, P.B. and D.H. Elliot (eds.) The Physiology and Medicine of Diving and Compressed Air Work. Williams and Wilkins, Baltimore. Pp. 291-318.

Kidd, D.J., R.A. Stubbs, R.S. Weaver. 1971. Comparative approaches to prophylactic decompression. *In:* Lambertsen, C.J. (ed.) Proceedings of the Fourth Symposium on Underwater Physiology. Academic Press, New York. Pp. 167-177.

Leitch, D. R. and E.E.P. Barnard. 1982. Observations on no-stop and repetitive air and oxynitrogen diving. Undersea Biomed. Res. 9: 113-129.

Royal Naval Physiological Laboratory. 1968. Air Diving Tables. Her Majesty's Stationary Office, London.

U.S. Department of the Navy. 1977. U.S. Navy Diving Manual (NAVSHIPS 0994-LP-001-9010). U.S. Government Printing Office, Washington, D.C.

Yount, D.E. 1978. Responses to the twelve assumptions presently used for calculating decompression schedules. *In:* Berghage, T.E. (ed.) Decompression Theory, the Seventeenth Undersea Medical Society Workshop. Undersea Medical Society, Bethesda, Md. Pp. 143-160.

Yount, D.E. 1979a. Application of a bubble formation model to decompression sickness in rats and humans. Aviat. Space Environ. Med. 50: 44-50.

Yount, D.E. 1979b. Skins of varying permeability: a stabilization mechanism for gas cavitation nuclei. J. Acoust. Soc. Am. 65: 1429-1439.

Yount, D.E. 1981. Application of a bubble formation model to decompression sickness in fingerling salmon. Undersea Biomed. Res. 8, 199-208.

Yount, D.E. 1988. Theoretical considerations of safe decompression. *In:* Lin, Y.C. and A.K.C. Niu (eds.) Hyperbaric Physiology and Medicine. Best Publishing Company, San Pedro, California. Pp. 69-97

Yount, D.E. and D.C. Hoffman. 1986. On the use of a bubble formation model to calculate diving tables. Aviat. Space Environ. Med. 57: 149-156.

Yount, D.E. and D.A. Lally. 1980. On the use of oxygen to facilitate decompression. Aviat. Space Environ. Med. 51: 544-550.

Yount, D.E. and R.H. Strauss. 1976. Bubble formation in gelatin: a model for decompression sickness. J. Appl. Phys. 47: 5081-5089.

Yount, D.E. and C.M. Yeung. 1981. Bubble formation in supersaturated gelatin: a further investigation of gas cavitation nuclei. J. Acoust. Soc. Am. 69: 702-708.

Yount, D.E., E.W. Gillary, and D.C. Hoffman. 1984. A microscopic investigation of bubble formation nuclei. J. Acoust. Soc. Am. 76: 1511-1521.

Yount, D.E., C.M. Yeung, and F.W. Ingle. 1979. Determination of the radii of gas cavitation nuclei by filtering gelatin. J. Acoust. Soc. Am. 65: 1440-1450.

PHYSICS SESSION DISCUSSION
Discussion Leader: Glen H. Egstrom

Bill Hamilton remarked that there was a problem with the titration. In several cases David Yount showed data points that he'd gotten from one or another source. It's important to keep in mind that a data point is a lot bigger than one thinks it is because of the variability. You can't titrate decompression sickness. If you're going to operate at a level of risk or conservatism or reliability, then 1% is still way too much. Just to quote a number: To get a 99% confidence that your incidence is less than 1%, does anyone have any idea how many clean dives it takes in a row to prove that statistically? 468 or so. The problem with taking this data out of the literature is that none of them has that much bulk in order to be good. The other thing is that you start looking at the U.S. Navy tables as a reference point, which is appropriate, you have to remember though that there is a huge difference in the reliability between the short dives and the long dives in the U.S. Navy. The data in one range has a lot less meaning and reliability than the data in the other range in terms of practical experience. David Yount agreed with Bill Hamilton's observations. One reason why we're using the so-called global approach is that no one piece of data is all that reliable. So only by looking at everything we can get our hands on do we start to feel that we have some confidence.

David Yount continued: There is another idea here which I call the principle of leverage. If you get saturation dives at one extreme end of the lever, you get no-stops at the other extreme, then you have the confidence about in the middle. Bruce Wienke made this point earlier: You don't mind interpolating between points, but when you extrapolate outside the M-values, then you're very nervous about it. So you try to get the widest possible range. Bill Hamilton countered that the TEKTITE dive was probably an N of 6 or something, but that's all we have to go on. Therefore, I do agree with you on the leverage aspect of it.

Glen Egstrom: Did I gather correctly, David, that you indicated that the rate of ascent could be compensated for within certain limits? David Yount answered that it was clear that there is a very wide range of ascent times that would be OK. If the ascent part of your dive is less than a minute, it probably isn't necessary to do anything. When the time you spend becomes significant, because of the time you would spend at a stop, if the ascent is very slow, you won't have to stop as long at the next stop. You could gain a little bit of advantage on the next stop. You could build it into the next stop. Your computer will calculate that for you. If you can take into account the time that it takes to make these ascents going into the next stage, then the issue arises, suppose different divers using the same table are using different ascent rates. They're not building it into the next stage. If one person is very fast, then the theoretician assumed that this was going to take a minute, but it only took 10 seconds, then you lose. Bruce Wienke added with reference to Glen's question that they had done a series of calculations for different ascent rates, from 200 fpm to 30 fpm and we found that as far as parameterizing the tables, we could always fold those ascent rates into an equivalent stop, somewhere in the range of 15 to 20 feet. Glen Egstrom recognized that that was a very valuable comment.

Hugh Van Liew asked David Yount to explain what happens to the nuclei that allows him to take that first plunge and go down so suddenly. David explained that the controlling tissue had a tension which was equal to τ, which is a bit less than the tension at the bottom at the depth that you're exposing a diver to. This tissue has not come up to the maximum. You haven't really saturated this tissue yet. Delta p is closely related to $2\gamma/r$, where this r is the radius of the nucleus at the end of the dive. Hugh further commented that that depended on the distribution of the nuclei and that there must be a maximum size nucleus existing. David insisted there wasn't. The nuclei are 1 micron. If you asked if there were any nuclei of 2 micron size, I would answer that there is 1/10 of a nucleus per mm^3 of tissue. It takes 10 mm^3 to find one nucleus. Hugh said if that was the case, with any decompression, you then would have nuclei transformed into bubbles. David stated it was his belief that you always get some bubbles. What we are really doing here is choosing a radius that we can tolerate that number of bubbles that we're going to get.

Glen Egstrom mentioned that it was obvious that we would have to come back to this point. You gentlemen have done a terrific job of stimulating the group and we will have to find time to be able to get back to this topic later on in the workshop.

GROWTH OF PRE-EXISTING BUBBLES AND GAS NUCLEI IN THE BODY DURING ASCENT FROM DEPTH

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To prevent bubbles from growing, or gas nuclei from developing into bubbles, P_{N_2} in the gas phase should be kept high and tissue P_{N_2} should be kept low so that N_2 will not diffuse into the gas phase. In this communication, computer simulations illustrate the relation of ascent rate to bubble growth and to the transformation of gas nuclei into bubbles. A slow ascent rate has the advantage that it keeps total pressure in nuclei and in bubbles high; it has the disadvantage that it slows the removal of N_2 from tissue but this effect is not very large quantitatively. The simulations all indicate that the advantages of slow ascents outweigh the disadvantages. It appears that the slower the ascent, the better.

Introduction

Size changes of pre-existing gas bubbles can be predicted quite accurately from fairly simple physical laws if the details about the bubble and its surroundings are known. Unfortunately, details about decompression bubbles and their surroundings in the body vary considerably from situation to situation, so that specific predictions about one bubble are not valid for another and predictions about effect of rate of ascent have to be made cautiously.

The question of whether a bubble in an air-breathing diver persists and grows can be rephrased to the question of whether nitrogen molecules diffuse in or out of the bubble (Fig. 1). Nitrogen partial pressure inside the gas phase depends on total pressure and O_2 and CO_2 partial pressures in the bubble, and the total pressure in turn depends on ambient pressure and pressure due to surface tension. The pressure generated by surface tension in a spherical bubble is inversely proportional to the bubble radius. Nitrogen partial pressure in the tissue or blood outside the bubble depends, in the long term, on N_2 partial pressure in alveolar gas but tends to lag behind changes in alveolar N_2; tissue and blood N_2, in the short term, depend on washin or washout of N_2 by blood circulation.

Rate of ascent and the concentration of O_2 in the breathing gas are under the control of the diver and bubble O_2 and CO_2 are usually relatively stable. However, two important items in Fig. 1 are out of the diver's hands:

a. if the body contains many bubbles or bubble nuclei, they probably will be various sizes, and therefore will have various surface tension pressures, and
b. if there are many bubbles or nuclei, they are likely to be located in tissues having a wide variety of washin/washout characteristics.

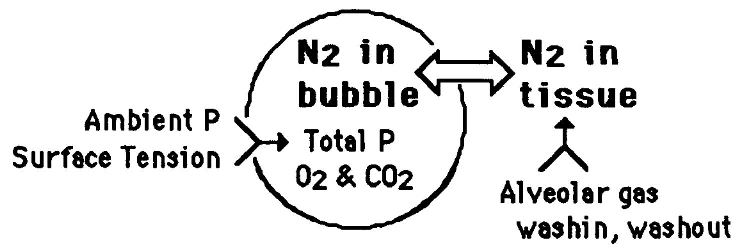

Fig. 1. Diagram of the main factors that determine whether a bubble grows or shrinks.

In what follows, specific examples of bubbles or bubble nuclei will be described. A broader perspective can be achieved by remembering that other bubbles or nuclei in the body may differ from the cases shown in size or in washout characteristics of their surroundings. Tissues with slow washin may still be taking up N_2 when the ascent occurs, so they may have relatively low N_2, and they will be slow in giving off N_2 after ascent.

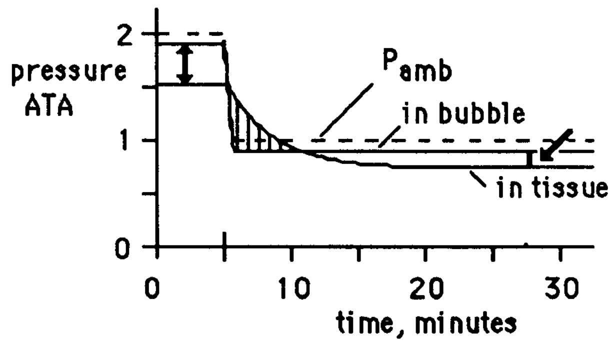

Fig. 2. Ambient pressure (dashed), and partial pressures of N_2 in a bubble and in the surrounding tissue in an ascent from 33 fsw to surface.

Decompression from 33 fsw to surface

Figure 2 is a diagram of events which occur during a simple ascent, at a rate of 1 fsw/sec, from an ambient pressure of 2 ATA to 1 ATA. When ambient pressure falls during the ascent, N_2 in a bubble falls too. If it is assumed that the sum of partial pressures equals ambient pressure, PN_2 inside (labeled "in bubble") is always a little lower than ambient pressure because the bubble contains O_2, CO_2, and water vapor as well as N_2, but if the tissue exerts significant pressure on the bubble, the PN_2 inside the bubble could actually be above the ambient pressure.

The hatched region in Fig. 2 emphasizes the time when PN_2 in the tissue (labeled "in tissue") is temporarily above PN_2 in the bubble because dissolved gas in the tissue awaits washout by the circulation. The phenomenon can be called a "crossover"; it is crucial for causing bubble growth or transformation of a nucleus into a bubble.

In steady states before and after the ascent, the PN_2 is higher in a bubble than in the tissue because of what is known as the "oxygen window", or "inherent unsaturation" (1). The two heavy arrows in Fig. 2 show the magnitude of the oxygen window before and after the ascent.

The author has developed a computer program in the BASIC language to predict size of a bubble, as a function of time, under various circumstances (Van Liew, 1989); the program includes the important aspects of dynamics of bubbles (Van Liew and Hlastala, 1969). The program assumes that bubbles are always spheres, which may be adequate for small bubbles, but bigger ones are probably distorted into cylinders or sheets by tissue or blood vessels.

Figure 3 shows the calculated radius of a bubble subjected to the pressures discussed in connection with Fig. 2. At first the bubble shrank from its original radius of about 80 micrometers due to the oxygen window. When the ascent occurred, the bubble enlarged because of simple decompression of the gas (Boyle's law), but there was a crossover of N_2, so the bubble also grew by diffusion of N_2 molecules. The Boyle's law effect alone would have increased the bubble from 50 micrometers to 63 micrometers, whereas it actually grew to 100 micrometers. When tissue N_2 became lower than bubble N_2 at 11 minutes, the bubble shrank again. When the radius became very small, at 27 minutes, surface tension became the overriding component, so total pressure inside the bubble rose precipitously, which led to an abrupt rise in N_2 partial pressure in the bubble.

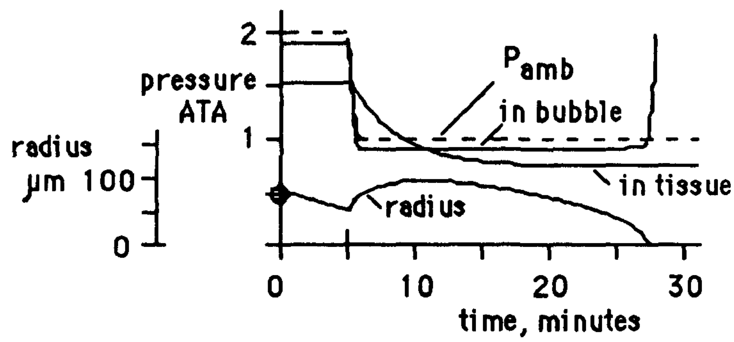

Fig. 3. Radius of a pre-existing bubble which is subjected to an ascent from 2 ATA to the surface.

When a bubble is very small, surface tension pressure inside is very large, so the tendency for diffusion out of N_2 is very large. Thus a simplistic interpretation of the physical rules indicates that bubbles cannot be small and therefore cannot exist in the body, where the oxygen window always tends to cause bubbles to shrink. This logical problem has led to the idea that the simple physical rules do not apply, or that something else is happening. The popular way around the problem is to assume that there are "gas nuclei", which do not obey the rules of surface tension for free bubbles in a liquid medium. When the circumstances are right, the very small entities of gas which persist as nuclei can grow into real bubbles that do obey the physical laws.

Nuclei

Gas nuclei were simulated with the abovementioned computer program by not allowing a very small initial bubble to become smaller, but allowing it to grow larger by Boyle's law and by N_2 diffusion.

Figure 4 illustrates some issues about nuclei. A large bubble would have PN_2 inside it of about 1.9 ATA as in Figs. 2 and 3 (light dotted line at the left in Fig. 4), whereas a nucleus of 1.57 micrometers radius has a PN_2 of almost 2.5 ATA as shown - the difference is caused by the high surface tension pressure consequent to the small radius of the nucleus. When the ambient pressure fell from 2 ATA to 1 ATA, the PN_2 in the nucleus fell in parallel so that after ascent, at the right, the nucleus would have a PN_2 of about 1.5 ATA whereas a bubble would have a PN_2 of about 0.9 ATA. At no time was nucleus PN_2 less than tissue PN_2 in Fig. 4; a crossover was narrowly avoided (at the big arrow).

When the nucleus was just one one-hundredth of a micrometer larger, a different picture emerged (Fig. 5). There was a tiny crossover at the arrow which allowed the nucleus to grow, and the growth caused a rapid decrease of surface tension pressure so that PN_2 inside fell (from the level of the arrow to 0.9 ATA). The nucleus became a bubble. When the bubble decayed to a nucleus again, the PN_2 inside was again high because of the surface tension pressure.

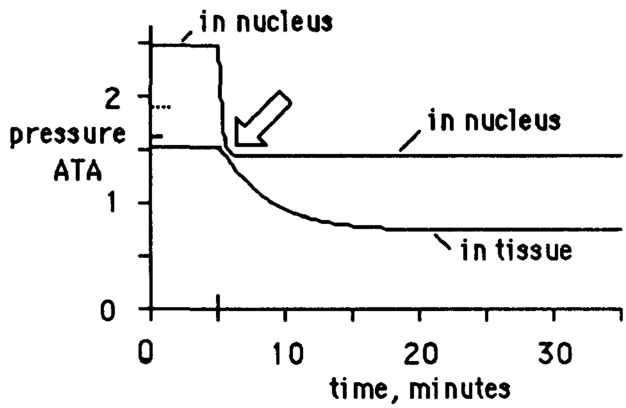

Fig. 4. A bubble nucleus subjected to the same ascent as in Figs. 2 and 3.

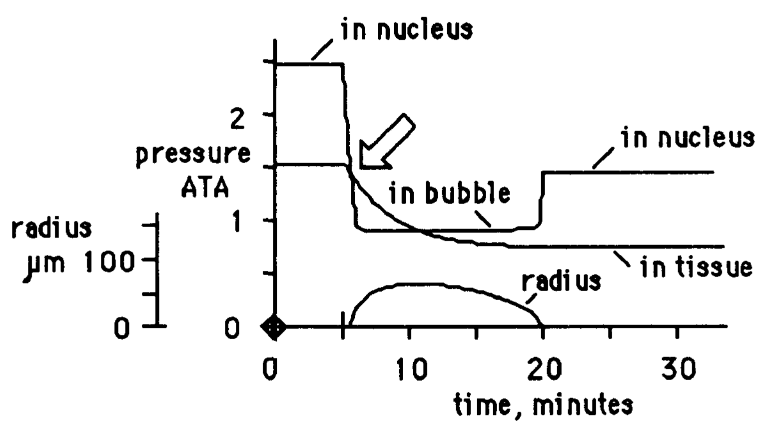

Fig. 5. In a nucleus slightly larger than the one of Fig. 4, a crossover allowed transformation into a bubble.

Several variables can be critical in the transformation of a nucleus into a bubble. One of these is initial size of the nucleus, as evidenced by the finding that an increase of less than 1% (from 1.57 to 1.58 micrometers) changed the situation from no-growth to growth. In a much smaller nucleus, the PN_2 inside would be much higher, so crossover would not occur unless PN_2 in tissue was also much higher than in the Fig. 5 case.

A second critical variable is tissue washout rate, as characterized by the washout halftime that would be observed after an instantaneous decompression. If the washout had been faster in Fig. 5, the tissue PN_2 would have fallen more steeply so the PN_2 crossover might not have occurred. The slower the washout, the higher the "in tissue" curve, and the more likely a crossover and bubble growth.

A third critical issue is the ascent rate. If ascent had been faster, the PN_2 in the bubble would have fallen more steeply and crossover would have been more likely. If ascent were slower, the fall of PN_2 in the nucleus would have been slower, but also the removal of N_2 from the tissue would have been slower. The relation between these competing influences is shown in Figs. 6 and 7. When washout halftime is held constant, decrease of ascent rate by factors of 10 and 20 from the usual 1 fsw/sec delays the removal of N_2 by factors of just 3 or 4 (Fig. 6). Only very slow ascent has an appreciable effect.

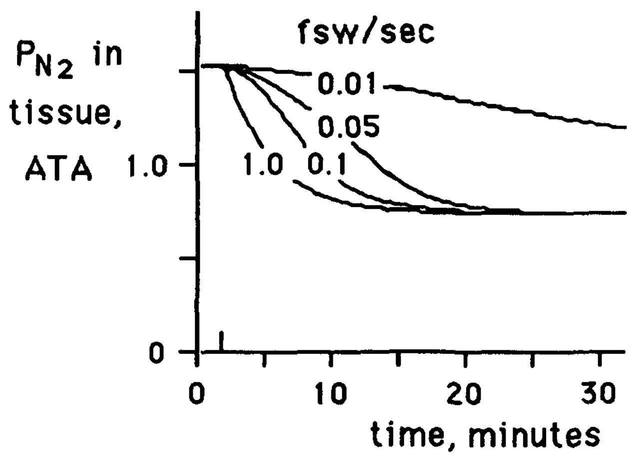

Fig. 6. Effect of various ascent rates on removal of N_2 from a tissue having a washout halftime of 2.5 minutes.

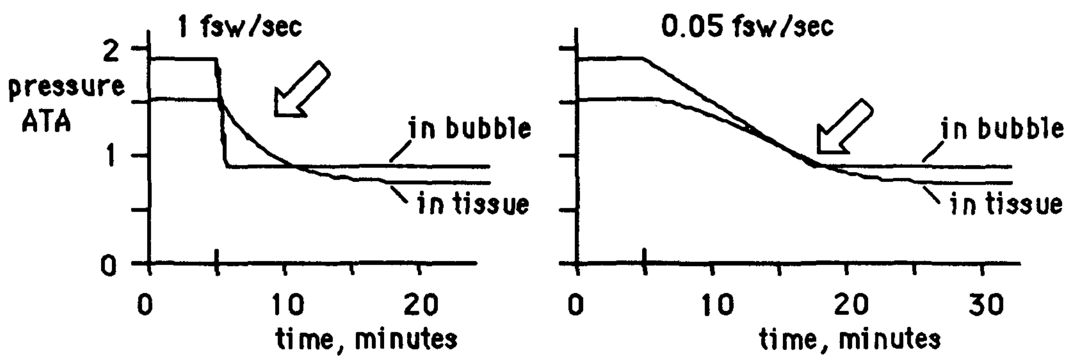

Fig. 7. Relation of tissue N_2 removal to PN_2 in the bubble when washout halftime is 2.5 minutes.

Figure 7 illustrates the relation between PN_2 in a bubble and in the tissue for the .05 and 1.0 fsw/sec profiles of Fig. 6. When ascent is fast, the N_2 removal has an essentially exponential form but with the slower ascent, the tissue PN_2 tends to be parallel to the bubble PN_2, which of course follows the ambient pressure. The fast ascent gave a big crossover region, whereas the slow ascent had almost no crossover. One could conclude from this comparison that the high ambient pressure (and high bubble PN_2) in the slow ascent is more of an advantage than the more rapid N_2 removal with the fast ascent. When washout is slow, such as in tissues with a halftime of 30 minutes, bubbles comparable to those shown in Fig. 7 have long-lasting crossovers for both 1 and .05 fsw/sec ascents, but for nuclei there would still be an appreciable advantage of a slow ascent.

Slow ascents may have an additional disadvantage: slow tissues which are not yet equilibrated may take on additional gas.

Two-stage decompression

The rectangular-appearing profile in Fig. 8 is PN_2 in a nucleus which became a bubble when the diver followed U.S. Navy table decompression for a dive to 60 fsw for two hours. Ascent is 1 fsw/sec in two stages; the diver goes from 60 fsw to 10 fsw, remains 26 min, then ascends to the surface. In the case shown, tissue washout halftime is 5 min. The transformation to a bubble occurred during the first ascent and the second decompression caused a small additional phase of growth. When the ascent rate in this particular case was decreased by a factor of 6, the nucleus did not become a bubble until near the end of the ascent. The PN_2 in the nucleus decreased along with the decrease of ambient pressure, but the nucleus PN_2 eventually was less than tissue PN_2, so the drastic decrease of PN_2 inside occurred, which allowed a drastic influx of N_2 by diffusion. Decrease of the ascent rate by a factor of 10 prevented the nucleus of Fig. 8 from becoming a bubble.

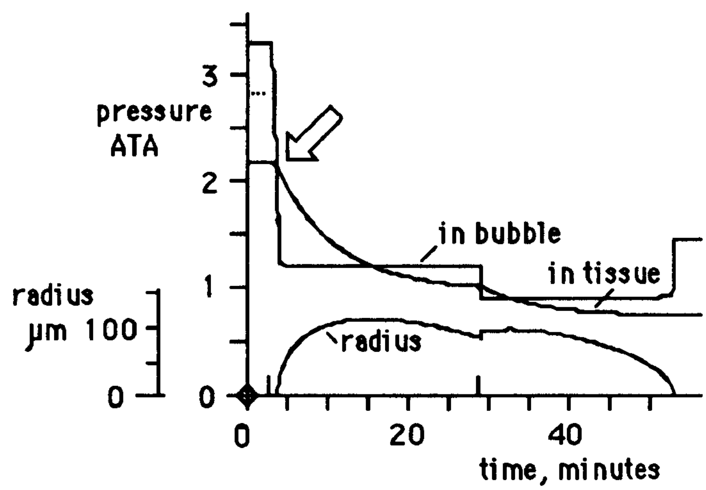

Fig. 8. Behavior of a nucleus during a two-stage decompression.

An alternative to the two-stage decompression shown in Fig. 8 would be a very slow linear ascent which would allow the diver to arrive at the surface in the same time, but without stops (Fig. 9). Ascent is .04 fsw/sec, or 2.4 fsw/min. Tissue N_2 removal is slower. A bubble would have a crossover, but PN_2 in the nucleus would not reach the PN_2 in the tissue. However, note that if tissue washout halftime had been so slow that tissue PN_2 remained almost level during the ascent, there could have been a PN_2 crossover and consequent nucleus growth in the region to the right of the big arrow.

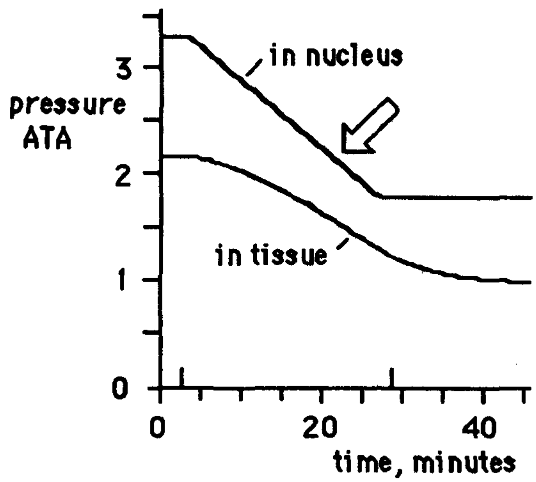

Fig. 9. Partial pressure of N_2 in a nucleus and the surrounding tissue during a very slow ascent from 60 fsw to surface.

The simulations above all indicate that the slowest possible ascent is desirable. However, a note of caution is advisable; only certain of the many possible combinations of dive profile, ascent rate, and tissue washout characteristics have been examined; other combinations of variables might modify the conclusions reached.

References

Van Liew, H.D. 1989. Gas exchanges of bubbles in tissues and blood. *In:* R.D. Vann (ed.). The Physiological Basis of Decompression. Thirty-eighth UHMS Workshop. Bethesda, MD: Undersea and Hyperbaric Medical Society Inc. pp. 73-83.

Van Liew, H.D. and M.P. Hlastala. 1969. Influence of bubble size and blood perfusion on absorption of gas bubbles in tissues. Respir Physiol 7: 111-121.

ASCENT RATE EXPERIMENTS AND DIVER SAFETY

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Submarine escape experiments in goats conducted by the Royal Navy offer an animal model of physiological responses to rapid ascent rate and decompression. Rapid ascents in submarine escape involve insults of rapid decompression, but these are usually tolerated by animals and humans. In those cases where injuries do result, arterial gas embolism and decompression sickness, frequently with CNS manifestations, characterize the injuries from such maneuvers. While tissue N_2 uptake and the incidence of decompression sickness decrease in submarine escapes with shortened compression and ascent times, such rapid ascents increase the risk of pulmonary barotrauma and arterial gas embolism. Ascent rates up to 2.6 m/sec (8.5 ft/sec) are tolerated in humans with a comparatively low risk of serious injury or death. However, recreational and scientific diving with compressed air require an even lower risk of serious outcome. This paper reviews ascent rate outcomes in animals and humans with the goal of improving diver safety.

"A life without adventure is likely to be unsatisfying, but a life in which adventure is allowed to take whatever form it will is likely to be short". -- Bertrand Russell

Introduction

Submarine escapes represent examples of extremely rapid decompressions and as such they can provide valuable insights about human physiological responses with extremely rapid ascent. Both animal and human findings in submarine escape experiments that sometimes provoke decompression sickness (DCS) and arterial gas embolism will be reviewed with most attention focused on the Royal Navy's submarine escape outcomes. Previous findings reported in the submarine escape literature are re-examined to determine if conventional ascent rates (60 ft/sec) and somewhat faster ascents pose a significant risk for the diver. Several implications that such findings have for recommendations of ascent rates with acceptable risk for recreational and scientific diving with scuba will be evaluated.

Risk in ascent: Pulmonary barotrauma and decompression sickness

The primary risks in scuba diving ascent are DCS and pulmonary barotrauma which causes arterial gas embolism (Elliott and Kindwall, 1982). Arterial gas embolism and some forms of DCS can seriously imperil the diver (Shilling, Carlston and Mathias, 1984), and these will be briefly described.

Pulmonary barotrauma from overinflation of the lungs during ascent is the usual cause of arterial gas embolism in the brain, heart and other organs. Lung dissection from overinflation during ascent can also result in pneumothorax, mediastinal emphysema, and subcutaneous emphysema (Shilling and Faiman, 1984). Pulmonary barotrauma can occur with a low intrapulmonary overpressure compared to ambient pressure. With the lungs fully inflated (at total lung capacity), pulmonary barotrauma would be expected with a 0.9-1.8m (3-6 ft) ascent to surface accompanied by overinflation pressures in the lungs as low as 80mm Hg (Lanphier, 1965; Elliott and Kindwall, 1982; Anthonisen, 1984).

Decompression sickness has three major manifestations caused by bubble formation and embolization in the body's tissues (Elliott and Kindwall, 1982). Central nervous system DCS (CNS-DCS) usually involves the spinal cord, often resulting in limb paralysis or numbness, and less frequently there are signs of cerebral involvement. The "chokes" is a respiratory form of DCS (Atkins *et al.*, 1988). It occurs when decompression generates massive quantities of circulating venous bubbles that transit the right heart and embolize the pulmonary arterial vasculature. Extensive pulmonary embolization causes the insidious symptoms of fatigue, coughing, dyspnea and labored breathing that are characteristic of chokes. The obstructive pulmonary hypertension that develops in chokes may lead to fulminant pulmonary edema with pleural effusion (Atkins *et al.*, 1988). Both CNS-DCS and the chokes can be fatal. By contrast, limb bends represents an often painful, but not life-threatening, form of DCS which is focused in the joint regions.

Animal and human responses to decompression

A classic paper in decompression physiology by Boycott, Damant and Haldane (1908) developed the early theoretical basis for practical decompression procedures to avoid DCS. Much of their work was based on decompression studies using goats as an animal model of human responses to decompression. The traditional use of experimental goats by the Royal Navy has continued in recent studies that tested various dive profiles, including submarine escape maneuvers characterized by extremely rapid ascent rates.

Human and goat responses to decompression appear similar. This fact is probably due to their similar tissue metabolisms and comparable tissue blood flows (perfusion rates) which result in corresponding rates of inert gas exchange (Lehner, Palta and Lanphier, 1987). Species' metabolisms and blood flow rates appear correlated to the 3/4 power of body weight (Lightfoot, 1974) so that smaller species have higher perfusion rates than larger species. Such relationships between species, based on body mass, are examples of allometric scaling (Schmidt-Nielsen, 1984).

Decompression studies at the University of Wisconsin-Madison used sheep and pygmy goats to simulate no-stop (without decompression stops) air dives (Lehner *et al.*, 1985). All no-stop ascents were at a 60 ft/min ascent rate to surface, often followed by a simulated altitude exposure at 570mm Hg (8000 ft) to provoke DCS signs. There were relatively few CNS-DCS cases after "long," 4-h and 24-h, dives. Most DCS cases in these long exposures involved limb bends and transient chokes. Interestingly, no-stop ascents from relatively deep, 1/2-h dives provoked a high proportion of CNS-DCS cases with transient signs of paraplegia or quadriplegia indicating spinal cord DCS. In sheep, the proportion of CNS-DCS in DCS cases went from less than 10% in the "long," shallow dives to 68% in the 1/2-h dives. In pygmy goats, CNS-DCS increased from less than 5% in the "long" dives to more than 30% in the 1/2-h dives. Both the long and short duration dives generated a similar incidence of DCS cases, but the manifestations of DCS varied according to dive profile. These findings indicate that no-stop ascents from short, relatively deep air dives provoke a higher proportion of CNS-DCS than ascents from longer dives at shallow depths.

In humans, the reported incidence of CNS involvement in sport diving accidents has increasingly gained the attention of the diving community (Dick and Massey, 1985). In some areas where relatively deep scuba diving predominates, a high percentage of CNS-DCS points to the importance of re-examining diving procedures to improve diving safety. Recent findings reported from the Royal Navy treatment of civilian and military divers as well as submarine escape trainees indicate that CNS-DCS and cerebral air embolism accidents may result in chronic cerebral perfusion deficits (Adkisson *et al.*, 1989). Chronic cerebral perfusion deficits occurred in all patients with Type II DCS, even those limited to classic spinal cord DCS presentations. These findings suggest that chronic brain dysfunction may be more widespread than previously recognized in DCS victims.

Goats in submarine escape simulations

Submarine escape experiments by the Royal Navy with goats and humans provide a rich source of information on extremely rapid ascents which is germane to an understanding of the risk involved in diving ascent rates. Goats were commonly used by the Royal Navy to test profiles for subsequent human experiments.

First, we will examine goat decompression experiments conducted by the Royal Navy at Alverstoke. A 1984 paper by Bell and associates on goat responses to simulated submarine escapes drew our attention because more CNS-DCS than limb bends occurred in deeper submarine escape profiles. As previously mentioned, we had observed a greater proportion of CNS-DCS cases in sheep and pygmy goats after relatively short, deep, no-stop ascent profiles.

Bell *et al.* (1984) observed similarly high percentages of CNS-DCS in DCS cases provoked by submarine escape maneuvers. Importantly, they also demonstrated a comparatively low risk of serious injury in very rapid ascents. Their simulated submarine escape profile using goats involved a mild 16-h "pre-escape" hyperbaric exposure followed by a quick simulated submarine escape. Abrupt submarine escapes involved a rapid exponential compression phase, a 4 sec hold at maximum pressure, and a linear ascent rate of 2.75 m/sec to surface pressure. Such escape maneuvers increased the CNS-DCS incidence compared to that of limb bends as the maximum escape depth increased: CNS-DCS in goat DCS rose from less than 20% to greater than 60% of the DCS cases as the depth changed from 135m to 280m. The Bell *et al.* (1984) observations in goat "escapes" on air are remarkably similar to the sheep responses in our 1/2-h "deep" dives.

A shift from limb bends to CNS-DCS in goats as well as sheep with profiles of decreasing time and increasing depth suggests a relationship between tissue blood flows and the manifestation of DCS. Presumably, CNS-DCS in the spinal cord occurs with bubble injury to those tissues characterized by relatively high blood flows and correspondingly fast washin and washout rates of nitrogen. It follows that limb bends affects tissues in the joint regions with presumably slower washin and washout rates which are largely controlled by lower rates of tissue blood flow. Moreover, sufficient bubble formation or embolization in those tissues susceptible to DCS injury appears necessary for the tissue injury mechanisms that produce the signs and symptoms of DCS. A rapid ascent from a brief deep dive tends to provoke more CNS-DCS manifestations than an equally rapid ascent rate from a shallow dive of long duration. Therefore, the risk of DCS, whether chokes, CNS-DCS or limb bends, would appear to depend on *adequate decompression time* rather than ascent rates per se.

Much of the information gained from Royal Navy studies in submarine escapes appears in Royal Navy reports with limited circulation. Eaton (1971) provides a particularly interesting account of the extreme depths that can be tolerated by goats in submarine escape. His experiments involved extremely rapid compression and decompression rates to minimize tissue gas loading. Decreased tissue gas loading, accomplished by rapid compression and ascent phases in submarine escape, prevented a high incidence of serious DCS and O_2-induced convulsions while the goats were briefly exposed to very high pressures of air. Hyperoxic seizures result from relatively short exposures to high partial pressures of O_2 (Clark, 1982; Shilling and Faiman, 1984). Ascent rates of 2.6 m/sec (8.5 feet/sec) and decompression from brief exposures at 200m (650ft) and 290m (950ft) were tolerated by most goats. In the 200m series, there were no adverse signs observed in any of the 12 goats. However, in the deeper 290m series, two of the twelve goats died.

Rates of ascent tolerated by goats were also explored by Eaton (1967) in earlier submarine escape experiments. From the goat responses, he concluded that *faster* rates of ascent were *safer* than slower rates in submarine escapes. Enhanced safety from faster ascents in submarine escapes may initially appear to represent a paradox. In submarine escapes on air, exceptionally brief pressure "spikes" reduce tissue gas loading that would otherwise cause DCS and obligate the "diver" to significant additional decompression time. In Eaton's study, ascent rates ranged from 1.8 m/sec (6 ft/sec) to 4.6 m/sec (15 ft/sec). Indeed, the conventional ascent rate of 60 ft/min or 1 ft/sec (0.3 m/sec) recommended by the U.S. Navy (1978) is remarkably slow by comparison.

Submarine escape in humans: Rapid compression and ascent

Submarine escape offers a practical basis for evaluating human risk in extremely rapid ascents. Submarine escape procedures were reviewed in an international workshop on this subject (Gell and Parker, 1974). Data of human responses to submarine escape maneuvers encompass numerous training outcomes in simulated submarine escapes as well as chamber and field trials. Rapid compression and ascent in submarine escape maneuvers focus on the lung's ability to withstand rapid pressure reduction without pulmonary barotrauma and on minimizing tissue gas loading and DCS risk.

Sir Robert Davis' insightful book on deep diving and submarine operations (1962) offers a useful historical perspective to submarine escape. Davis points out the simple but essential maneuvers required of those who engage in submarine escapes. Avoidance of breath-holding during ascents in both submarine escapes and scuba diving is essential. Davis states, "There is a natural tendency in men escaping from submarines to hold their breath, whether they are wearing apparatus or not. This is a fundamental protective reflex under water.... The act of venting easily, and suppressing the desire to hold one's breath is acquired by training practice." By inference, inadequate training appears strongly implicated in diving accidents that involve arterial gas embolism, except for those cases where lung defects predisposed the diver to pulmonary barotrauma (Elliott and Kindwall, 1982; Saywell, 1989).

Another factor in submarine escape and diving involves the psychological condition of the individual (Biersner, 1984). Inadequate training can set the stage for inappropriate, life-threatening behavior in certain divers susceptible to panic. The personality of the diver appears to play a crucial role in panic behavior that may lead to breath-holding and a pulmonary barotrauma accident upon ascent (Morgan, in press).

In a Royal Navy report, Barnard, Eaton and Snow (1971) described 112 submarine escapes simulated by 20 men during chamber experiments. Men tolerated compression to 150m in 20 sec at a compression rate of 7.5 m/sec (24.6 ft/sec) and an ascent rate of 2.6 m/sec (8.5 ft/sec) to the surface. Somewhat deeper exposures were also simulated in an exposure to a maximum depth of 191m (625 ft). No cases or air embolism or DCS were reported. Mild itching was provoked in a few instances, but the symptoms were usually slight, transient and restricted to the ears. The ears have a large surface to tissue mass ratio and probably become vulnerable to bubble formation by a significant transcutaneous flux of N_2 at high pressure and by cooling upon rapid decompression. Five cases of otitic barotrauma or "ear squeeze" occurred; one resulted in a perforated tympanic membrane.

Much of the submarine escape research conducted by the Royal Navy has been comprehensively reviewed by Donald (1979). His review summarizes many of the human and some of the animal experiments that led to submarine escape procedures adopted by the Royal Navy.

Chamber-simulated and sea trial data found in Table 1 of Donald's paper are summarized in Fig. 1 that plots submarine escape maneuvers at various ascent rates and depths. Donald reported 295 decompression outcomes. Most were uneventful, but two escapes provoked Type II CNS-DCS. There were no reported cases of gas embolism in these experimental escapes despite many 2.6 m/sec ascents. We have grouped the same data from Donald by ascent rate (Fig. 2), and they indicate no correlation between ascent rate and CNS-DCS. Despite such rapid ascent rates, decompressions were generally well-tolerated in these trained subjects.

Figure 1. Submarine escape ascents from various depths. Two of 295 individual ascent trials provoked CNS-DCS, but no pulmonary barotrauma and arterial embolism cases were reported (Data from Table 1, Donald 1979).

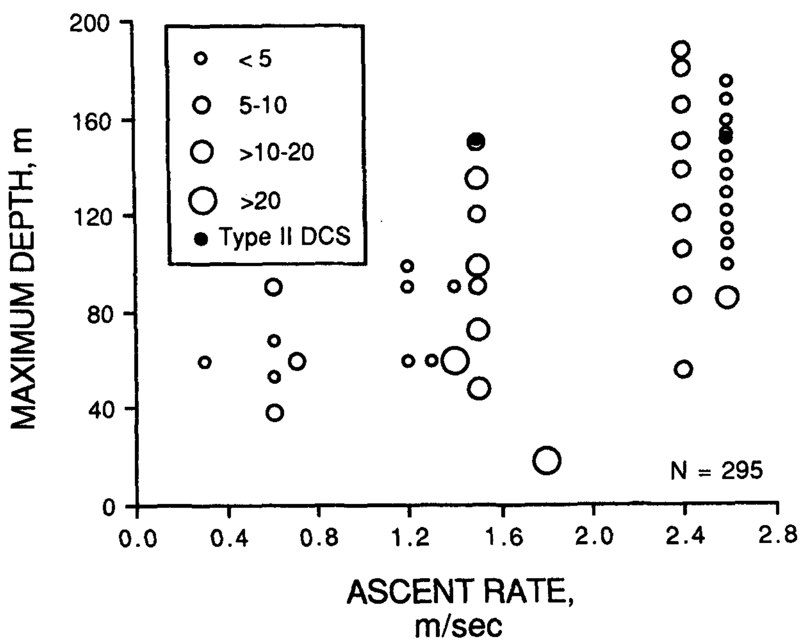
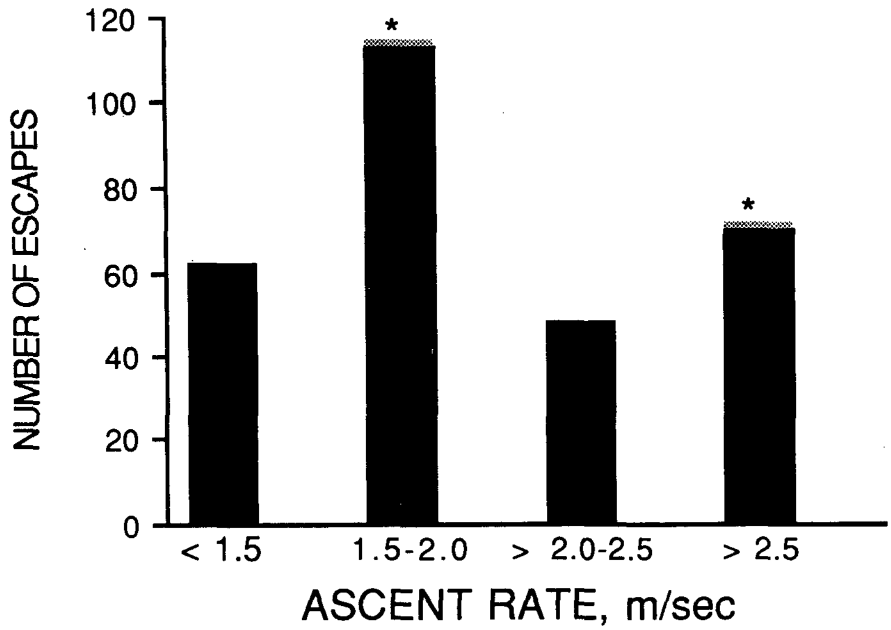


Figure 2. Histogram of ascent rates and number of individual trials represented in Fig. 1. All submarine escapes were uneventful outcomes except for two cases of Type II DCS (cross-hatch and stars).



Although there were no reported cases of pulmonary barotrauma or cerebral air embolism in Donald's studies, these conditions pose grave risks to individuals practicing submarine escapes. Brooks *et al.* (1986) reviewed the submarine escape outcomes from an extensive series of training exercises. The Royal Navy's training protocol for submarine escapes involved ascents from shallow depths that achieved a terminal velocity of 2-3 m/sec. In 232,000 tabulated submarine escapes, there were 84 reported cases of arterial gas embolism. This represents an incidence of 1 in 2771 decompressions or a 0.036% incidence of arterial gas embolism. In this series, there were 4 mortalities with a mortality rate of 1 in 58,211 decompressions or 0.0017%.

Rapid ascent and acceptable risk in diving

With submarine escapes we face a dilemma: shortened compression times and faster ascents lower the incidence of DCS, but faster ascent rates also increase the risk of pulmonary barotrauma and arterial gas embolism. In a well-instructed population such as submariner trainees, the risk of a pulmonary barotrauma accident and arterial gas embolism is comparatively low. Rapid ascents are routinely tolerated in this setting with relatively few accidents.

Based on the experience gained from animal decompression experiments, we may begin to answer the question: How important is the dive profile in determining the risk of DCS and the manifestations provoked? It appears that certain pressure profiles will provoke a high incidence of CNS-DCS. Such profiles are comparatively deep air dives (>100 ft) with rapid ascents, typically with no-stop rapid decompression.

With the submarine escape model, extremely rapid rates of ascent are routinely tolerated by animals and humans, and the risk of arterial gas embolism is relatively low. Based on the submarine escape experience, currently recommended rates of ascent, as high as 60 ft/min (18.3 m/min) or 1 ft/sec (0.3 m/sec), should be well within the bounds for a comparatively low risk of cerebral arterial gas embolism.

Factors other than small differences in recommended ascent rates, particularly the diver's training, physical condition, personality type, and dive profiles with a significant DCS risk, largely determine risk in scientific and sport diving.

Any endeavor that we undertake, including diving, involves some risk. Informed choices appear to offer a useful approach towards answering two questions which are important for both the diver and those asked to provide diving recommendations: What is a voluntary acceptable risk in diving, and are the risks of pulmonary barotrauma and CNS-DCS voluntarily assumed by sport and scientific divers too high? A comprehensive body of literature now exists on risk analysis (Waller and Covello, 1984; National Research Council, 1982; Shrader-Frechette, 1985) and acceptable risk (Lowrance, 1976; Fischoff *et al.*, 1981). In this context, risk assessment can provide a decision-making approach for determining what is acceptable risk in diving.

Current information about diving risk has improved with the gathering of epidemiological data from scuba diving accidents by organizations such as DAN (Diver's Alert Network, Duke University). Other sources of information include well-controlled decompression experiments in both animals and humans. With additional information about risk, we can then make informed choices about dive profiles. Clearly, the risk voluntarily assumed by certain divers is not necessarily the same that would be freely chosen by informed individuals in other diving populations.

Acknowledgments

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Literature cited

Adkisson, G.H., M. Hodgson, F. Smith, Z. Torak, M.A. Macleod, J.J.W. Sykes, C. Strack, and R.R. Pearson. 1989. Cerebral perfusion deficits in dysbaric illness. Lancet 15 July: 119-122.

Anthonisen, N.R. 1984. Respiration. Lung volumes: effects of gas compression and expansion. The Physician's Guide to Diving Medicine. C.W. Shilling, C.B. Carlston, and R.A. Mathias (Eds.). Plenum Press, New York, Ch. 3: 71-85.

Atkins, C.E., C.E. Lehner, K.A. Beck, R.R. Dubielzig, E.V. Nordheim, and E.H. Lanphier. 1988. Experimental respiratory decompression sickness in sheep. J. Appl. Physiol. 65: 1163-1171.

Barnard, E.E.P., W.J. Eaton, and R.E. Snow. 1971. Experiments in submarine escape. Rapid compression of men to 625 feet (191 metres). Royal Naval Physiological Laboratory, Alverstoke, United Kingdom, RNPL Report 10/71: 1-8.

Bell, P.Y., D.W. Burgess, M. Summerfield, and E.J. Towse. 1984. The effect of presaturation on the maximum submarine escape depth of goats and the implications for human research. Underwater Physiology VIII, Proceedings of the Eighth Symposium on Underwater Physiology. A.J. Bachrach and M.M. Matzen (Eds.). Undersea Medical Society, Bethesda, MD. pp. 241-248.

Biersner, R.J. 1984. Psychological standards for diving, Physical and psychological examination for diving. The Physician's Guide to Diving Medicine. C.W. Shilling, C.B. Carlston, and R.A. Mathias (Eds.). Plenum Press, New York. pp. 520-529.

Boycott, A.E., G.C.C. Damant, and J.S. Haldane. 1908. Prevention of compressed air illness. J. Hyg., London 8: 342-443.

Brooks, G.J., R.D. Green, D.R. Leitch. 1986. Pulmonary barotrauma in submarine escape trainees and the treatment of cerebral arterial air embolism. Aviat. Space Environ. Med. 57: 1201-1207.

Clark, J.M. 1982. Oxygen toxicity. The Physiology and Medicine of Diving, 3rd Edition, Bennett, P.B., and D.H. Elliott, (Eds.). Bailliere Tindall, London, Ch 9: 200-238.

Davis, R.H. 1962. Deep Diving and Submarine Operations. A Manual for Deep Sea Divers and Compressed Air Workers. Saint Catherine Press Ltd., London.

Dick, A.P.K., and E.W. Massey. 1985. Neurologic presentation of decompression sickness and air embolism in sport divers. Neurology 35: 667-671.

Donald, K.W. 1979. Submarine escape breathing air. A review and analysis of animal and human experiments by the Royal Navy. Bull. Europ. Physiolpath. Resp. 15: 739-754.

Eaton, W.J. 1967. Experiment in submarine escape. 1. Goat experiments with fast decompression from pressures equivalent to depths of from 300 to 500 feet of sea-water. 2. Extension of the maximum safe depth of escape for goats by increased rates of ascent. Royal Naval Physiological Laboratory, Alverstoke, United Kingdom, RNPL Report 1/67: 1-9.

Eaton, W.J. 1971. Depth limitations of the buoyant (hooded) ascent submarine escape procedure. Royal Naval Physiological Laboratory, Alverstoke, United Kingdom, RNPL Report 9/71: 1-12.

Elliott, D.H., and E.P. Kindwall. 1982. Manifestations of the decompression disorders. The Physiology and Medicine of Diving, 3rd Edition. P.B. Bennett and D.H. Elliott, (Eds.). Bailliere Tindall, London, Ch 18: 461-472.

Fischoff, B., S. Lichtenstein, P. Slovic, S.L. Derby, and R.L. Keeney. 1981. Acceptable Risk. Cambridge University Press, Cambridge.

Gell, C.F., and J.W. Parker (Eds.) 1974. International Workshop on Escape and Survival. U.S. Navy Submar. Med. Res. Lab. Rep. (NSMLR 794).

Lanphier, E.H. 1965. Overinflation of the lungs. Handbook of Physiology. Respiration II. W.O. Fenn and H. Rahn (Eds.). American Physiological Society, Washington, D.C. Sect. 3, Vol. 2: 1189-1193.

Lehner, C.E., G.G. Adler, T.M. Kanikula, M. Palta, E.H. Lanphier. 1985. Influence of dive profile on manifestations of decompression sickness. Undersea Biomed. Res. 12 (Suppl): 12.

Lehner, C.E., M. Palta, and E.H. Lanphier. 1987. The role of testing in animals. Decompression in Surface-based Diving. I. Nashimoto and E.H. Lanphier, (Eds.). Undersea and Hyperbaric Medical Society, Bethesda, Maryland. pp. 125-129.

Lightfoot, E.N. 1974. Transport Phenomena and Living Systems: Biomedical Aspects of Momentum and Mass Transport. John Wiley and Sons, New York.

Lowrance, W.W. 1976. Of Acceptable Risk. Science and the Determination of Safety. William Kaufmann, Inc., Los Altos, California.

Morgan, W.P. In press. Psychological considerations in the use of breathing apparatus. Physiological and Bioengineering Aspects of Underwater Breathing Apparatus. C.E.G. Lundgren and D. Warkander, (Eds.). Undersea and Hyperbaric Medical Society, Bethesda, Maryland.

National Research Council, Committee on Risk and Decision Making. 1982. Risk and Decision Making: Perspectives and Research. National Academy Press, Washington, D.C.

Saywell, W.R. 1989. Submarine escape training, lung cysts and tension pneumothorax. Br. Jour. Radiol. 62: 276-278.

Schmidt-Nielsen, K. 1984. Scaling, why is animal size so important? Cambridge University Press, Cambridge.

Shrader-Frechette, K.S. 1985. Risk Analysis and Scientific Method. D. Reidel Publishing Company, Dordrecht, The Netherlands.

Shilling, C.W., C.B. Carlston, and R.A. Mathias (Eds.). 1984. The Physician's Guide to Diving Medicine. Plenum Press, New York.

Shilling, C.W., and M.B. Faiman. 1984. Physics of diving and physical effects on divers. The Physician's Guide to Diving Medicine. C.W. Shilling, C.B. Carlston, and R.A. Mathias (Eds.). Plenum Press, New York, Ch. 2: 35-69.

U.S. Navy. 1978. U.S. Navy Diving Manual. Air Diving, Vol 1 (NAVSEA 0994-LP-001-9010). U.S. Government Printing Office, Washington, D.C.

Waller, R.A. and V.T. Covello (Eds.). 1984. Low-probability/High-Consequence Risk Analysis. Plenum Press, New York.

ASCENT AND SILENT BUBBLES

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In 1971, when the Doppler "Bubble Detector" became readily available to research, studies were initiated at the University of Southern California's Catalina Marine Science Center to document the degree of "silent bubble" occurrence after open ocean scuba dives. One hundred ten Doppler monitored subject-dives were done. Dives conformed to the limits of the U.S. Navy Standard Air Decompression Tables. Exact bottom times, depths and ascent rates were adhered to. No symptoms of DCS were seen. However, venous gas emboli (vge) were found to some degree in all subjects after all dives. It was found that with small increases in decompression times, vge scores could be greatly reduced. Thus, short "safety stops" could be beneficial in reducing the occurrence of "silent bubbles" in divers using the limits of the U.S. Navy Tables.

Preface

This paper is a summary of one part of a 3-year study done by the author between May, 1972 and June 1975. The complete report has the following reference:

Pilmanis, Andrew A. 1975. "Intravenous Gas Emboli in Man After Compressed Air Ocean Diving." USN Office of Naval Research, Final Technical Report, Contract No. N00014-67-A-0269-0026, May 1, 1972 to June 30, 1975.

Background

The condition of decompression sickness stems from the inert gas partial pressure gradients developed after hyperbaric exposure between the ambient breathing gas and the body tissues. The degree and rates of various tissue inert gas saturation and desaturation determine if, and to what extent, tissue gas emboli formation and growth occurs. Specifically, the primary variables associated with the evolution of gas bubbles in the body during and/or after hyperbaric exposure are:

1. ambient pressure (depth of water)
2. bottom time
3. decompression time.

In addition, under actual open ocean diving conditions, there are other factors that influence inert gas uptake and elimination, including:

1. degree of exercise
2. water temperature

3. water immersion
4. constrictive equipment worn
5. psychological factors.

The development of non-invasive methods of detecting *in vivo* intravascular gas emboli opened a relatively objective field of study for the problems of decompression sickness in man. Through the use of the Doppler ultrasonic flow-meter, modified for use as a bubble detector, definitive evidence has been obtained that circulating non-symptomatic venous gas emboli (vge) exist after certain dive profiles previously considered "safe". These non-symptomatic gas emboli have been termed "silent bubbles". Despite the lack of apparent symptoms from these vge, it is highly probable that there is some degree of tissue damage associated with frequent "silent bubble" foundation.

Most of the Doppler studies have been done in hyperbaric chambers under very controlled conditions. Thus, many of the inert gas uptake/elimination variables listed above for open ocean diving were not considered in these studies. The task of bubble detection in an immobile man in a hyperbaric chamber is much less complex than the task of bubble detection in a working diver in the ocean environment where pressure change is but one of the influencing factors.

The overall purpose of this study was to attempt to define the occurrence and extent of decompression "silent bubble" formation in man after ocean diving to the limits of the U.S. Navy Standard Air Decompression Tables (USN Tables). The initial objective was to demonstrate the feasibility of *in vivo* intravascular bubble detection during the post-dive period of open ocean air scuba dives. This was immediately followed by a characterization of the post-dive time course of vge occurrence.

Methodology

All experimental work was done at the University of Southern California Catalina Marine Science Center, located at Big Fisherman Cove, Santa Catalina Island. The diving site for these studies was approximately 300 yards from the dock in 100 to 200 feet of water. A powered diving platform was always anchored over the site during the diving operations.

A model A 5 MHz Precordial Doppler Ultrasonic Bubble Detector was acquired from the Institute for Environmental Medicine and Physiology, Seattle, Washington. This was replaced with a Model B in the second year. These units were successfully used during the project for the detection of venous gas emboli. The large precordial transducer consisted of two 1/2 inch square piezoelectric crystals separated 1.3 cm. and tilted at a 13° angle so that the ultrasonic transmitter and receiver beams cross in a region 3 to 4 cm. distant. The advantage of this unit was that it covered a large tissue volume at its focus and, thus, positioning was less critical and there was higher probability of detecting vge in the pulmonary blood.

During the course of the 3-year study, 18 resident scientific divers of the U.S.C. Catalina Marine Science Center were used as subjects. These people routinely perform working dives and are thoroughly familiar with the diving station. All dives were free-swimming air scuba dives. After extensive experience with several brands of depth gauges (in a test chamber and in the ocean) it was concluded that none of them had the reliability and accuracy required for these experiments. Thus, a steel cable lead-line was used as the primary depth sounder and was dropped and left suspended during all dives. Markers on this line every ten ft. permitted accurate ascent rates. Horizontal visibility was between 40 and 80 ft. Water temperature was between 11 and 13°C. The subjects' descents were totally passive. During the resting dives, the subject knelt motionless on the bottom for the full bottom time. The ascents were at 60 ft./min., were passive, and controlled through buoyancy regulation. The Doppler recordings were made on the diving platform. Two-minute control recordings were made prior to each dive. Due to the time required for boarding the dive platform and the removal of diving gear, the earliest bubble detection recordings were made 3-5 minutes after the point of surfacing.

Eight two-minute post-dive recordings were made at 5, 15, 30, 45, 60, 90, 120, and 180 minutes after surfacing. The data was simultaneously recorded on tape and monitored with earphones. Subjects were seated and motionless during the recordings.

The following 3 dive profiles were used:

	Depth (ft.)	Bottom time (min.)	Decompression (min./ft.)
1.	100	25	none
2.	100	30	3/10'
3.	190	10	2-3/20' 4-5/10'*

*(decompression was added to USN requirements for safety reasons)

Animal studies were done to verify the electronic characteristics of the intravascular bubbles as recorded by the bubble detector. The animals and human data were subjected to audio and oscillograph analysis and a method was then developed for quantification of the data. It is important to note that these signals are termed "events", not bubbles, because occasionally, there are cardiac events which also elicit above-control level characteristics. However, the majority of these electronic events are interpreted to represent gas emboli passing through the right heart. The events are tabulated for each 2-minute period and compared with the audio counts made for the same period (Figure 1). There were two problems encountered with this method of bubble quantification. The sensor placement had to be very critical, since it was found that signals produced by valve closures and/or peak flow were sometimes as high as those produced by bubbles and, thus, masked the bubble data. Secondly, a substantial portion of the bubbles that were audible in the earphones did not display above control frequencies. Because of these problems, the human ear continued to be considered the most accurate method.

Figure 1. Brush recording from the "Bubble Counter"

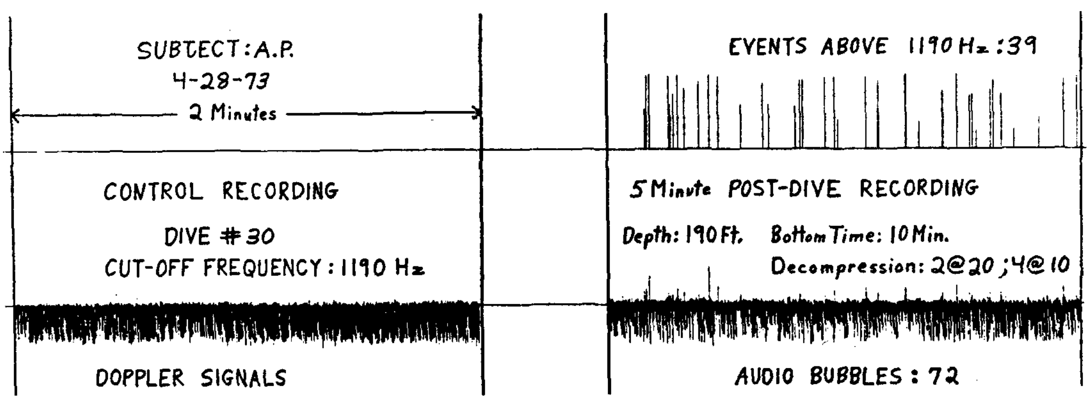
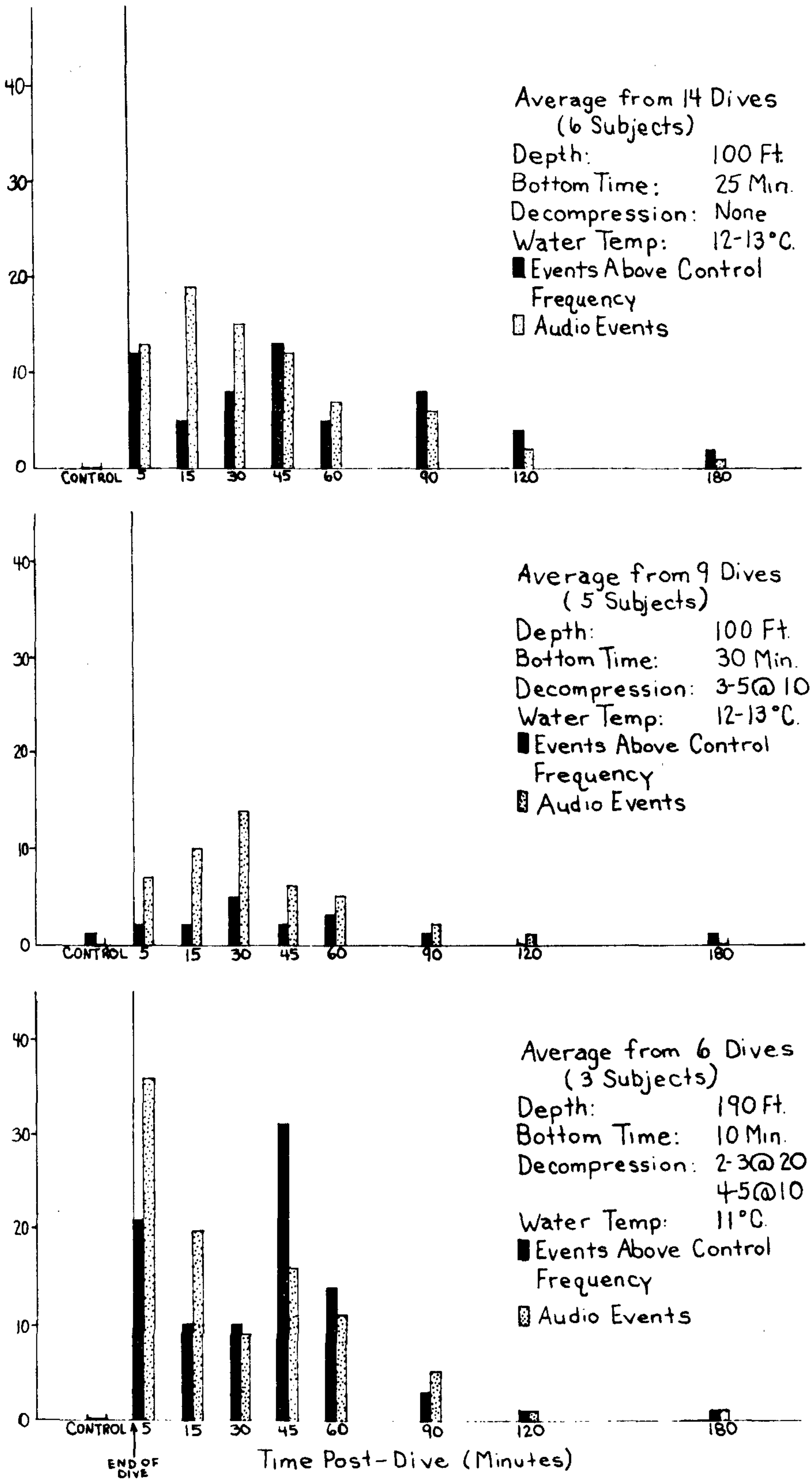


Figure 2. Averaged vge data from 3 dive profiles



Results

One hundred ten subject-dives were made in the open ocean. No symptoms of decompression sickness were seen as a result of any of the diving. Intravascular "silent bubbles" were present, to some degree, after all of the dives reported. The averaged vge occurrence time-courses of the three dive profiles are seen in Figure 2. "Silent bubbles" were present within a few minutes after surfacing from the dives. The number of events generally peaked within an hour post-dive, declined and was close to control levels by three hours post-dive. Table I gives the levels of significance of each averaged recording to the control levels. Significant differences occurred at the 5, 15, 30, and 45 minute post-dive recordings. A great range of individual variability was seen. Furthermore, each individual showed a relatively consistent degree of bubble formation on various dive profiles and repeated dives. In particular, the subject in Figure 3 consistently produced large numbers of events, even after a relatively "safe" dive profile. A bottom time of 25 minutes is the "no-decompression limit" for a depth of 100 feet according to the USN Tables. Yet, this subject always exhibited large numbers of events after such an exposure. **However, when relatively short decompression periods were added to the dive profile, the number of post-dive events was drastically reduced.**

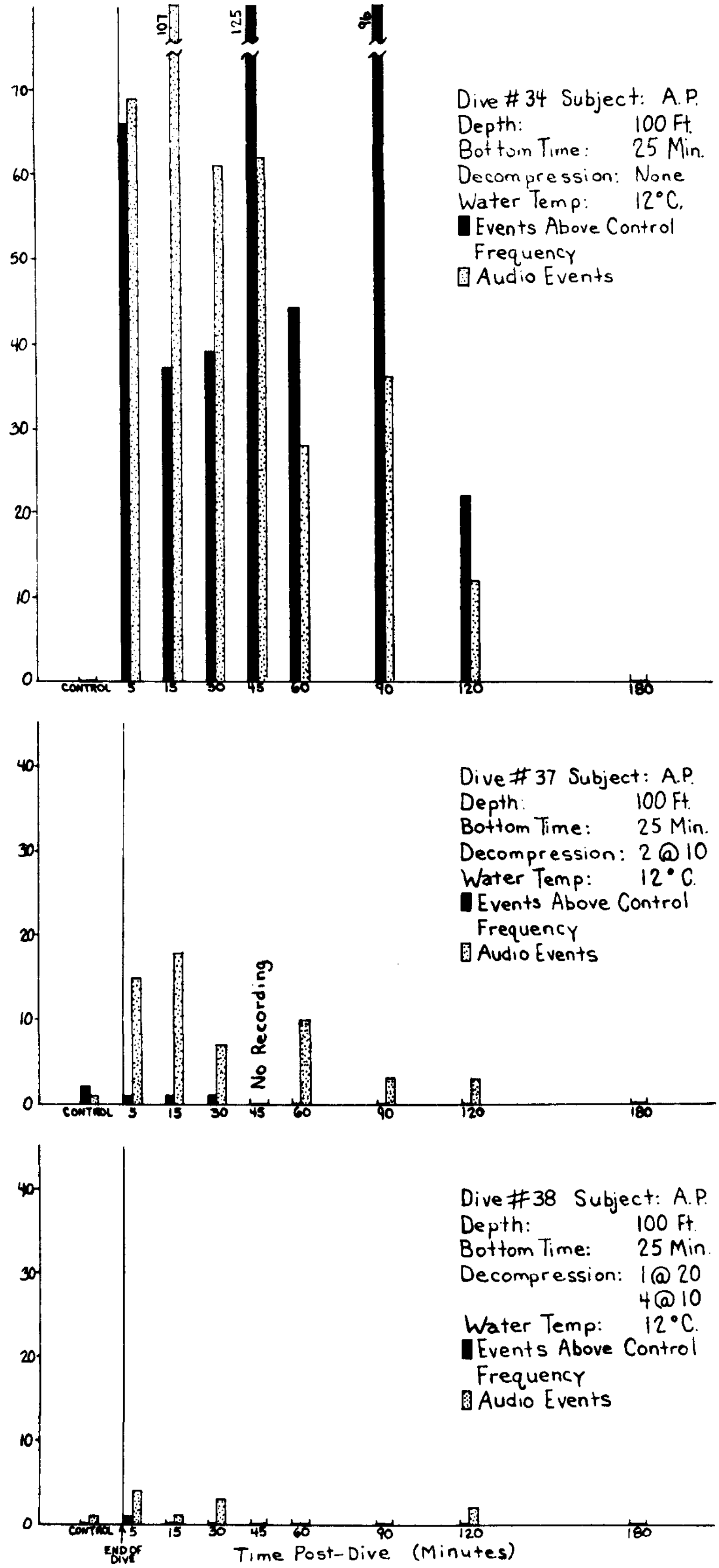
Table 1

Dunnet's t Statistic

	Dive Profiles	Recordings Post-Dive (minutes)							
1.	100 ft / 25 min No decompression	5	15	30	45	60	90	120	180
	Audio	**	**	**	**	NS	NS	NS	NS
	Electronic	**	NS	NS	NS	NS	NS	NS	NS
2.	100 ft / 30 min 3 min @ 10 ft								
	Audio	NS	*	**	NS	NS	NS	NS	NS
	Electronic	NS	NS	*	NS	NS	NS	NS	NS
3.	190 ft / 10 min 2 min @ 20 ft 4 min @ 10 ft								
	Audio	**	*	NS	NS	NS	NS	NS	NS
	Electronic	**	NS	NS	NS	NS	NS	NS	NS

NS = Not Significant
* = P less than 0.05
** = P less than 0.01

Figure 3. Vge data from subject A.P. after 3 dive profiles; depth and bottom times were identical, only the decompression was changed.



Discussion

The full extent of the pathophysiological complexity of decompression sickness has recently become more and more apparent. At the same time, many of the basic mechanisms of action that lead to the varied and interrelated clinical manifestations of decompression sickness remain elusive. The existence of asymptomatic venous gas emboli is now generally accepted. However, the pathophysiological significance of these bubbles has still not been adequately defined.

It is clear from this study, as well as others, that man can tolerate and eliminate at the lungs relatively large quantities of gas emboli from the venous system without developing clinical symptoms of decompression sickness. It is also clear that pre-symptomatic bubbles are present in large numbers after open ocean dives which strictly adhere to the limits of the USN Tables. It is suggested that silent bubble formation and clinically symptomatic bubble formation are not two distinct conditions, but rather, the same condition at various levels of gradation. In addition, the point of development of obvious symptoms is not necessarily synonymous with the start of tissue damage. The pathology from vge may simply be a milder form of "symptomatic" tissue damage. Any gas emboli in the tissues are potentially harmful.

It should be noted that the bubbles detected by the Precordial Doppler are, physiologically, relatively unimportant. These venous bubbles funnel into the right heart, pass to the pulmonary circulation and dissipate. It is unlikely that they cause any tissue damage, except perhaps for hematological alterations. Pathophysiologically, the stationary bubbles in the various tissues are the prime contributors to the disease. However, we cannot detect stationary bubbles. The circulating gas emboli may only be **detectable** indicators of the presence of bubbles in other tissues.

In conclusion, these data suggest that by increasing decompression times by a few minutes over those required by the USN Tables, "silent bubble" formation into the venous system can be significantly reduced. Thus, the routine use of "short safety stops" when diving the U.S. Navy Tables to the "no-decompression" limits is strongly encouraged. However, it is also emphasized that this conclusion is based on an N of 1, and additional research is needed to confirm these findings.

PHYSIOLOGY SESSION DISCUSSION
Discussion Leader: Glen H. Egstrom

Andy Pilmanis answered what safety stop was instituted at his facility by saying that it was a historical question and that the stops were arbitrary. Andy: When we still used the Navy tables, first of all we didn't go to the limit; Secondly, we stopped at 10 feet for whatever air we had left; Ultimately we stopped for 5 minutes and then we said stop at 15 feet for whatever time you have left. This evolved gradually. When the Huggins tables came out we shifted to them as a better solution and then to the Canadian tables after that.

Glen Egstrom wondered: If when you say symptom free in that circumstance with an N of 1, you had no symptoms whatsoever? Andy: Anybody who has worked with the Doppler close to the limits, I think, will probably bear out that you can get individuals that bubble a lot and still don't bend. One thing we did not do were objective neurological examinations and, remember, this is back in the early 1970's before we had the chamber experience. At this point what I would do is a serious examination of every subject after the dive, because one of the things we found in patients is we don't see type I limb pains in the chamber. Mainly, this is because if somebody walks in complaining of a shoulder pain, you give him a thorough neurological exam and almost always you find a neurological finding that they are not aware of. Therefore, I would always do an examination in a grade 4 bubbler before I would say they were symptom free. Dennis Graver asked what the physical characteristics of the bent diver were? Andy: About 6'3", 200 lbs, male caucasian, young man, good-looking, initials A.P!

Woody Sutherland remarked that there was a lot of variation between individuals, but that within individuals, it was fairly consistent. Given that, and assuming that there is some sort of correlation between silent bubbles and the risk of DCS, is there any prophylactic use in using the Doppler and adjusting tables for individuals? Andy: Theoretically, you probably could, but practically I don't quite know how to do that. You would practically have to push every one of your subjects to a clinical bends case to find out. You're talking about screening exams and that becomes a whole world in itself, with large populations especially.

Bob Stinton reported on a French Navy experiment where they were doing a 300m dive and trying to establish decompression profiles using Doppler devices. The interesting aspect was that during the first two days of decompression there were no bubbles. The second day, when the divers started walking around a little more, there were all kinds of bubbles. Then they realized that listening to people who were laying on bunks were quiet, versus the people walking around who sounded like "fizzies". Next, they had the people on bunks walk around and they too sounded like "fizzies". I never heard the final discussion, but they stopped doing that method of schedule development. Andy responded that they should have controlled for that, it was a bad experimental design. The way you elicit bubbles if you want to find them, is to have people move around. There is no consistency though in the field and I believe a workshop is convening in October just on that point, to try to standardize Doppler measurements. How can you otherwise compare data between still and exercising subjects? That's just one of the problems.

Phil Sharkey asked about the length of bubble life on Andy's Doppler versus Hugh's model. Hugh Van Liew: I did the models on short halftimes, just because it showed up in my picture a little better. I do believe that what I was saying would also pertain to longer halftimes. The 1 foot per second is almost like an instantaneous, explosive decompression as far as the time of the bubbles and the tissue washout are concerned. I found that out when I brought the ascent rate towards the timeframe of the bubbles and the tissue washout, then it seemed as if things were getting better. Phil continued that his concern was how long we had to sit between the pending dives? Andy clarified a major point that the bubbles seen by the Doppler were meaningless in themselves. They tell you nothing about the damaging bubbles. All they tell you is that a bubble passed through this field and went on to wherever it goes in the lung. It doesn't tell you when they disappear. John Lewis wondered if it wouldn't be reasonable to presume that the population number of bubbles equated with a probability of DCS. Andy stated that wasn't a reasonable assumption at all. John then asked what the proper conclusion of Doppler work was? Andy: This is just a window into the body, because it's the only one we have and it tells us yes, there are bubbles occurring, they pass through, go on to the lungs, they are no longer being broken free from the tissues. But it says nothing about stationary, extravascular bubbles and nothing about when bubbles go away. John then inquired if Andy wouldn't be willing to go back to Spencer's work and correlate the gap between bubbles and decompression sickness? Andy: No, because symptoms are a gross manifestation of the existence of bubbles also. What we need is a device to measure stationary bubbles.

Hugh Van Liew observed that Andy's talk changed the ball game a little bit because some of us have been talking about avoiding bubbles and the transformation of nuclei into bubbles. Andy is essentially telling us that there are always bubbles there so the problem gets to be what kind of bubbles are going to give you trouble, rather than avoiding bubbles. Andy responded that there are only bubbles there when you go to the limit of the U.S. Navy tables, but if you back off, they are not there. I believe I was preventing bubbles from forming by slowing the ascent.

Bill Hamilton amplified two points that Andy made about the bubbles you hear going by the Doppler being on their way out. That is indeed true, but they're not necessarily innocuous and I have heard this from you also. Those bubbles represent foreign bodies in the blood stream and they do have measurable effects. It's curious though that these people who bubble a lot, don't seem to have more symptoms than anyone else who doesn't bubble very much. Andy felt that was a point to be determined yet. Bill thought this got into biochemistry and lung pathology and other things. Bill further pointed out that there seemed to be occasionally cases of decompression sickness that aren't explained. They don't fit any pattern in the profile and the patients don't get just pain in the knee, they get a debilitating embolism type effect. The investigation going on in that today is that it is possibly due to a defect between the right and left heart. This is congenital in some people and everybody has it as a fetus, but sometimes the opening between the right and left heart does not close completely: the patent foramen ovale. It may not ever have any physiological effect on their normal lifestyle, but bubbles can get through from the venous side, instead of going to the lungs and being trapped, they may go to the brain. We aren't sure that is the case though. There are still ongoing studies investigating that phenomenon, to build more evidence. There are several reasons why the hypothesis is good. The point is, a lot of bubbles, even in an asymptomatic person, are to be discouraged. Unanimous agreement.

Charlie Lehner observed that he and Ed Lanphier had done a whole series of experiments involving sheep as animal models in decompression sickness. In that series they had animals under pressure for 24 hours and brought them to altitude and produced chokes in all of the sheep. Charlie: We had extraordinary numbers of bubbles detectable by Doppler and in that situation, where there were such excessive numbers of bubbles, we had a very serious manifestation developing with the chokes and, in fact, approximately half of the animals would have been fatally affected, we feel, by that. More recently, we found even with short, deep dives or half hour profiles, in some instances, extraordinary numbers of bubbles in the pulmonary artery. Usually associated with that are early signs of chokes, mainly mild, labored breathing in the animals. Obviously, fatigue is a symptom which would be correlated with that. We presented this in the Journal of Applied Physiology in 1988.

Glen Egstrom asked what the characteristic of the lungs as a filter was, what kind of loads it could handle before you started seeing respiratory manifestations? Charlie responded that typically, in sheep at least, the respiratory manifestations in those animals scored 4 with the Spencer grades. We start seeing signs of labored breathing. At Spencer levels 1 and 2 we rarely see anything that would be indicative of labored breathing. Chokes is very bad decompression sickness. Most recently, we had a dive where we were modelling the japanese diving fishermen profile reported by Kawashima and had disastrous results. The animals died of chokes. In fact, in that series I didn't even go to the maximum pressure reported by Kawashima, so all those japanese fishermen are undergoing extraordinary exposures, certainly from the standpoint of potential chokes development. In this instance, I think our animals probably had a higher fat composition in the body. I think in chokes the fat composition in the body is extremely important. It may not be as important in spinal cord decompression sickness, but I think with chokes it is a very high risk factor. Andy remarked that in 15 years of a total of 600 patients at the Catalina Chamber, we've seen two questionable cases of chokes and they were very minor, very questionable, if they were chokes at all. Charlie added that the interesting thing about chokes is that oftentimes you see manifestations of labored breathing and these tend to remiss, so we don't see any manifestations later. In the more severe cases, we'll see early manifestations, apparent recovery and then a catastrophic relapse that sometimes will occur 3 or 4 hours after the animal has reached the surface. I think one has to be extremely careful with chokes. In that instance, it may be blood factors that are involved in terms of coagulation and so forth as mentioned by Bill.

Ray Rogers made the point to Hugh that it was unclear if nuclei that became bubbles "lay in wait" or revert back to nuclei. Hugh: That is the way I fixed the model up, but it may not necessarily be true, but that's all we need. I don't see any reason why a nucleus shouldn't revert back to being a nucleus after it's been a bubble, but on the other hand I don't have any information about it.

John Lewis: With respect to the animal experiments, what is the role of acclimization to hyperbaric exposures like the japanese fishermen? Have you ever tried acclimization experiments with animals to reduce bends incidences? Charlie answered that they typically run two experiments with an animal per week and most of the exposures in the japanese fishermen involve 6 exposures per week, they take out 1 day. If the information I've received is true, they're doing extraordinary exposures, similar to the caisson work acclimatization. John: Have you ever tried to simulate a gradient to that? Charlie: It might have been some mild acclimatization, but given the span between exposures, it is largely one dive per weekend. I would suspect that in the case of what Ed talked about, our animals have a body fat composition that is greater than 25%, which is obviously very high and I would suspect that the japanese fishermen probably have a body fat composition less than 8% and therefore probably get away with what they're doing.

David Yount: Regarding the discussion of whether bubbles become nuclei again, I have observed this with gelatin. You find bubbles occurring at certain points and then we'll dissolve those bubbles by raising the pressure, decompressing, then getting the same number of bubbles as before in the same location, so that does happen. Bubbles can become nuclei again and bubbles again. On the other hand, the acclimatization suggests that some of the nuclei can, after repeated exposures, offer some resistance. Hugh Van Liew added that the body was much more complex than gelatin so that it could be that the bubbles migrated some place else. If there are surfactants, other possibilities arise. But I guess if there are plenty of nuclei, it doesn't matter whether one nucleus becomes a bubble and then goes back to being a nucleus or not.

Steve Blair questioned if with the formation of the nuclei it were possible that it were the structure per se serving as the nucleus or source or point of nucleus formation rather than actually a bubble itself being present. David Yount disagreed because the fact that you can get rid of nuclei by high pressure means there is gas present. When we see nuclei with microscopes, there is gas present. The structure might be a crevice in some cases or surfactant skin, but in either case there will be gas present. David pointed out a very nice paper by Johnson and Cooke in which they injected air bubbles into sea water and observed these bubbles rise, but then they were under a glass plate and although some bubbles dissolved completely, others stopped decreasing in size abruptly and remained as microbubbles apparently stabilized by films. Originally, the radial distribution ranged up to 7 microns and peaked at around 2 microns. During the first 4 hours, there was little change in this distribution. After 22 hours, although there was little reduction in the number, the microbubbles were generally smaller, and the radial distribution resembled a decaying exponential cut off at the microscope resolution, about 0.3 microns. It appears, therefore, that Johnson and Cooke observed the creation of stable microbubble nuclei in sea water.

There is some question about whether bubble formation nuclei are always present in plant and animal systems. It seems very likely that they are. For example, we have carried out an experiment in Hawaii and we see bubbles in hen's eggs, which is even more pristine than an embryo and yet it has the bends.

Walt Hendrick asked Andy if the incidences of symptoms were correlated with grades of bubbles? Andy: All patients that we monitored had grade 4 bubbles. The consensus currently in the field is that there is no correlation between Doppler bubbles and the bends. I personally don't agree with that. Walt: Is it possible that you could, on a single dive, not looking at multiple dives where you would have secondary problems like the offloading of gas, have less problems if you have any symptoms because you had silent bubbles as opposed to being more prone because you had silent bubbles? Andy: Dumping nitrogen with silent bubbles? More efficiently eliminating nitrogen through bubbles? The other side of it is that some people believe bubbles are superfat and take on more gas, thereby making it worse. Again, we are looking at one small window in the body, only at moving bubbles, only in the right heart and they're going on their merry way. We don't know anything about what's going on elsewhere in the body in the damage areas, in the spinal cord, the brain, the bone, etc. Walt: Andy, from your own diving experience, would you include a safety stop because you feel that is a positive way to reduce the probability of bends? Of course I do, but only in situations where you're approaching some kind of limit. If I dive 5 minutes at 20 feet, I don't stop at 10 feet for 15 minutes. So, yes, if I'm approaching any limit or if I'm diving anywhere below 100 feet, I always do just as a general practice. It doesn't hurt.

Mark Walsh: Charlie, some of the data that you showed on the studies of what the various ascent rates looked like, it seemed all of them had zero bottom time. Did any of the studies you looked at show rapid ascent rates after longer bottom times?.Charlie: In the literature it became obvious based on the experiments that the Royal Navy was doing that if the bottom time, for example, lasted 15 or 20 seconds, there was a high incidence of decompression sickness. When they decreased the amount of bottom time ascents, the time that the maximum pressure was held, then the frequency of decompression sickness dropped dramatically. There is a very strong correlation in terms of the amount of time for gas to wash in and the occurrence of decompression sickness in those subjects, both in the animals as well as the humans. These were extremely short times we're talking about, from the standpoint of maximum pressure, in terms of seconds.

Walt Jaap: Andy, is there new technology coming on line for better detection of bubbles and better confidence in terms of what they mean? Andy: The only new technology I know of is in our own lab where we have echoimaging simultaneously with the Doppler. We actually see the bubble as you hear it on the headset. That's one more parameter that is helpful. But again, those are still moving bubbles that are going out, they are not the important ones.

Mark Walsh: Andy, I wish that Tom were hear to make this statement concerning the critical size, not the existence of the bubbles being the factor. I'm not sure whether he's talking about stationary bubbles or trapped bubbles. Andy: I'm sure critical size has a lot to do with it, but what that critical size is, I don't know. Mark: Now that you've brought up echoimaging, you're still talking about stationary bubbles? Andy: If you watch that movie that Hallenbeck made about spinal cord decompression sickness, where you actually see in a living system bubbles going through the epidural venous system, you'll see all bubbles of the same size. It's like marbles all the same size going through. Now, once it becomes cold, they coalesce and it looks like foam. They all appear to be the same size initially in the cardiovascular system, I don't know about tissues. Hugh Van Liew: The bubble that is moving along like it was a red cell, isn't going to do any damage probably unless it does damage by reacting with blood elements. Andy: Well, that and in the epidural venous system they do cause occlusion there. Hugh: Eventually, when they're bigger than a red cell. Andy: When the volume reaches a critical load, when enough of them get together.

SLOW ASCENT RATE: BENEFICIAL, BUT A TRADEOFF

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It should be obvious that the key to avoiding decompression sickness (DCS) is to ascend slowly. What this means specifically depends heavily on the profile of the dive (or pressure exposure) and the gases breathed. A "slow ascent" may be managed by doing stops for a standard commercial or military dive, or perhaps may be a linear ascent taking several days for a saturation dive. Short scientific and recreational dives regarded as "no-decompression" dives are no different in type, only in degree. All dives except perhaps the most trivial breathhold dives involve decompression to some extent., and proper management of the ascent rate can greatly reduce the risk of DCS. Computational models, although they should not be regarded as true pictures of gas biophysics, nevertheless can afford a means of comparing profiles with enough validity to be enlightening. Analyses show in general that for a given exposure it is better to ascend slowly, and that there is an optimal linear ascent rate that will result in the lowest theoretical gas loading and hence the lowest risk of DCS. They show further that it is possible to go too slowly, and that ascent at two or more rates can be even more beneficial. An additional benefit of a slow, controlled ascent is that it is also less likely to result in embolism.

Some years ago it was my good fortune to work with a laboratory whose objective was to develop decompression tables for deep mixed gas bell diving. We were working in the range 500 to 650 fsw (150 to 200 msw). We had our algorithms, but a lot of what we did was still cut and try. One thing we decided on early was that the 60 fsw/min ascent rate used by the US Navy (and as we are hearing today, the recreational diving community) was too fast. We did not have any data to justify a slower ascent, really, but we rationalized that when one ascends, an unstable state exists, and this could and should promote bubble formation.

It is like a champagne bottle. If one pops the cork, one can shoot the cork at a nearby stuffed moose head and spray everyone nearby, but if one opens the bottle slowly the entire bottle is available for drinking. Recognizing my self-classification as a "decompression expert" I now make it a practice to open champagne gently, and it rarely fizzes when it is done slowly. The difference is impressive.

Without the sophisticated bubble dynamics modeling of a Yount or Wienke, the champagne bottle approach led us to try to avoid jumps or abrupt ascents. Again, I acknowledge no real data, but we implemented the slower ascent and we think it helped. In addition to the 30 fsw/min for travel from the bottom to the first stop, we also kept the travel between 10 fsw stops slow, making it take at least one minute (Hamilton and Kenyon, 1976).

If your diver is so "fizzy" that he has to be decompressed as one might handle explosives, it suggests the entire decompression is probably inadequate, and in retrospect we feel that was true about our early deep heliox decompressions. But if one gets better results by moving slowly with a fizzy diver, then the same approach should reduce the risk in a more routine ascent.

This is perhaps an extreme example, but it should make the point. This reflects a long standing prejudice against fast ascents.

However, another story shows there is another aspect to this. I had the dubious good fortune to be asked to help Sheck Exley, a Florida schoolteacher and recordsetting cave diver, to plan a dive to 800 fsw in a Mexican spring. The philosophy behind this is beyond the scope of this meeting, but can be summarized that if I would not help him, he was going to go ahead and calculate the tables himself. Not really confident I could do it better than he could, I nevertheless gave it a try. His descent was fixed at about 25 fsw/min due to an upwelling current, and the bottom time was to be no more than a minute. I tried the calculation using the Tonawanda II (Haldane-type) algorithm, and the first try required an unacceptably long decompression (approx. 16 hr). This used the 30 fsw/min ascent I had become so comfortable with. It made the decompression a lot longer that the dive Exley had done the year before, successfully.

Again without much confidence, I asked him if he could ascend faster during the travel to the first stop, which was at about 500 fsw. He agreed he could, so we recalculated it at an ascent rate of 120 fsw/min. The total decompression time dropped to about 11 hr, and a version of this approach was the dive that was done. I felt that with such a short bottom time and being so deep, this would be all right. For an N of 1, it worked. Actually, it is an N of 2 now, because he did the same dive, but a bit deeper, this year, again without incident. The lesson is that a rapid ascent early in a dive with a short bottom time worked well. I feel the faster dive involved less risk overall than would a slower ascent which would effectively be a longer bottom time. Again, these are impressions, but the message seems clear enough.

So, we have a strong feeling with limited evidence that a slow ascent rate is beneficial, and a case, again with limited data, that says the rate can be fast at first, especially when deep and after a short bottom time.

These judgements were based on vague guesses of what might be happening physiologically. This caused me to have the obvious curiosity as to the effect of ascent rate as seen by the computer, the neo-Haldanian algorithm based on hypothetical halftime compartments and limiting M-values of exponential gas loading and unloading. This example uses a conservative air matrix that is close to the relatively reliable USN rates in the no-stop range but is more conservative for deeper and longer dives. The results are as you might guess (Fig. 1 and Table 1). Initially, decreases in ascent rate improve the decompression and allow (for example) longer no-stop times when everything else is equal. Further decreases reduce the allowable time.

The example shows that reducing from an ascent rate of 60 to 30 fsw/min gives one more minute of no-stop time at 130 fsw (11 to 12 min). An additional decrease from 30 to 10 fsw/min gives still another minute of no-stop bottom time. An additional decrease to 5 fsw/min now reduces the allowable no-stop time back to 11 min. This is not unexpected. Eventually, when the rate gets slow enough, the "no-stop" bottom time will increase again.

Table 1. Times from sample dive with various ascent rates.

GAS: Air — Basecase D99NA0.H01, DEPTH: 130 fsw — Matrix MF11F6.DCP, RATES: 60 to 5

No-stop time	Ascent rate	Ascent time, min	Run time, min
11.	60	2.	13.
12.	30	4.	16.
13.	10	13.	26.
11.	05	26.	37.

From a practical point of view, however, this does not make a case against a short stop at say 10 fsw, and in fact that is easier to perform and is theoretically more beneficial. Three min at 10 fsw, with travel at 60 fsw/min, allows 15 min at 130 fsw. Again, the effect is in the expected direction, but perhaps it is not as great as one might expect (Table 2).

Figure 1. No-stop times for various ascent rates

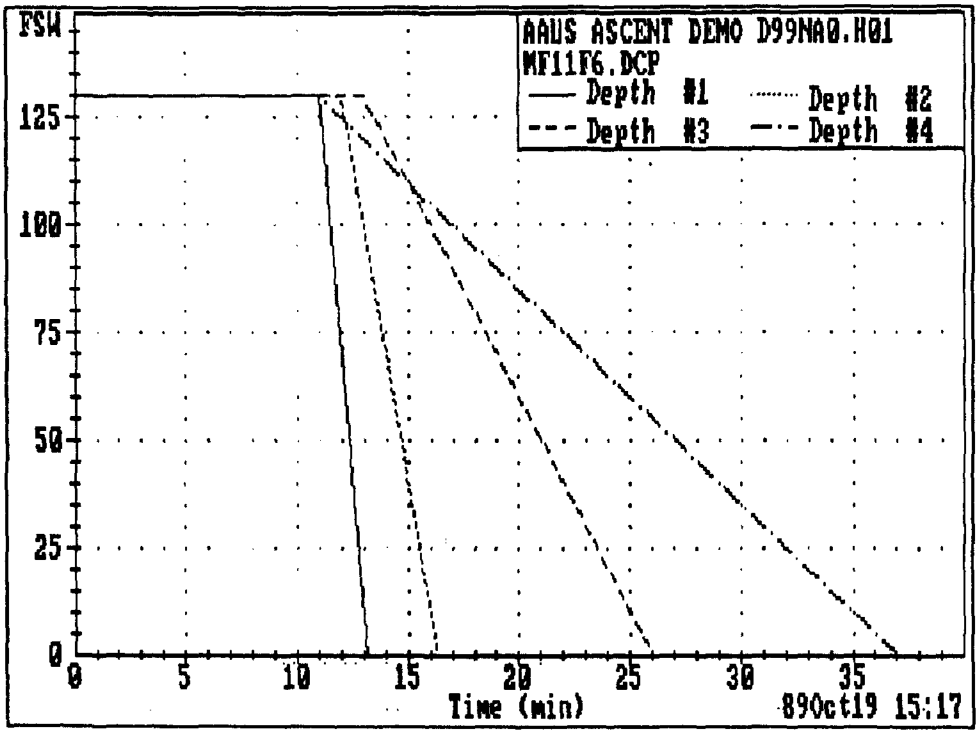

Table 2. Times from sample dives with various 10 fsw stops

GAS: Air — Basecase D99NA0.H03, DEPTH: 130 fsw — Matrix MF11F6.DCP, STOPS: 1 to 4 min

No-stop time	Ascent rate	10 fsw stop time, min	Run time, min
12.	60	1.	15.
13.	60	2.	17.
15.	60	3.	20.
16.	60	4.*	22.

* Includes 1 min at 20 fsw

Thus we can conclude that as far as hypothetical gas loadings are concerned, slightly slower rates improve the decompression, but when still slower ascent rates are used, the result is a penalty in bottom time. Over the range which could reasonably be done by a scuba diver, however, the effect is not prominent and slow ascents can be regarded as beneficial. A short stop is slightly more beneficial than a slow rate and does not increase the dive time as much.

Reference

Hamilton, R.W. and D.J. Kenyon. 1976. Decompression work at Tarrytown. *In:* R.W. Hamilton (Ed.) Development of decompression procedures for depths in excess of 400 feet. WS: 2-28-76. Undersea Hyperbaric and Medical Society, Bethesda, MD.

ASCENT RATES VERSUS INERT GAS DYNAMICS ALGORITHMS

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The bulk diffusion model of Haldane and the diffusion-perfusion model of Krogh are developed For a representative set of dive profiles and ascent procedures the gas tension in excess of ambient pressure is calculated. Based on these calculations, it is recommended that for all dives to a depth in excess of 60 feet, that a three minute stop at 20 feet be taken, the "no-bubble" no-decompression limits be used, and that the standard 60 foot per minute ascent rate be used. Following this recommendation will result in an approximately 30% reduction in the calculated peak gas tensions in the most highly perfused tissues

Introduction

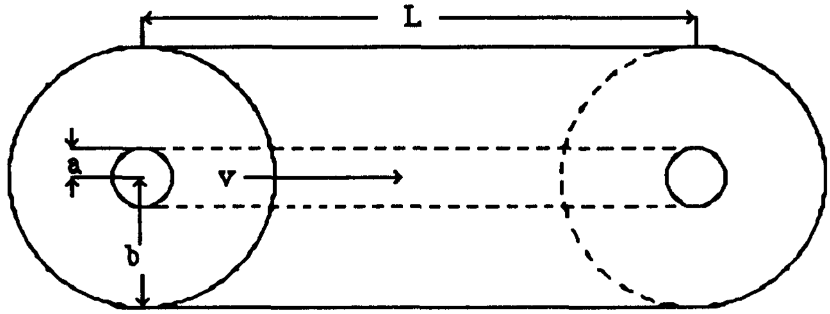
The bulk diffusion model of Haldane, which has been the standard model for controlling diving hyperbaric exposures, does not have the time scale resolution for detailed evaluation of an ascent procedure Typically, the ascent is a small fraction of the total dive time. However, this model being the standard is well calibrated to determine the limits of safe exposure. For improved time resolution the Krogh Model was chosen. This model is a contemporary of the bulk diffusion model of Haldane and has been used by physiologists for detailed analysis of uptake and release of various substances by the capillaries for the last seventy years. The major disadvantage of the Krogh Model is the computational effort required for the solution of the equations. From this study, the gross properties of the two models are in agreement However, as expected, the time courses are usually quite different.

Krogh Model

Krogh (1919a , 1919b) first introduced this model in 1919 for the study of oxygen supply to tissue. Subsequently, many investigators (Levitt, 1972; Tepper *et al.*, 1979) have used this model to study the transport of various substances by the capillaries. A very good description of the assumptions of this model can be found in a paper by Hennessy (1974)

The model consists of two co-axial cylinders of length L with inner radius a and outer radius b. The inner cylinder represents the capillary which is perfusing the surrounding tissue annulus. The blood flow in the capillary is assumed Newtonian with a uniform velocity of v. Radial diffusion within the blood is assumed instantaneous. Thus, the blood is well stirred in the radial direction. The surrounding tissue annulus is assumed to consist of only cellular material. Roughton (1952) has shown that the saturation time of any interstitial matter is very rapid, on the order of one second. Thus, this material can be thought of as incorporated within the capillary cylinder.

Figure 1. Krogh capillary model



The outer boundary and the ends of the tissue compartment are assumed impermeable by symmetry. If the diffusion equation describes the inert gas dynamics within the tissue compartment, and the mass balance equation on a disk of blood within the capillary compartment describes the inert gas transport down the capillary and into the tissue, then the following equations and boundary conditions apply.

$$\frac{\partial g_t}{\partial t} = D\left[\frac{1}{r}\frac{\partial g_t}{\partial r} + \frac{\partial^2 g_t}{\partial r^2} + \frac{\partial^2 g_t}{\partial z^2}\right]$$

$$\frac{\partial g_b}{\partial t} = -v\frac{\partial g_b}{\partial z} + \frac{2D}{a}\left[\frac{\partial g_t}{\partial r}\right]_{r=a}$$

$$\frac{\partial g_t}{\partial r} = 0, \quad r = b, \quad 0 \le z \le L, \quad t \ge 0$$

$$\frac{\partial g_t}{\partial z} = 0, \quad z = 0, L, \quad a \le r \le b, \quad t \ge 0$$

$$g_b = g_t, \quad r = a, \quad 0 \le z \le L$$

The gas tension in the blood is denoted by g_b and the gas tension in the tissue is denoted by g_t. The diffusion coefficient in the tissue compartment is given by D. The inert gas tension in the blood on the arterial side is assumed to be in equilibrium with the breathing mixture, which is delivered at the ambient pressure.

An approximate solution of this set of equations can be found numerically using the implicit method of Crank and Nicholson as found in the book by Ames (1972). The resulting linear system is solved for a transition matrix which describes the change in inert gas tension for each time step. An implicit method of discretizing was chosen to avoid the usual stability problems associated with the numerical solution of the diffusion equation. Even with this choice, the time step required for stability was .01 seconds. Various powers of this transition matrix were calculated to provide time steps of 10 seconds, 1 minute and 10 minutes. These longer time steps provide for the rapid calculation of models for any dive profile without sacrificing accuracy.

For the current application the physiological parameters were set to the following values:

a = .0005cm	(.0004 - .0005cm - Krogh, 1936)
b = .003cm	(.0015 - .003cm - Krogh, 1936)
L = .1cm	(.04 - .1cm - Krogh, 1936)
D = 10^{-5}cm^2/sec	(.4x10^{-5} - 1.3x10^{-5}cm^2/sec - Homer and Weathersby, 1980)

The blood velocity v was calculated from the perfusion rate P and is the critical variable in this model. The velocity was expressed in terms of capillary transit times T for the blood. From the physiology book of Bell *et al* (1961) we find that the perfusion rate varies as $.01 \leq P \leq 5.6$ ml of blood/ml tissue per minute. Active muscle and central nervous system tissue have perfusion rates near the upper end and tissues subject to vascular constriction would have perfusion rates near the low end. Using these values and the chosen values for the capillary geometry, one obtains, $.00058 \leq v \leq .33$ cm/sec for the capillary velocity, or a range for the capillary transit time of $.3 \leq T \leq 170$ seconds. It is possible that under environmental conditions of cold or exertion, the perfusion rate could change during the course of a dive profile. However, for the purpose of this investigation transit times of 1/5, 1, 5, 10 and 50 seconds were chosen and were considered constant throughout each dive. The very short transit times would correlate with highly perfused tissue such as the central nervous system and the long transit times with tissue subject to vascular constriction.

While one can calculate from this model the inert gas tension at each point within the cylinder, only the venous side gas tension in the capillary will be used. The rationale for this choice was based on the work of Hemmingsen and Hemmingsen (1979), where it was shown that cells seemed to withstand large differences between internal and external inert gas tensions. Thus, any potentially damaging bubbles should occur in either the blood or in the interstitial areas. Since both of these areas are lumped together in the inner cylinder of this model and since the blood pressure is at a minimum on the venous side, it follows that this should be the site for the first formation of damaging bubbles.

Haldane Model

The Haldanian Model assumes that the change in the internal pressure of inert gas is proportional to the difference between the external and internal pressures. Thus, the equation governing the Haldanian decompression model is the rate equation:

$$\frac{dP_{int}(t)}{dt} = C\,(P_{ext}(t) - P_{int}(t))$$

If we define the half time T as the time required for the change in the internal pressure to reduce the difference between a constant external and the internal pressure by half, then

$$C = \frac{\ln(2)}{T}$$

Assume that all pressures are gage pressures which we measure in feet of sea water (fswg). Since a scuba regulator delivers compressed air at ambient pressure and the inert gas component of air constitutes 79%, the external pressure of the inert component is given by:

$$P_{ext}(t) = 0.79\ d(t)$$

where d(t) is the depth measured in feet of seawater at the time t. Then the solution of the rate equation can be conveniently expressed as the following integral:

$$P_{int}(t) = P_{int}(0)\ e^{-Ct} + 0.79\ C \int_0^t e^{-C(t-r)}\ d(r)\ dr$$

In the model for the Navy Tables, six different half times were used namely; 5, 10, 20, 40, 80, and 120 minutes. The solution of the rate equation, the internal pressure for each of the six compartments, can be calculated for any time t, given any dive profile d as a function of time The final component of the Haldanian model assumes that at all times during the dive the internal pressure of the inert gas will not exceed a preset maximum amount denoted by M(d) which can depend on the depth and which differs for each half time compartment. While descending, the internal pressure is always less than M(d) so the problem of exceeding an M-value is never encountered. However, on ascent the reverse is usually true. This condition in practice leads to limited bottom times, controlled ascent rates, and decompression stops. For the implementation in the Navy model, the formula for the M-values which depends on depth is determined by two constants for each compartment, denoted by M_o, the maximum allowed at the surface, and ΔM, the increment allowed for each foot of depth in sea water. M_o is usually measured in feet of sea water absolute.

$$M(d)_{fswg} = \left[M_0\right]_{fswa} - 26.1 + \Delta M\ d$$

For the Navy Model these values are given in Table 1. For latter use M_o is given in feet of sea water gage.

Half time(min)	5	10	20	40	80	120
M_o (fswg)	78	62	46	32	26	25
ΔM (fsw)	2.27	2.0	1.71	1.4	1.29	1.27

Table 1. Navy model M_0 values

Based on this model, if at each point in time,

$$P_{int}(t) \leq M(d(t)) \quad \text{(fswg)}$$

then the dive profile is considered safe from decompression sickness problems.

Application to ascent procedures

To study the efficacy of various ascent procedures the inert gas tension in feet of sea water was calculated using both the Krogh and the Haldanian models. Three different depths 60, 100 and 140 feet of sea water were investigated with two different square dive profile bottom times, the Navy no-decompression limits and the Edge no-decompression limits. The following tables summarize the results of this investigation. The numbers in the body of each table are the maximum inert gas tension in excess of the ambient pressure, measured in feet of sea water as calculated from the two models for the given ascent procedure. For the shorter transit times and the shorter compartment half-times, two peaks were noted in both models. The first is attained on reaching the stop depth and the second on surfacing. In the Krogh model only, the maximum for the longer transit times was attained after surfacing. In particular, for the 50 minute transit time, the maximum was attained some 30 minutes after surfacing. This delay in the maximum gas tension for the low perfusion tissues correlates well with the delayed onset of Type 1 decompression sickness. The immediate onset of Type 2 DCS correlates well with the high perfusion tissues of the central nervous system, or those with small transit times, achieving their maxima on or before surfacing.

Referring to Table 2, for the depth of 60 feet, both models are in good agreement. Limiting the bottom time to the Edge no decompression limits reduces the maximum gas tensions in the low perfusion or long half time compartments by approximately ten percent. A stop of some form reduces the maximum gas tension in the fast compartments, but since these values are well below those attained in deep dives with or without stops, such a procedure seems unnecessary at this depth. From the data in these two models, differences in both time and depth of the stop are small.

60 feet for 60 minutes

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	34	47	28	17	7	44	45	41	30	19
20 ft/min	13	40	30	19	8	39	42	40	30	19
60ft/min stop for										
3 min at 20ft	23/16	28/39	29	18	8	26/34	26/40	38	30	19
5 min at 20ft	23/16	28/36	29	18	8	26/30	26/36	37	29	19
3 min at 10ft	29/9	38/38	28	18	7	35/32	36/38	38	29	19
5 min at 10ft	29/8	38/33	28	18	8	35/26	36/34	36	29	19

60 feet for 53 minutes

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	34	47	23	13	3	44	45	39	28	17
20 ft/min	13	40	25	14	4	39	42	38	28	17
60ft/min stop for										
3 min at 20ft	23/16	28/39	24	13	4	26/34	26/39	37	28	17
5 min at 20ft	23/16	28/35	24	14	4	26/30	26/36	35	27	17
3 min at 10ft	29/9	37/38	23	13	4	35/32	35/34	34	27	17
5 min at 10ft	29/8	37/33	23	13	4	35/26	35/34	34	27	17

Table 2.

At the depth of 100 feet (Table 3), reducing the bottom time reduces the maximum gas tensions in the longer time constant compartments by approximately 15 percent. The extra time spent at depth in a 20 fpm ascent increases the intermediate time constant compartments gas tensions. The benefit of this difficult slow ascent procedure over that of a stop is not supported by either gas tension calculation. At this depth, there is a clear advantage to taking the stop, since the short time constant maximum gas tensions are approaching their allowable maximum in the Haldanian Model (See Table 1). There is a strong preference in both models for this stop to be taken at 20 feet, with very little difference between a stop duration of 3 or 5 minutes.

100 feet for 25 minutes

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	38	75	43	32	21	68	62	45	28	15
20 ft/min	13	50	48	35	22	56	56	44	28	16
60ft/min stop for										
3 min at 20ft	33/16	57/57	44	33	22	51/50	43/53	42	27	15
5 min at 20ft	33/16	57/50	44	33	22	51/42	43/48	40	27	15
3 min at 10ft	35/9	66/55	44	32	22	60/48	52/51	41	27	15
5 min at 10ft	35/8	66/47	44	32	22	60/38	52/46	39	26	15

100 feet for 19 minutes

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	38	73	35	25	16	66	55	37	22	12
20 ft/min	13	49	41	28	17	54	51	37	23	13
60ft/min stop for										
3 min at 20ft	33/16	54/56	37	26	17	48/49	36/47	35	22	12
5 min at 20ft	33/16	54/49	37	27	17	48/41	36/43	34	21	12
3 min at 10ft	35/9	64/54	36	26	17	57/46	45/46	34	21	12
5 min at 10ft	35/8	64/47	36	26	17	57/37	45/41	33	21	12

Table 3.

At the depth of 140 feet, the short time constant compartments have reached their maximum allowable gas tension in the Haldanian Model and are controlling the bottom time. Thus, a reduction of bottom time to the Edge no decompression limits reduces all values. As with the 100 foot case, the slow 20 foot per minute ascent procedure has a mixed effect. Again, there is a strong preference for a stop depth of 20 feet, with little difference between stop durations of 3 or 5 minutes.

140 feet for 10 minutes

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	39	86	32	21	12	72	52	32	18	9
20 ft/min	13	52	44	28	13	59	51	35	20	11
60ft/min stop for										
3 min at 20ft	35/22	67/78	33	22	12	55/53	33/45	30	18	9
5 min at 20ft	35/18	67/71	33	22	13	55/44	33/41	29	17	10
3 min at 10ft	37/9	76/63	33	22	12	63/50	42/44	29	17	9
5 min at 10ft	37/8	76/54	33	22	12	63/40	42/39	28	17	9

140 feet for 7 minutes

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	39	78	26	16	8	60	40	24	13	7
20 ft/min	13	51	38	23	9	53	53	28	16	9
60ft/min stop for										
3 min at 20ft	35/16	58/61	27	17	8	42/45	21/36	23	13	7
5 min at 20ft	35/16	58/54	27	17	9	42/38	21/33	22	13	7
3 min at 10ft	37/9	68/60	26	16	8	51/42	31/34	22	13	7
5 min at 10ft	37/8	68/51	27	17	8	51/34	31/31	21	12	7

Table 4.

The following table summarizes the maximum gas tensions in excess of the ambient pressure found in the three dive depths considered above. From Table 1, the Navy's gage M-values are 78 fswg for the 5 minute compartment, 62 fswg for the 10 minute compartment and 46 fswg for the 20 minute compartment. Since the maximum values for the Haldanian Model, 60 fpm ascent rate, in Table 5 are close to these Navy M-values, the selection of dive profiles used generate close to the maximum allowable inert gas loading in the fast time constant compartments of the Navy Model. Thus, this analysis is based on cases which define the boundary of safety in the Navy Model.

Maximum at Navy Limits

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	39	86	43	32	21	72	62	45	30	19
20 ft/min	13	52	48	35	22	59	56	44	30	19
60ft/min stop for										
3 min at 20ft	35	78	44	33	22	55	53	42	30	19
5 min at 20ft	35	71	44	33	22	55	48	40	29	19
3 min at 10ft	37	76	44	32	22	63	52	41	29	19
5 min at 10ft	37	76	44	32	22	63	52	39	29	19

Maximum at Edge Limits.

	KROGH					HALDANE				
Ascent Rate	1/5	1	5	10	50	5	10	20	40	80
60 ft/min	39	78	35	25	16	66	55	39	28	17
20 ft/min	13	51	41	28	17	54	53	38	28	17
60ft/min stop for										
3 min at 20ft	35	61	37	26	17	49	47	37	28	17
5 min at 20ft	35	58	37	27	17	48	43	35	27	17
3 min at 10ft	37	68	36	26	17	57	46	34	27	17
5 min at 10ft	37	68	36	26	17	57	45	34	27	17

Table 5.

In summary, for all dives with a maximum depth greater than 60 feet, a stop at 20 feet for 3 minutes provides a substantial reduction in the maximum gas tension excess over ambient pressure. When this ascent procedure is coupled with a reduced bottom time in accordance with the no-bubble tables, reductions of approximately 30% in the largest values are realized.

Literature Cited

Ames, W.F. 1977. Numerical Methods for Partial Differential Equations. New York: Academic Press.

Bell, G.H., J.N. Davidson and H. Scarborough. 1961. Textbook of Physiology and Biochemistry. London: Livingston.

Hemmingsen, E.A., B.B. Hemmingsen. 1979. Lack of intracellular bubble formation in microorganisms at very high gas supersaturations. J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 47: 1270-1277.

Hennessy, T.R. 1974. The interaction of diffusion and perfusion in homogeneous tissue. Bull. Math. Biol. 36: 505-526.

Homer, L.D. and P.K. Weathersby. 1980. The variance of the distribution of traversal times in a capillary bed. J. Theor. Biol. 87: 349-377.

Krogh, A. 1919a. The number and distribution of capillaries in muscles with calculations of the oxygen pressure head necessary for supplying tissue. J. Physiol. 52: 409-415.

Krogh, A. 1919b. The supply of oxygen to the tissues and the regulation of the capillary circulation. J. Physiol. 52: 457-474.

Krogh, A. 1936. The Anatomy and Physiology of Capillaries. New Haven: Yale University Press.

Levitt, D.G. 1972. Capillary-tissue exchange kinetics: an analysis of the Krogh Cylinder Model. J. Theor. Biol. 34: 103-124.

Roughton, F.J. 1952. Diffusion and chemical reaction velocity in cylindrical and spherical systems of physiological interest. Proc. Roy. Soc. B. 140: 203-221.

Tepper, R.S., E.N. Lightfoot, A. Baz and E.H. Lanphier. 1979. Inert gas transport in the microcirculation: risk of isobaric supersaturation. J. Appl. Physiol.: Respirat Exercise Physiol. 46: 1157-1163.

MODELING SESSION DISCUSSION

Discussion Leader: Glen H. Egstrom

Discussion following Bill Hamilton's presentation

David Yount addressed Bill Hamilton, remarking: The crucial point as far as you're concerned is that any change in the ascent rate can be compensated for by changing bottom time. Bill: We did it the other way, we changed the ascent rate to see what no-stop time would come out; there are all kinds of combinations.

David: Or, you could have compensated by passing stage. Bill: By ascending slower, from 60 fpm to 30 fpm, all the way down to 10 fpm we actually got more no-stop time. These two act as decompressions. One acted as an additional gas uptake period so it ends up giving us the same bottom time. I think taking up gas and then unloading is not in your best interest. The longer you're exposed to this gas, the more chance you have of developing a problem.

Glen Egstrom: If you take the same dive profile, quickly come up to a certain point and then slowed your rate down, when you use a variable rate of ascent as for example the Edge does, does that give you a benefit? Bill: Sure. If we had come up fast deep and then slowed down, we could have more no-d time. It probably doesn't hurt to use a fast ascent rate (60 fpm) at that zone. This pattern is not going to be very effective for a 100 ft dive. Some years ago Kent Smith did that with goats. In other words, instead of a deep dive with a lot of stops, he came back with two linear rates: A fast one at first and could vary that according to conditions, and using goats and looking at the Doppler, was able to titrate this thing to a dogleg that got rid of the bubbles almost entirely, whereas in more conventional decompression, you'd get a lot of bubbles.

Walt Jaap: We're doing lots of three repetitive dive profiles per day. Would you think stops versus slower ascent rates would be more beneficial? Bill: There is almost no difference. Operational aspects are probably more important. You give someone a kind of exercise that is hard for them to do, then you're not going to get such good compliance, you'll get the tendency not to try to follow it at all, whereas if you give them something they can do easily, it's more likely to be followed. If the physiology is the same on both, then operationally, the easier way is better.

Bruce Wienke: To reiterate a comment that was made before, if you take any set of stops and ascent rates and make them equivalent to the other set of stops and ascent rates, as far as the tissue tensions at the surface, it is a mathematical exercise that anybody can do. The question really boils down to: What are the important features you're addressing by making stops and slower ascents?

Bill: Indeed we can adjust the stops, bottom times and ascent rates, and end up with an equal set of calculated theoretical gas loading. However, does that mean our decompression risk is equal? Probably not, because we practice a philosophy that could be called *delta p* or the time under supersaturation. If you have two dive profiles, one of which gets you out fairly quickly with a given supersaturation load, another one with the same supersaturation load, but takes a lot longer to get you out, you're exposed to that improbable but undesirable event for a longer period of time. Since decompression is fairly statistical in the range that we are working now, I think that anything you can do to make it quicker with equal gas loadings is going to be more favorable.

Bruce: Let's just stick with objective criteria for now. You can take all these dive profiles and skew them with different rates or stops, but the point remains, what are we trying to control by the ascent rate and the safety stop? Then you can factor into that, given that you have leeway in assigning safety stops and ascent rates, what happens operationally. Most divers probably can't make a slow ascent rate. Bill: They won't even maintain 60 fpm. Bruce: 60 fpm is the lower limit, so maybe we ought to be looking at how to optimize our procedures assuming that we're going to follow 60 fpm and then introduce the appropriate regimens. Bill: As this workshop goes on, you'll hear this over and over again, as with the dive computers, the only way we can be sure these things are going to work is to put in a stop. A stop you can do. A slow ascent rate is going to work, but people can't do it.

David Yount: I just want to respond to *t-delta p*. Essentially, the *t-delta p* is the volume of gases released, because the number of nuclei that we get is related to *delta p*. The longer those nuclei are around, the more gas is going to go into them and the bigger the volume of the bubble. Bill: But it is spread over a longer period of time, so theoretically the wheelbarrows can haul it away.

David: And then there is some gas that's leaving the gas phase. In no-stop decompressions, the very deep, short stops, you have lots of bubbles for a short time. There's a big *delta p*, but the *t* is very small. The long no-stops, *t* is very long but *delta p* is small. Bill: Yes, but as you heard from Ed Lanphier and Charlie Lehner, the short fast ones often had worse symptoms.

Bill Hamilton mentioned that if there were a minute left, we didn't attack Bruce nearly enough. Maybe we let Dave off too easy also!

John Lewis: Your last example was 130 ft, no-stop, 11 minutes for the standard ascent and it went up a little as you took a slower ascent. I puzzled about the difference between your conclusion that I would regard as relatively ineffective (a stop at 10 ft) versus what Bruce showed, virtually a 70% reduction in nitrogen loading. Bill: I said that it didn't show up as effective as I expected it to be, so I wonder whether I recall these calculations correctly.

Bruce: The quite critical moments were in bubble sizes and volume of gas. Bruce then reviewed two tables he showed during his presentation. One table was a comparison of the tissue loadings at the surface for a dive to 120 ft for 12 min, followed by a 3 min safety stop at 15 ft, assuming 60 fpm ascent rate. The other one was tissue loadings for an actual dive to 120 ft for 15 min with the idea to compare tissue tensions against what a diver could do when he went into the tables. In the fast compartments there were large differences obviously, in the slow compartments, there was not much difference. The 120 min tissue was used to designate the repetitive group. There wasn't much penalty in assigning the stop time to the bottom time. John Lewis: That was why it confused me because the reductions there are consistent with things I've done myself and they are profound. It was a 70% net reduction in maximum nitrogen loading.

Discussion following Don Short's presentation

Walt Jaap: How do these times relate to physical exercise, versus sitting sedentary in the water. Don: You'll probably have to ask a physiologist, I'm professionally a mathematician, but I think that the top level of resting will be right in here. Glen Egstrom remarked that one of the questions that came to mind early on is that you make the presumption of a fixed system in the capillary. You did increase the transit time, but you also have to increase the internal pressure, because you're going to change the diameter of that capillary rather dramatically in short periods of time. The size of that structure is thus not a constant and the size of the lumen is not a constant. Don responded that in a certain exercise regime when you have this system set up and going, it probably does work. Glen: I find it very interesting to see that, I'm just not sure whether you can get from a fixed system to a flexible system with that same logic. Don: I think the general behavior will be the same.

Hugh Van Liew felt that Don introduced a very interesting assumption and wanted to know if there was a body of experimental data to accompany it. I think what you've been saying is that supersaturation in the venous blood or at the venous end of the capillary is the only supersaturation that matters. In order to get those very delayed peaks you must have had supersaturation within the tissue or within the capillary in the middle of the system which eventually worked its way out to the end. I've never thought about that before, but it does seem as if your results have some merit in that they seem to explain the delayed onset of bubbles that we've been hearing about, but what do you have to say about the supersaturation within the tissue, not giving bubbles?

Don stated he had thought about that a lot and cited a paper by Hemmingsen. They originally wanted to use the bends to rupture cells to blood type work. They tried to rupture cells by saturating them and then decompressing very rapidly, and the cells didn't rupture. Hugh: That's what I meant, it doesn't happen in the tissue, but you still have supersaturation in the capillary blood that is in the middle of your system. Don pointed out that regarding transit times, the blood was moving through the system fairly rapidly.

Hugh then wondered if the blood in the middle was not in equilibrium with the tissue that was just outside of it? In other words, a slice down through the middle or near the arterial end. Don responded that in the model it was in equilibrium, and that the supersaturation in the tissue surrounding the system didn't make a whole lot of difference. I also think that any fluids in between these cells is in very quick equilibrium with the blood that is adjacent to it. So as long as you stay outside the cells, you have very fast times.

Hugh further commented: When I saw those very long delays that were way after the decompression was over, I thought there must be a lot of supersaturation upstream there somewhere, in the tissue and consequently in the blood too. Don concurred. One approach would be to take some sort of average where the bubbles formed, then you can just do these calculations. The assumption I'm making is that is the important place.

Bruce Wienke: Are you using the diffusion equations for the gas in the boundary layers and cellular regions? Don: Yes. Bruce: The whole exchange process is still pretty limited because the diffusion coefficients are so high. Don: Right. This slice through this system is eliminated very, very rapidly. The depth of penetration out of this if you calculate tangents, it's about a third of what is in here.

Hugh Van Liew likened it to a gas chromatograph: The gas goes in and is delayed if you put it in a tissue in your system. Don: Right, but I wouldn't call it my system. Krogh developed it in 1919 and then Hennessy reviewed it again in 1971.

To the question of how one got a range of transit times, Don responded that the transit times essentially came from the blood velocities. Krogh, in 1936, claims that these lengths are 0.4 - 1.0mm. Glen Egstrom: These are 50-100 units long, as opposed to 6 units depth? Don: Right these are relative lengths. When you have this kind of diffusion coefficient you essentially get very fast equilibrium at this level. The diffusion doesn't seem to be that important in this mechanism. Hennessy had some velocities as did Bell and they both gave maximum ranges, which go a few orders of magnitude below this.

Glen Egstrom: A 50 second transit time through a capillary seems to me incredibly slow. They're off the scale and could shut down, which would yield a transit time of zero. Except for a small amount when you start getting some flushing, but the system itself shuts down. Don: But if I look at one fixed velocity, if this thing oscillates or pulsates from zero to some low grade step, it could probably be approximated.

Glen: Well, I think this is a very interesting point. If you would maintain your position, Dr. Yount has agreed to start off a discussion period with yourself, Bruce Wienke and Bill Hamilton so that some of us can reach some kind of understanding of what you five speakers said today.

Physics, Physiology and Modeling Discussion

David Yount retold the story of the five blind men who were standing in front of the elephant and one is grabbing the tail, one the leg and one the trunk and so on, each one describing the elephant in a very different way. What I'd like to say is that we all are describing the same elephant, but are doing it in different ways.

David Yount started with the statement that in the beginning there was the bubble. There is a certain pressure inside the bubble (P_{in}). This bubble has a permeable skin allowing gas to come in and out of it very freely. There is a tendency for the gas tension inside to be the same as the dissolved tension outside which I am calling τ and Bruce is calling P_t. Because of the diffusion equilibrium, these would like to be the same. In addition, you have the ambient pressure, hydraulic pressure or hydrostatic pressure and you have the surface tension. So there is a mechanical equilibrium in which Q should equal $2\gamma/r$ and possibly M. But there is also the diffusion equilibrium in which P_{in} would like to equal τ. You literally cannot have diffusion equilibrium and mechanical equilibrium at the same time except where you have just the right, unique radius, which you most likely won't have, so we don't have to worry about that. So most of the time you don't have both kinds of equilibrium and that means that something is changing. The thing that is changing is P_{in} is a bit larger than τ, gas is leaking out of the nucleus, so it's getting smaller. Or, the other way around, is if you supersaturate it and τ is larger, if the supersaturation is large enough to overcome the surface tension, it will grow. If it's not large enough, it will collapse. If you look at the equation of Epstein and Plesset, the term that drives it and determines whether the radius is increasing or decreasing, is also the supersaturation. Ordinarily, there is no stable radius.

Hugh Van Liew: I agree with what you're saying but oxygen and CO_2 will give you a little bit of a different baseline. David: Sure. The final radius is what you have after you complete your maneuver. The easiest maneuver would be to start at some initial pressure P_o, go to some P_{max}, hold it for a while, decompress and stop at some point, P_{ss}. Meanwhile, the gas tension τ is increasing with that pressure, but then suddenly you decrease it so that τ is trying to decrease. If you left everything else alone, you would gradually approach this new value exponentially. The radius we are talking about is the radius at this final point. The model that I've been telling you about, the varying permeability model, is a model of a nucleus. The purpose of a nucleus is to get you a gas bubble at this point f. The whole function of that model is to explain how it is you can have a gas bubble at that point f. With the model, I can work backwards and tell you what is going on in order to get to that point. What Bruce is telling you is whether you have a gas bubble. I will tell you what happens next.

David Yount: I will start with a certain bubble, with a certain original radius size 0. I will compress that bubble, get a smaller nucleus, I will decompress it and get a somewhat larger radius. With the model I can calculate this gradient and work back and tell you what happens. What we're saying is that the final radius corresponds to a certain initial radius, which is not a critical radius and all the nuclei that are larger than that make bubbles. The number of bubbles you get is the area within this curve. What happens when you change pressure is that this size distribution remains a straight line, but the slope changes. What I can do for you is to trace the evolution of these nuclei as compression changes so I can tell you what the shape of this curve is as compression changes. But in the end it really doesn't matter. What matters is that we have a bubble here. Once we have the bubble, we can forget about the nucleus and everything else, it behaves just like a free bubble. From then on, Bruce and I certainly agree on the results of that calculation.

If there's only one time constant, we've said that the ideal decompression schedule would be to hold it fixed, which turns out that you get a straight line. This would be a fixed number and if you only had one time constant in the system then that would be the best to compute.

What Hugh Van Liew has said is that in fact what we're doing is as this gas tension comes down, there's this awkward kink and that's where the problem occurs because here's the point where you have the biggest supersaturation and the smallest radius. The smallest radius means the most area, the most bubbles, the most problems. So what Hugh is saying is let's round this off a bit so we don't get those small radii and what I'm saying is you could round it off if you wanted to.

This leads to the theorem that there's probably very little or maybe nothing that you can do to the ascent rate that you can't compensate for by using different times at depth. Bill Hamilton has shown us that when he changes the ascent rate 5 fpm up to 60 fpm, you get the same changes in times at the bottom. That says that the different ascent rates could be taken into account just by having different bottom times. Another way is to say we'll put in safety stops, we could have different ascent rates and then make up the difference with different safety stops. You could have a staged decompression with slightly different times at the different stages. In every case, no matter what schedule you are using, it is possible to calculate a radius that goes with that schedule. Every ascent, no matter what shape it has, corresponds to a certain radius. As long as we have the same radius, basically, we're going to have the same number of bubbles and the same outcome. You may have less time at depth, you may have to wait longer in the steps, but these are really just operational points and now this gets back to Ed Lanphier's point of why they chose 60 fpm: Because it was operationally convenient If you would rather do 20 fpm, that's fine, we could make tables with 20 fpm or 60 fpm or anything you like, whatever is operationally convenient.

This raises still another question: Suppose you built your tables on the assumption of 60 fpm, but the diver doesn't do a 60 fpm ascent. Well, it's probably alright over quite a large range. Whether it's 60 fpm or 30 fpm probably doesn't matter, because the time that you spend ascending is probably small compared to the time at the stops. Where it starts to make a difference is when the ascent time between stages becomes a significant fraction of the time at depth or the time that you spend at one stop, then you probably need to recalculate the tables.

The first thing is it would be nice to have something in the ball park of what the theoretician assumed when he calculated the table, but even so you can probably get away with quite a large range of ascent times around the one that was put into the table. I don't see anything intrinsic about the ascent rate and decompression sickness that would say there's no way you could decompress at 200 fpm. That certainly is true. If your ears can stand it and your lungs can stand it, then you can make a table for that. I guess those are the main points.

I haven't really absorbed Don Short's paper, but it seems to me that probably it's a way of getting different time constants and probably the phenomenon that he's described can be created with time constants. We've seen already in Bill Hamilton's paper that if you went to the slowest rate of 5 fpm, you have to reduce the bottom time and we saw that again in Don's paper, that if you go too slow, you might have to reduce the bottom time. So I think we're seeing different parts of the same knowledge coming to similar conclusions, but I don't fully understand all of the parts either.

Don Short: How persistent are these microbubbles? David: They are very persistent in the sense that if you denucleate a sample, it stays denucleated for a long time (like a month). On the other hand, the nuclei are always there if you don't do anything. Somehow, they're not recreated in a time constant shorter than a month. Therefore, they must persist in that time constant.

Glen Egstrom: Is that *in vivo*? David: That is in gelatin. We haven't seen any regeneration in gelatin. The acclimatization studies by Walder *et al* suggest that acclimatization lasts only a few weeks and the effects of diving sort of go away after only a few weeks and that suggests that *in vivo*, the nuclei are restored in a couple of weeks. There are various ways they can be restored. I don't think I'll have difficulty thinking of ways to get new ones. One of the more interesting ways is that we observed with microscopes that there are some nuclei down at the limit of electron microscope resolution. You can get homogeneous, spontaneously created nuclei in Ångstroms. So, one way would be this spontaneous generation of nuclei which tends to capture surfactant molecules and gradually make this curve. I was able to show mathematically that if you take a sample of nuclei and put them in, they will eventually create this curve. This a natural curve, nature likes this curve. But that probably takes a very long time.

Andy Pilmanis: If you take 1 micron nuclei at sea level to a saturation situation, you go down, Boyle's Law would dictate a very large percentage growth of the bubble, right? And yet, how do you reconcile that with the fact that altitude decompression sickness is almost a non-problem compared to diving decompression sickness? Clinically, most people don't even bother reporting it, and yes there are a few serious case, but generally speaking it is very mild and as soon as you come back to sea level, 95% of it is gone.

Glen Egstrom: This is excluding explosive decompression sickness? Andy: I'm just talking about aviators going to altitude. There seems to be a contradiction there.

David Yount: The first approximation is that altitude bends is the same phenomenon as decompression sickness and fits on the same curve. The manifestations of decompression sickness are varied. We talked about chokes and CNS and the particular manifestation you get may depend on the tissue, or it may depend on whether it's a short deep dive or a long shallow dive. You seem to get more bends on long shallow dives and more CNS on the short deep dives and that may be the kind of difference. The tissues that are excited in this case may be less serious tissues and furthermore, as soon as you're at the surface, there should be a relief because now you're spending your time at depth, the surface being the highest pressure, and that's great because you don't need to get a chamber, you'll be treated forever at 1 atm. So there are some things like that that might mount to a second approximation: Why is this form of decompression sickness a little different from the other forms? I don't think it's intrinsic that they're non-distinct, maybe the tissues are.

John Lewis: What is the influence of the pressure spike on the bubble? David: A typical pressure spike would be 1000 atm. The pressure spike has the effect of making the nucleus smaller. So you don't have any nuclei larger than 30-40 Ångstroms.

John: Does that mean if I go rapidly to 200 ft, then rapidly back to 100 ft, I would be better off? David: You should be better off. There are some experiments with mice and shrimp using an enormous spike and in classical bubble formation experiments in superheated water (170°C) or ultrasonic cavitation experiments or the experiments of Hemmingsen where they get these enormous bubble formation thresholds. Hemmingsen has reached 300 atm before seeing any bubbles at all. In the range we're talking about here there is no discontinuity. That's important to the modelers because there's a 1:1 correspondence between these two graphs. If all the nuclei have the same radius, nothing would happen, then suddenly, everything would happen. There would be a certain pressure where everything happens at once. The fact that you get different outcomes as you change these pressures, you get different radii and different bubble numbers. The famous model of the impermeable skin, where they assumed that skin does not allow gas to go in and out, and they said either the skin remains intact and then there's no effect on the pressure spike or the skin breaks in which case there's a complete effect on the pressure spike. They would say nothing happens as you raise the pressure, then suddenly all the nuclei break and then nothing more happens. They did an experiment and found this wasn't true, then abandoned the model. What they found was they got a straight line rather than a threshold.

John Lewis: Is this an admonition to dive deeper first? I've never known where that came from? David: Absolutely. It has exactly the right effect. It makes the nuclei smaller and it has less chance of getting bends later on.

Glen Egstrom: Is this where the tiny bubble theory comes from, why the Hawaiian black coral divers drop down to 350 ft first? David: The Hawaiian divers are an undisciplined lot, but found from their own experience that they could get away with some incredible practices, deep dives, repetitive dives, grossly violating the Navy tables. On the other hand, when we analyze their dives, we can understand how they could get away with it, because they did what you were saying. They take the deepest dive first and crush nuclei, then do their shallower dives later on. To some extent there is a bit of luck involved because you accumulate large supersaturations and small nuclei. The large supersaturations mean that if anything does go wrong, you have a real problem with all that gas if it forms bubbles. To get rid of the nuclei, they can take on more gas than you might expect, but then if they have a problem, it's likely to be a serious one.

Glen Egstrom: Are we able to get any action that would be acceptable to the discussants at this point by asking when it is best to slow the ascent rate down to some limit and when it would be best to stop? David: Approaching this as a theorist, I would be satisfied if I felt that I understood what was going on and I could in principle calculate those things. I think several of us here could make those calculations. As a practical matter then I would say that if the people who designed the table were using 60 fpm, I would use an ascent rate of that order. It doesn't have to be right on 60 fpm as we know, but that has been calculated as part of the table. So you should follow the instructions of that particular table. It doesn't mean that a table based on 60 fpm is safer than a table based on 20 fpm. As Bill has done for us, if you go 5 fpm you can stay 11 min at the bottom, if you ascend 60 fpm then you can stay 13 min at the bottom. He said: You give me an ascent rate and I'll calculate a table. I'm satisfied with that as a theorist. I think we have the right things to do the calculations.

Glen: Maybe I wasn't clear. If, as has been suggested, this 60 fpm came out as a result of no calculations but rather as an operational compromise, then, given what you all know, safety stops, faster ascent rates and safety stops, what would be a better combination? I understand what you said about being able to calculate all of these things, but with the state of knowledge that we have now, what would be the most reasonable?

David Yount: My feeling is that if you're happy coming up at 60 fpm, then we'll make our tables so that you come up at 60 fpm. If you'd rather come up at 100 fpm, we'll make our tables that way. The tradeoffs are not that much. They are things like a couple of minutes of bottom time, or a little bit of more time at a stop, they're not big tradeoffs. But if we knew everybody was going to do 120 fpm ascents, we'd probably do our tables with that.

Glen: Spencer Campbell did an experiment some years ago where he took a group of some number of sport divers to exactly 60 ft of sea water, then turned them loose to the surface, at which time they were timed precisely. My recollection is that they were finding average times of ascent rates in the range of 170 fpm, roughly three times as fast as they should be. Asked how fast they were coming up, they all answered 60 fpm. There was no incidence of decompression sickness associated with that and so as a practical matter, most of us recognize that people don't come up at 60 fpm.

David Yount: OK, why is that alright? You're at 60 ft depth. If you come up at 60 fpm, it takes you 1 min to reach the surface. If you come up at 180 fpm, it takes you 1/3 of a minute to reach the surface.What we're talking about is whether we add or subtract 2/3 of a minute to the bottom time. A fraction of a minute is probably not a problem for us, and therefore it really doesn't make much difference if it's 60 or 180 fpm.

Bill Hamilton: But physiologically, we don't have any way whatsoever, as far as gas loading is concerned, to calculate whether 30 fpm or 180 fpm is better.

Walt Hendrick: I saw enough cases in the chamber that made me wonder when people had been short term diving, to about 120 ft., something went wrong, rapid acceleration to the surface and invariably ended up with big problems.

Bill Hamilton: Walt, that's not a calculation, that's data. Seriously, we can't do it with calculations. We have to go back and look at what our experience is.

Andy Pilmanis: I want to reinforce what Walt said. What's the worth of this workshop if that is not a problem? It is a problem, because the patients we have at the Catalina Chamber followed the profile, then you ask them about the ascent rate and it was undoubtedly along the lines of what you were saying.

David Yount: What is happening is you're exciting time constants that are much shorter than you normally have in your decompression program. If you ascend at 180 fpm, you're looking at time constants that are less than 1 min long. You probably don't have those in your program.

Bill Hamilton: I played with the things Charlie Lehner talked about in the submarine escape. The first thing I did was take 1 min equals 1 sec, and found out I could get away with a 1 or 2 min halftime, which we never use, because nobody does it. David: In our programs we have a 1 min halftime that we've never used, because we have a 60 fpm ascent rate. We never hit the 1 min halftime. As we increase the ascent rate, we're going to start using the 1 min halftime and maybe we'll need a 0.5 min halftime.

Bill Hamilton: I think the point Walt made was good and Andy followed up on it, that we need to look at data and experience, as well as what we can calculate. Walt: In addition to what you were saying Glen, as far as looking at ascent time, they may be travelling at depth at 10 fpm. They may, in fact, become too heavy and think they are ascending, but are descending, and add lots of air. The overall ascent time may have been 2 min, but they may have been accelerating at 300 fpm just under the surface. That is not uncommon. I think that is very dangerous when you get down to the implementation of it.

The other question I had is how long does it take following the longest route for the blood to make a complete path through the body? Hugh Van Liew: Variable. Walt: Does it vary from individual to individual? Hugh: No, from capillary bed to capillary bed. Sometimes it's slowed down so the blood is not moving fast.

David: That's the right answer, the wrong answer is.... If you're a physicist, the blood volume is 5 pints or something, the stroke volume of the heart is 100 cc's. Hugh: Cardiac output is 7 liters in a man weighing 70 kg, so it should be 1/10 of his weight. David: How many volumes of blood is that, about 10 volumes of blood?

Bill Hamilton: Cardiac output is about the same as blood volume, in other words 1 min is the average circulation time. David: So there is a 1 min time constant if you treated the blood as a tissue and it's probable because the short time constant tissues are the brain, the lungs, the blood, where you get symptoms like chokes, CNS. Those are the bad ones because they have short time constants and really need the blood.

Dick Long remarked that just for the sake of oversimplification: We are all here because we have a customer. The customer is the diver in the field. Either he's supported through the university system or is a recreational diver. We need to go home with some kind of a product for our customer and tell him something that he/she can do in the field. I would say that military and commercial divers have their diving prescribed for them. But the amateur sport diver or the scientific diver are waiting for us to come back and tell them something regarding their rate of ascent and safety stop. I think if we go back and tell them we can calculate the decompression tables any way they want them, now tell us how you want them, we do not serve the right purpose. They are expecting us to take the incredible, vast diving experience we have assembled here and create a vehicle that's going to serve them If not, they're better off without us. I suggest that we spend a little time and create three scenarios with recommendations for which procedures of ascent rates and stops would be better for each scenario.

David: Let me put this out as a possible answer: If you're working with a certain table, follow the instructions of that table. If it says 60 fpm, ascend at 60 fpm, knowing that if you don't get it exactly right, it's still OK.

Bill Hamilton: But you're not helping those of us who are designing tables. David: My comment is for the people we're talking about. Now we can look at the details such as: Do we want to get a little more bottom time by optimizing the ascent rate? You can maximize the bottom time. Bill: That doesn't interest me very much because that, as you say, is under control. The question is what happens to the physiologists, why do we have accidents?

Jim Norris observed: Can't it just be that the data doesn't allow us to go any further at this point? We keep hearing that a lot of this has been empirical, compromise, etc. We can't make strong statements at this point other than tell people to follow guidelines of the tables they're using. Bill: If we could calculate it easily, we wouldn't be here. Glen

Egstrom: Again, if, in fact, there were data that we better understood, it would come to light that there might be some better solutions to the problems.

Karl Huggins: All this information is fine. You can calculate just about anything based on any parameters you want, but once we have the table out there, then the whole point is how to get people to follow that? How can you help them control themselves in a situation? We're talking about buoyancy situations and how to monitor the ascent rate? With the dive computers coming out now, they have the advantage to be able to monitor ascent rates. Glen Egstrom: You're right, those topics will be discussed tomorrow. We're still trying to get the physicists and physiologists the chance to say what they want to say.

Hugh Van Liew: I've heard a call for some kind of a definite change at this point. Mike Lang: No, I don't think so. This situation happens at this point in all workshops. We're just a step ahead. What we've really just looked at today are some aspects of diving physics and physiology. We still have to address training questions and the operational aspects of dive equipment associated with ascent. The end product we really want to get out is a safer diver. So we need to address all these different aspects first. I would say that if you want to make some kind of comment on the actual ascent rate in itself, this might be a good time.

David Yount: I wanted to make a comment about the lack of data. Hugh Van Liew: I want to finish my comment first. It takes a lot of thought and care before you make a definite change. Unless you have a really good reason and understand all of the ramifications, don't change. What we did today is simply start thinking about how changes might go, and I wouldn't advise anyone to change things just on the basis of our discussions. We're not together yet.

David: Now I'll say something about the lack of data. When you have a graph, a famous straight line, you have that graph because you have data. You know that if you exceed this *delta p*, you're going to get bends. The reason we don't have a lot of data on ascent rate is because of the first approximation, it doesn't matter. We don't automatically get bends if we go faster than 60 fpm. We can go 180 fpm and usually get away with it. So, the reason there's no data is because there's a wide range of ascent rates that is permissible.

John Lewis: We've heard a lot of comments regarding it's probably just fine to go 180 fpm on ascent. Nobody is obviously arguing for a greater ascent rate, the issue is that we hear calls for slower ascent rates. Independent of the impracticality of it, there's an enormous database with respect to 60 fpm, very controlled ascents. The ones that Andy did, which were actually much more important with respect to safety stops, and every set of experiments you look at starting with Spencer and all of the Navy's experience and experiments, and see how all of them are controlled at a 60 fpm rate of ascent. There's no issue that the rate of ascent per se is influencing decompression. To take it one step further, we have no database for a slower rate of ascent. Theoretically, it turns out it is totally ineffective as a means of decompression compared to a safety stop. I think there is absolutely no reason to vary the present 60 fpm rate of ascent, with one exception, in terms of procedure, as Andy demonstrated: It's a big deal to make a stop. Indirectly, that does a lot of things, such as it slows you down so you can make the stop.

Bruce Wienke made his personal recommendation of an ascent rate of 60 fpm and a safety stop between 15 and 20 ft for 3-5 min, and add that time to the bottom time of the dive. This procedure provides some additional safety.

Phil Sharkey noted that if we adopt tables with slow ascent rates, deviations from that ascent rate appear to be more damaging than if we develop tables for faster ascent rates. I've always believed slower is better no matter what. I therefore believe we should table the decision of ascent rate numbers and look at some of the operational parameters that go into that and to what people really do.

Mark Walsh asked Bruce Wienke that when using a dive computer based on Bühlmann with a 33 or 40 fpm ascent rate in its model and you do a lot of altitude diving, you can see a difference when going 33, 40 or 60 fpm in that algorithm. Bruce: I think I would make the same kinds of arguments I just did, for using whatever ascent rate is appropriate at altitude. I would make the safety stop at 10 or 12 ft instead, so there is a scaling. The problem at altitude is reducing the ascent rate which is built into the tables that is built into the dive computer algorithm, which means you have to go very slow. The problem with 60 fpm is that we're having problems with it at sea level. At altitude, it's a nightmare.

Glen Egstrom: It appears as if we haven't made much ground on the dilemma that is in current practice and the theoretical level with models. We have ascent rates ranging from 20 fpm to 60 fpm, when in fact what we know, for those of us that spend time doing this sort of thing, is that it's the rare bird who comes up at 60 fpm and when you're not coming up at 60 fpm, there's this little funny flashing light that catches my attention, because I see it a lot.

Lloyd Austin: As soon as we start talking about a required stop, we're no longer talking about no-decompression diving, and that is a real consideration for the average diver who can't make an emergency ascent directly to the surface.

Ed Lanphier concluded that if the point here was to be safer, the method of being safer is to shorten your bottom time or to go to the next increment in the table, greater bottom time and decompress accordingly, or greater depth and decompress accordingly. If you're making a no-decompression dive on purpose, of course a stop makes it into a decompression dive of a sort. So, shorten your bottom time. Is that such an irrational approach about it?

DIVE SUIT BUOYANCY CONTROL PROBLEMS AND SOLUTIONS

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The principle and methodology for regulating buoyancy in a dry suit is the same as that used in a wet suit. The difference lies in the device used. In the wet suit, the device used is the buoyancy compensator, and the buoyancy compensator is totally separate from the suit. Whereas in the dry suit, the suit functions as the buoyancy compensator, and the separate buoyancy compensator serves only as a surface flotation device. There are two classes of dry suits in common use today. The first class, foam suits, consists of suits made from closed cell neoprene foam (FS). In the FS class, the suit provides both a waterproof barrier and all or a portion of the insulation. The FS class, because of its closed cell structure, loses its intrinsic buoyancy and insulation with depth. The second class, the membrane suits (MS), is made of a variety of materials ranging from plastic to rubber coated fabrics. The basic material in the MS class suits provides only a waterproof barrier. The suit provides only a very minimal amount of insulation and in most cases is nearly neutrally buoyant. The buoyancy component of the MS suit system comes from the insulation undergarments worn under the suit. The buoyancy and insulation of the MS suit is constant without regard to depth. The MS class of suit requires a smaller volume of air to achieve neutral buoyancy than the FS class suits since air is only added to the suit to reduce suit squeeze. The FS suit has a much greater change in buoyancy and therefore need for skill of operation. The keys to good buoyancy control in the dry suit are proper weighting (the amount of weights needs to be adjusted with changes in insulation), understanding of the function of the equipment, and development of the skills required. This paper will discuss the basic control problems during ascents and the requisite skills needed by the user.

Introduction

I will talk about the impact of dive suits on the safe rate of ascent. I am going to confine these remarks to the scientific and recreational diver and leave out the military and commercial sector. I will address this issue from a system standpoint and Bob Stinton will address valves as a specific equipment item. First, a very brief review.

The average 1/4 inch wet suit has about 20 pounds of buoyancy on the average person. It loses buoyancy and insulation with depth. The buoyancy compensator was invented to compensate for the lost buoyancy in the wet suit. Depending on its age, the foam material the wet suit is made of will become neutrally buoyant somewhere between 85 and 130 feet, requiring the BC to displace 100% of the belt's weight.

The foam rubber dry suit has, in addition to all of the characteristics of a wet suit, an air gap between the diver and the suit which provides some additional insulation and buoyancy. You can also add insulation to the foam dry suit. You must add air as you descend to both compensate for the compression of the material of the suit, and to equalize the squeeze within the insulation.

The membrane suit has no insulation of its own and therefore, no inherent buoyancy of its own. You can vary the insulation inside the suit with the requirements of the dive whether it will be a warm or cold water dive, or whether it is at a high or low exercise rate. The amount of air required to equalize the squeeze will depend on how much insulation you would have.

We have prepared a chart (Table 1) in which we have referenced the surface and a depth of 60 feet on four kinds of suits: A wet suit, a foam rubber dry suit used without underwear, a foam rubber dry suit with underwear, and a membrane suit with underwear. Our sample wet suit has 20 pounds of buoyancy within it. The foam dry suit has the same. The shell suit has none. The air inner layer is worth about 5 pounds of buoyancy. Both the foam rubber and shell dry suit have this. We put an underwear system underneath one of the foam suits and the shell suit. Each system is about equivalent insulationwise to that of a wet suit, so we have an equal situation here. You can see if we are on the surface we wear 20 pounds in the wet suit and 25 pounds in the foam rubber dry suit. If we put insulation underneath the foam dry suit, we must use 45 pounds because we want to have insulation at depth. The 25 pounds in a shell suit stays constant. If we take each system down to a depth of 60 feet, the literature will tell us that the foam rubber will lose about 60 percent of its buoyancy. Therefore, the wet suit has only 13 pounds left of the surface buoyancy. That is the same for the foam rubber dry suit. The shell suit would have lost nothing. All of the dry suit's inner layers are going to stay constant as will the underwear because you are going to add air to equalize the squeeze. If you did not add air to the dry suit, this shows how much positive buoyancy you would have left and the depth No equalization at 60 feet is going to be a real exciting dive.

Table 1. Air volume required to achieve neutral buoyancy

Buoyancy at the surface

Buoyancy	lb.	lb.	lb.	lb.
shell	20.00	20.00	20.00	0
interlayer	0	5.00	5.00	5.00
underlayer	0	0	20.00	20.00
Total lb.+	20.00	25.00	45.00	25.00

Buoyancy at 60 fsw

Buoyancy	lb.	lb.	lb.	lb.
shell	13.00	13.00	13.00	0
interlayer	0	1.67	1.67	1.67
underlayer	0	0	6.67	6.67
Total lb.+	13.00	14.67	21.34	8.34

Air volume required to achieve neutral buoyancy (ft^3)	0.203	0.229	0.333	0.130
Surface equivalent volume (ft^3)	0.609	0.688	1.000	0.391

The chart shows the total amount of air that will have to be added for each suit to achieve neutral buoyancy again.When diving in real cold water, the diver must add more underwear. In foam dry suits, it is not uncommon to find divers with 65 pounds of lead at the surface in order to get themselves down. With the foam dry suit you must add enough air to bring the lead required to sink the collapsing foam to neutral buoyancy. The result is that the bubble of air that you are going to be holding in your foam dry suit at depth to neutralize the lead is going to be greater than any membrane suit. At 100 feet this is 20 pounds greater. Therefore, you have a much larger bubble in back of the shoulder of the suit. We suggest wearing a buoyancy compensator for surface flotation only and using the suit to neutralize the buoyancy, which results in having only one volume of air that is moving back and forth. When the diver starts to ascend, this is the amount of air that must be released from the suit under controlled conditions. The central issue is how to release the excess air from the suit during ascent to maintain neutral buoyancy.

Where are we now?

Most divers train in one set of gear and buy a different set of gear. If we travel to another location we often are required to rent or use a third set of gear that may or may not operate in the same manner as that in which we were originally trained, which is particularly relevant for the beginning diver. In the U.S., the instructor organizations are not training divers in dry suit diving. Dry suits and buoyancy control are totally left out of the curriculum. As a group, most instructors are uncomfortable with the issue of dry suits. They also are not trained in neutral buoyancy control. Buoyancy compensation yes; neutral buoyancy no. Therefore, as a group they can't teach the U.S. public how to use dry suits and they can't teach neutral buoyancy or buoyancy control while ascending, whether in a wet suit, dry suit, or only a bathing suit. In Britain, 85 percent of diving is done in dry suits; it is mandatory to have buoyancy control and dry suit diving as part of the fundamental basic scuba course.

The limit of 3 dives/day to the amateur sport diver is not an acceptable alternative to him. Today he is diving between 3 to 6 dives on a diving boat diving his deepest dive first and his shallower dives last. He is not experiencing any cases of the bends. So, he believes that what he is doing currently works. Therefore, any suggestion to confine himself to 3 dives a day is not going to get wide acceptance.

What are the problems of today?

In all of the models that we have seen and which are being used today, there is no component which considers the diver's thermal state during the dive. In some cases, the diver enters the water very warm, even hyperthermic as he goes down. In a wet suit, they pass a thermal neutral phase passing into hypothermia. If they stay down long enough, they come up cold. Therefore, at a minimum, major blood flow shifts occurred.

There is nothing in the models accounting for the differences in ages. There is nothing about size or sex or physical conditions.

If you descend on a dive and your buddy gets separated from you on the bottom at 60 feet, you either have a choice of taking 3 minutes (@ 20fpm) to get to the surface to find out where he is, go back down and untangle him from wherever he is, or you can rise at 60 feet per minute, find out where he is and go back down again. If you find yourself coming up in a strong current and you swim forward of the boat and make the dive in 90 feet of water, by the time you come to the surface you may not be near the boat unless you calculate the current.

Most sport divers today are trained to start their dive oriented to be neutrally buoyant at the beginning of the dive. The wet suit diver normally starts with the water level at nose level which is about 5 pounds positive. They count on suit compression to make them neutral at about 20 feet. If they are using an 80 cu.ft. cylinder, the cylinder itself has 6 pounds of air in it. By the time they finish diving, they are now 6 pounds positively buoyant. That is assuming that 100 percent of the air is used upon reaching the surface. Therefore, it is very hard for them to stop or slow themselves as they get closer to the surface. The ascent is the busiest time of the dive. During the ascent we must maintain buddy contact. We must look up and turn 180 degrees to make sure we are not coming up under the boat, and we must watch our dive computer.

In dry suit diving the most common mistake divers make to ensure against positive buoyancy is to overweight themselves. It is not uncommon to find people swimming 10 or more pounds overweighted. Their dry suit diving skills are not yet instinctive. Most people use a dry suit only in cold water and only on occasion because it is more expensive than a wetsuit. As a result, there is a genuine lack of proper maintenance of the equipment, especially the valves. The valves often stick or don't perform properly particularly after having been stored a while. If left unrinsed, the salt crystals form on the seat and make operation difficult.

The average diver today cannot control his rate of ascent. We have confirmed that from several sources here today. The average diver cannot learn how to control his rate of ascent because there is no mechanism or method within the field for them to acquire this training or education or to practice this skill. It simply isn't there. Even if it were available, I suspect that the majority of the diving public would not choose to learn the skill. In any case, the point I wish to make is that you can control the rate of ascent with the equipment currently on the market from a wide variety of manufacturers. However, I would suggest that the average diver doesn't use the equipment properly and he does not have the skill to maintain a 20 foot rate of ascent.

What do we need?

1. We need a gauge to monitor our rate of ascent (*i.e.* a device on our meter, a type of speedometer so we know how fast we are going). We don't need a light that flashes.
2. We need to improve the education of the diver, which means we need to improve education for the instructor.

Let me be blunt. Three to four years ago I brought this subject to the attention of the instructor agencies because I was manufacturing equipment for the field. Other manufacturers agreed to cooperate in performing generic training for instructors. SSI and PADI both commented that they thought it was important but haven't gotten around to it yet. They can't endorse any kind of industry training program and they will do their own. NAUI has been very openminded about it, saying they weren't prepared to do it but they would support our doing it. This year NAUI has given me the guidelines by which to contact the people to set up programs. And I must say that my plate has been overly filled and I have not been able to do this yet. So far they are the only ones to come forth and bite the bullet. As far as we are concerned, we will do it in any form that is acceptable to the agency and organizations, and in cooperation with any other manufacturer. We simply want the education in the field.

I suggest we determine what is needed and develop strategies that maximize the operational requirements of our customers. I think we need to standardize operational methods as in the automobile, where the gas pedal is one place, the brake pedal is next to the gas pedal and the steering wheel is always on the left hand side. On the gear shift for automatic transmissions park is all the way up, reverse is next, neutral next and drive is last. That is standard in any automobile. It does not take away the competitiveness of any car manufacturer. And you know as well as I that the automobile industry is very competitive. In dry suits, I think we can standardize inlet valves on the chest, exhaust valves on the left arm. The valves adjust counterclockwise lowering the amount of back pressure on the bias spring; clockwise tightens it. Air inlets have a QD that pulls back to disconnect. We have seen some that operate exactly opposite. Therefore, if we standardize, once you have trained someone in one, then you have trained them in all. I offer to you the Dry Suit Guidelines that were developed and agreed to by all the major dry suit manufacturers in the U.S. (Fig. 1). This is a step in the right direction, but there is still a long way to go.

Figure 1. Drysuit guidelines 1/89

Most of the drysuit manufacturers have published a set of drysuit guidelines. These guidelines are to assist the diving public as a checklist that we feel divers should follow before using any drysuit. They are as follows:

1. Complete a drysuit diving course from an instructor and stay current.
2. Use a buoyancy compensator device for surface flotation and backup.
3. Know your equipment and emergency procedures.
4. Practice your drysuit diving skills under controlled conditions until they become second nature.
5. Dive with a buddy who understands your drysuit system.
6. Use the correct amount of insulation for the water temperature you're diving in and your exercise rate.
7. Don't weight yourself heavier than neutral buoyancy with an empty tank. Or, upon completion of your dive, your weighting should allow you to make a decompression stop at ten feet with a tank that has 500 psi of air or less.
8. Check your valves, zipper and seals before each dive.
9. Perform preventive maintenance and repairs on your suit and valves regularly, or have them serviced by a qualified individual.
10. Know your limitations and do not exceed them.

Water or air temperatures below 70 degrees F constitute cold water diving.

Water or air temperatures below 40 degrees F constitute ice diving. Ice diving is very dangerous and requires special equipment, training, preparation and procedures.

These guidelines have been recommended by the following drysuit manufacturers:

American Diving Systems, Inc.	O.S. Systems, Inc.
Amron International Diving Supply, Inc.	Seatec
Brooks Wet Suits, Ltd.	Typhoon Water Wares, Ltd.
Dacor Corporation	U.S. Divers Company
Diving Unlimited International, Inc.	Viking America, Inc.
KME Diving Suits, Inc.	White's Diving Equipment

If you have any questions on any part of these, come by our dive store and we will be glad to go over these guidelines with you or contact DUI at 800-325-8439.

What do we recommend?

1. The diver should use a minimum amount of weight for the amount of insulation he is carrying, and not be grossly overweight. Calculate neutral buoyancy with an empty cylinder (Fig. 2). If you practice in a swimming pool, you don't have to wait to get to a dive site to calculate your buoyancy. What usually happens is that a diver gets to a site and throws an extra 15 pounds on to make sure he has it covered. You want neutral buoyancy at the surface at the end of the dive with an empty tank.

We suggest that before you ascend, you adjust your exhaust valve all the way open and vent any air left in the suit. At the end of a dive you cannot have that much air left in the suit anyway because you have been venting it off. Swim to the surface as opposed to "rise" to the surface. Dry suit valves are not elevator buttons! They are simply equalizing buttons.

Use a membrane suit that does not expand or contract with depth.

2. Use an automatic dump valve as opposed to push-to-dump. That way your hands are free to hold your dive computer or carry the gold bars that you have recovered from the sunken galleon. This requires less air in your suit. Therefore, you have less volume of air to expand and less air to control. Where the valves are located determines when it pops off more than what the spring is set at. We use a system we call passing gas. One passes gas by raising the upper arm (with hand downward) above shoulder level, making it the highest point on the suit. When the desired amount of air has been lost, lower the arm. The system works well because it's simple and easy to remember.

3. Use suits that fit properly. It should fit you properly when you have the maximum amount of insulation that you will ever need for the type of diving you will be doing. If you are doing Arctic diving, then the suit has to be large enough to accommodate the insulation. You don't want it so large that there are a lot of places for air to gather.

4. Use the buoyancy compensator for surface flotation. Under no circumstances should you use the dry suit alone for surface flotation. This way, if you have a ruptured seal, you still have flotation at the surface.

5. Do not look for engineering solutions to training problems. The agency needs to teach dry suit and buoyancy control because those are becoming issues and are mandatory for the well being of our divers.

6. Keep your divers in thermal equilibrium so that the ongassing and offgassing will be normal and we can live up to the models' assumptions.

7. Use dry suits in water below 65 °F at 60 feet.

8. Keep dry suit skills as current as your worst case scenario dives dictate. The only way a diver is going to be able to do that is to use dry suits every day. Either that or consider that a diver is not qualified to use a dry suit until you reach those skill levels.

If you are a diving officer, you are the leaders of your group and the troops will try to follow your example. They are not as big or as strong as you are, nor as experienced. They do not have the muscle to body mass ratio you have. Therefore, their heat output is less than yours. If you dive in a wet suit, they will dive in a wet suit too. Many diving officers I have spoken with say they are not comfortable yet with dry suits and only use them when they get into a really difficult dive. A diving officer confided in me that he does not use a dry suit for diving in San Diego, but instead uses a 3/8 inch wet suit. Here we have an intelligent man acting like a Neanderthal.

Those really tough dives have a lot of high stress. You need to concentrate on the job at hand, not on where your skills went or what you are supposed to do next. The ascent under these conditions is going to be the most difficult part of the dive to control. That is when accidents happen. We can always go down in technology to a wet suit but you can't go up in technology on demand and expect to be able to perform well.

In conclusion, let me answer the following: Can a 20 foot continuous rate of ascent be done? Yes it can. Should the 20 foot rate of ascent be adopted? I suggest, based upon the field conditions and our customer of today, that the practicality is questionable. Should a safety stop be done? Yes. We need to supply our divers with a control device and training that tells them how fast they are coming up.

Figure 2. Calculate your weight and buoyancy - the easy way

The amount of lead or ballast you will require with your dry suit will vary greatly depending on the amount of insulation, and therefore the air you are carrying. This could require a loss of valuable diving time to experiment with finding the right amount of weight you will need. Therefore, we suggest the following:

* First, gather together all the different combinations you might use for insulation under your dry suit.

* Take all your normal scuba gear and your dry suit to a swimming pool.

* Take a weight belt with lots of extra weights in different denominations. Example: 2, 3, 4, 5 lbs. weights or shot pockets.

* Suit up using the different possible insulation packages from the lightest (for warm water) to the heaviest (for cold water).

* With each package, weight yourself until you are truly neutrally buoyant. If you inhale, you rise; if you exhale, you sink. Note in your log book the underwear combination and the amount of weight it took to neutralize it (be sure you have totally purged all the air out of your suit and have swum around to verify there were no air pockets left in the suit).

* To convert from fresh water to salt, for the body weight of:

125	add 4 lbs.
155	add 5 lbs.
186	add 6 lbs.
217	add 7 lbs.

* Now make the corrections for your scuba cylinder. Example: 80 cu.ft. cylinder add 6 lbs. to allow for the increase in buoyancy as the air in the tank is used up. Also, an 80 cu.ft. tank is about 1 lb. more negative in a pool than in salt water.

You are now ready for the ocean with the knowledge of just how much you will need in your weight system. It is reasonable to need to make a few pounds of adjustment one way or the other once you start diving in salt water. Having established neutral buoyancy, locate your weights so that you are in trim. Ideal trim is a horizontal plane when not moving at all. Depending on how your gear fits, this will determine how the weight is distributed. If your legs are much lower than your torso, swimming will be very inefficient. You should perfect this balance in a pool first.

DRY SUIT EXHAUST VALVE PERFORMANCE: EFFECT ON BUOYANCY CONTROL AND RATE OF ASCENT

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The control of buoyancy is pivotal in maintaining a predetermined rate of ascent in both wet and dry suits. In general, the buoyancy control technique used with the wet suit or dry suit systems is the same. In the dry suit, the compensating volume is contained in the suit gas interlayer (the air space between the dry suit shell and the divers skin) and not in the BC. In the case of the BC used with the wet suit, the air volume is regulated by means of inlet and exhaust valves. In the dry suit, the air volume in the dry suit interlayer is regulated by a valve system consisting of an inlet and an exhaust valve. The inlet valve provides air to the suit interlayer by means of a low pressure hose from the diver's regulator. A dry suit exhaust valve in turn is used to vent gas from the suit interlayer. The most common exhaust valves fall into two basic groups: The manually activated version and an automatic adjustable opening pressure version with manual override. In the ascent phase of the dive the performance of the exhaust mechanisms in both the the BC and dry suit is critical for maintaining proper buoyancy and rate of ascent. This is because the volume of air in the BC and dry suit interlayer expands according to Boyle's Law ($P_1V_1 = P_2V_2$), and during the ascent as the diver nears the surface the greatest rate of change in the free air volume is taking place. The greatest performance demands are put on the exhaust mechanisms. This paper reviews the requirements placed on the dry suit exhaust valve during the ascent phase of the dive, and the base line performance of six commonly used dry suit exhaust valves.

Buoyancy regulation in the dry suit

In dry suit diving, though a BC is worn, it is not used for buoyancy control once the diver leaves the surface. Instead, the dry suit gas interlayer is used (the air space between the diver's skin and the dry suit shell). During the ascent phase of dive, the suit exhaust valve is the most important control the diver has for regulating his or her buoyancy. There are several factors which determine the performance requirements placed on the dry suit exhaust valve during the ascent phase of the dive. These factors are:

1. The configuration of the dry suit system
2. The rate of ascent
3. The schedule of valve operation (continuously or intermittently)
4. The level of inflation in the suit

Configuration of the dry suit system

The dry suit configuration is important because it determines the compensating air volume that must be maintained to achieve the desired level of buoyancy. This paper examines the buoyancy requirements of the three most common dry suit system configurations. Depending on the configuration, there are two (2) to three (3) layers of air filled spaces that respond to the pressure volume relationships described by Boyle's Law. The three air filled spaces are:

1. The dry suit shell, if made of closed cell neoprene foam;
2. The air interlayer;
3. The trapped air in the undergarment.

The last two of the spaces are free air volumes and functionally are considered as one. The free air volume in this combined air space is vented through the suit exhaust valve.

The wet suit diver using a buoyancy compensator has two changing volumes to deal with:

1. The closed cell foam in the wet suit;
2. The free air volume in the buoyancy compensator.

In both dry and wet suits the diver basically only has one control to deal with the expanding free air volume (the air trapped in the closed cell foam material is not free to be vented in either the wet suit or dry suit). In the case of the wet suit/BC it is the BC dumping mechanism, and in the case of the dry suit it is the suit exhaust valve.

There are three basic dry suit configurations in use today:

1. The foam shell dry suit;
2. The foam shell dry suit used in conjunction with underwear;
3. The fabric shell dry suit used in conjunction with underwear.

Each of these suits respond differently to the increasing pressure with depth. Table 1 shows a compression of air volume required to achieve neutral buoyancy at the depth of 60 fsw for the three dry suit systems and the wet suit.

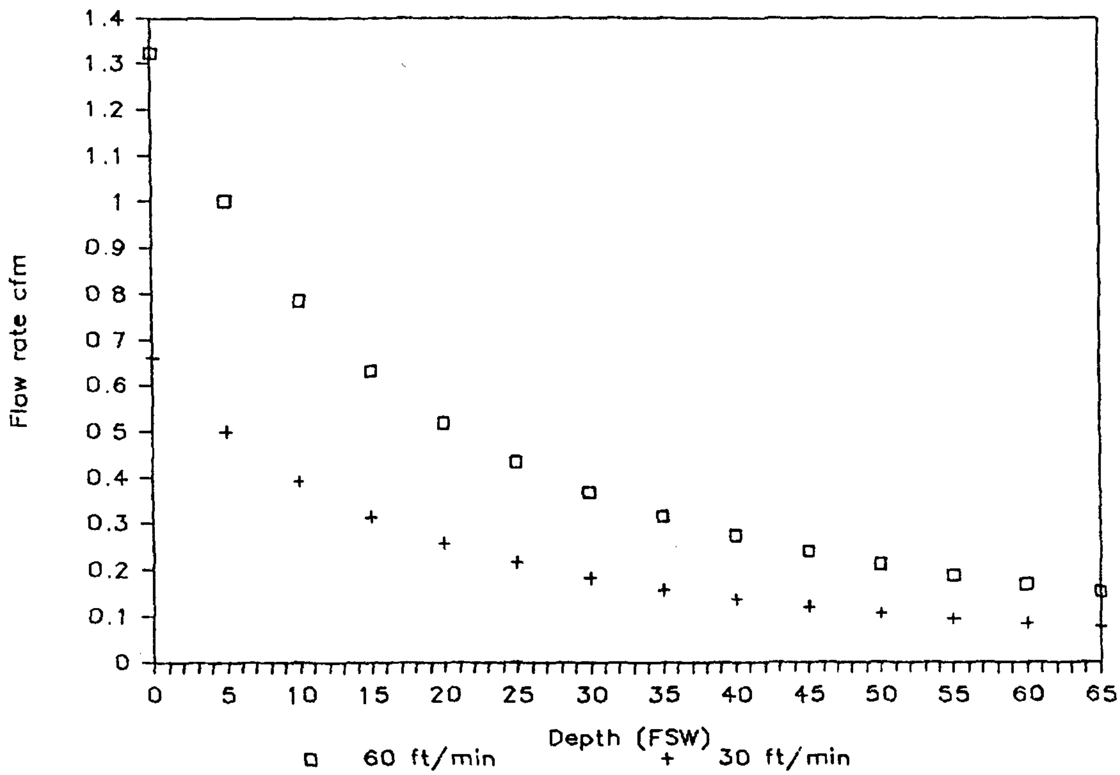
The foam shell dry suit with underwear requires the largest volume of air to achieve neutral buoyancy at 60 fsw. The foam shell requires 64% more than the wet suit and 156% more than the fabric shell dry suit and underwear. The volume required to achieve the neutral buoyancy at 60 fsw for the three styles of dry suits ranges from 0.13 cu ft to 0.333 cu ft.

Figure 1 shows the flow rate requirements for a starting volume 0.25 cu ft at the rate of ascents of 30 ft/min and 60 ft/min. These figures assume that the air is vented from the suit at a continuous rate. The figure shows that the greatest expansion and highest valve flow rate requirements are placed on the exhaust valve in the last 10 to 5 feet of depth. The figure also shows that the rate of ascent of 60 ft/min puts twice the flow rate demand on the exhaust valve as does the 30 ft/min ascent.

Table 1. Air volume required to achieve neutral buoyancy

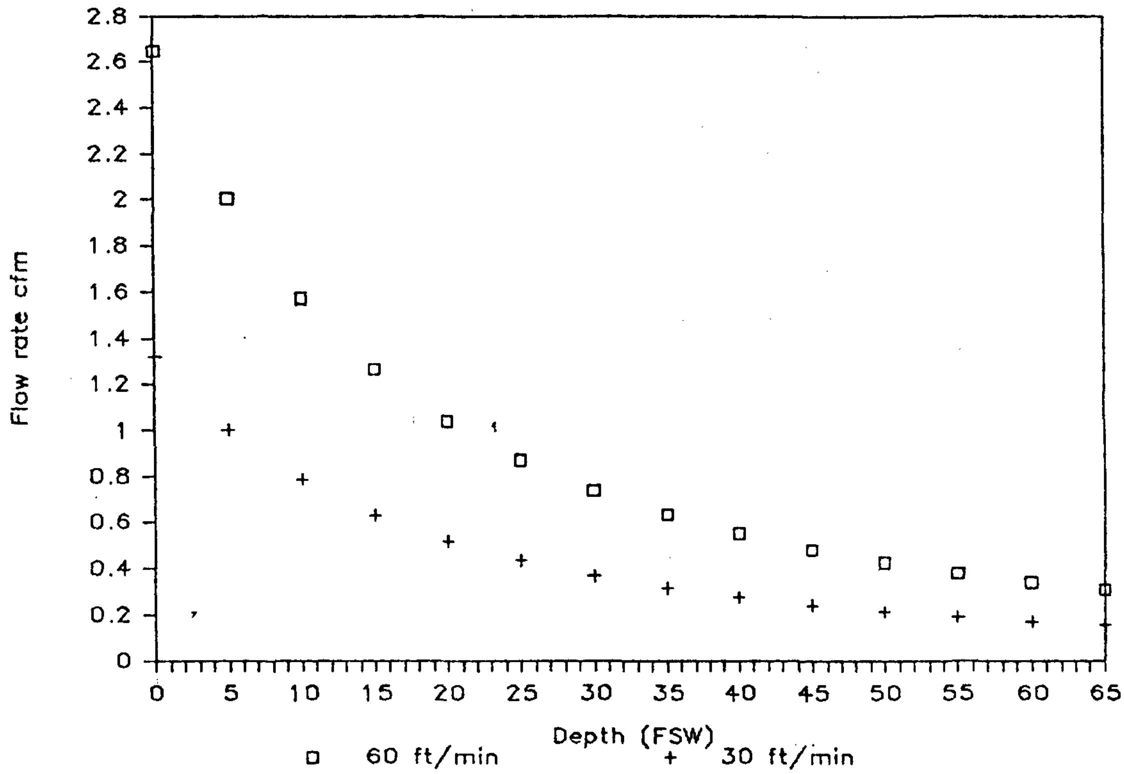
Buoyancy at the surface				
Buoyancy	lb.	lb.	lb.	lb.
shell	20.00	20.00	20.00	0
interlayer	0	5.00	5.00	5.00
underlayer	0	0	20.00	20.00
Total lb.+	20.00	25.00	45.00	25.00
Buoyancy at 60 fsw				
Buoyancy	lb.	lb.	lb.	lb.
shell	13.00	13.00	13.00	0
interlayer	0	1.67	1.67	1.67
underlayer	0	0	6.67	6.67
Total lb.+	13.00	14.67	21.34	8.34
Air volume required to achieve neutral buoyancy (ft^3)	0.203	0.229	0.333	0.130
Surface equivalent volume (ft^3)	0.609	0.688	1.000	0.391

Figure 1. Exhaust valve flow rate requirements
Starting volume: 0.25 cu.ft.



With a higher starting volume, figure 2 shows the flow rate requirements placed on the exhaust valve if the starting volume is twice as large as that in fig.1 (0.5 cu ft.). As one would expect, the flow requirement is also twice that of lower starting volumes.

Figure 2. Exhaust valve flow rate requirements
Starting volume: 0.5 cu.ft.



Exhaust valves

Dry suit exhaust valves currently are available in two basic operating modes: The Manual Push to Dump (MPD) valve and the Automatic Adjustable Opening Pressure valve with Manual Override (A2OP). With the MPD valve, each time the diver wishes to vent air from the suit, the diver must position the valve at the high point in the suit and press the button. With the A2OP valve, the diver sets the opening pressure of the valve by means of the adjustable valve body. To vent air from the suit, the diver only has to position the valve at the highest point in the suit and the air vents automatically. In most cases, the adjustable automatic exhaust valves are mounted on the forearm so it is only a matter of raising the forearm to be the highest point in the suit.

All the available dry suit valve systems were examined. However, only the results of the six predominantly used valves are presented here. The six valve systems are a mixture of two functional groups. Four are A2OP valves and two are MPD valves. In most cases, the valves are not manufactured by the suit manufacturers and are available to most dry suit manufacturers. The four A2OP valves are: Whites, Apeks, GSD, and SI-Tech (Note: the SI-Tech valve is most commonly identified as the Viking valve). The two MPD valve are Delphi and Poseidon. Two of these valves, the SI-Tech and the Poseidon valves, have been in use for over 10 years.

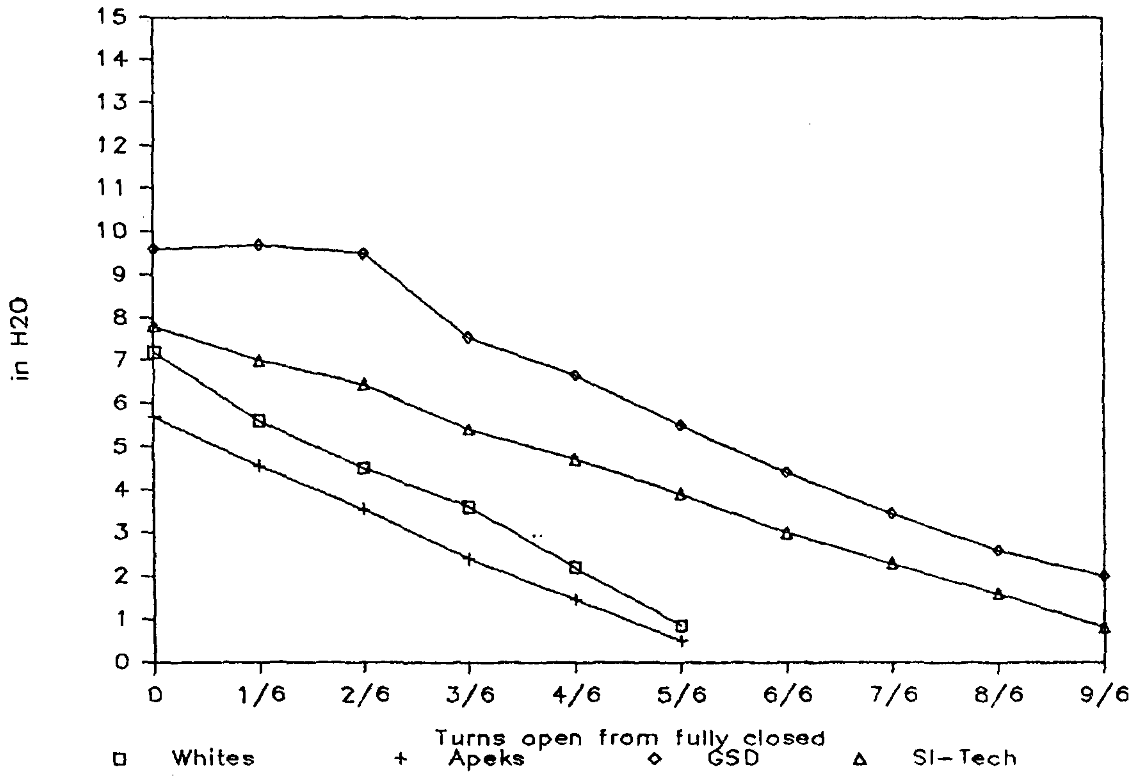
The A2OP valves were evaluated in the following modes at one atmosphere:

1. The pressure drops were measured for the valve adjusted from the highest opening pressure to the lowest in 1/6th of a turn. (Note: the range of adjustability is different between the valves at three flow rates: 1 cfm, 2 cfm and 5 cfm).

2. The pressure drops when the valve is manually operated at the lowest and highest opening pressure.

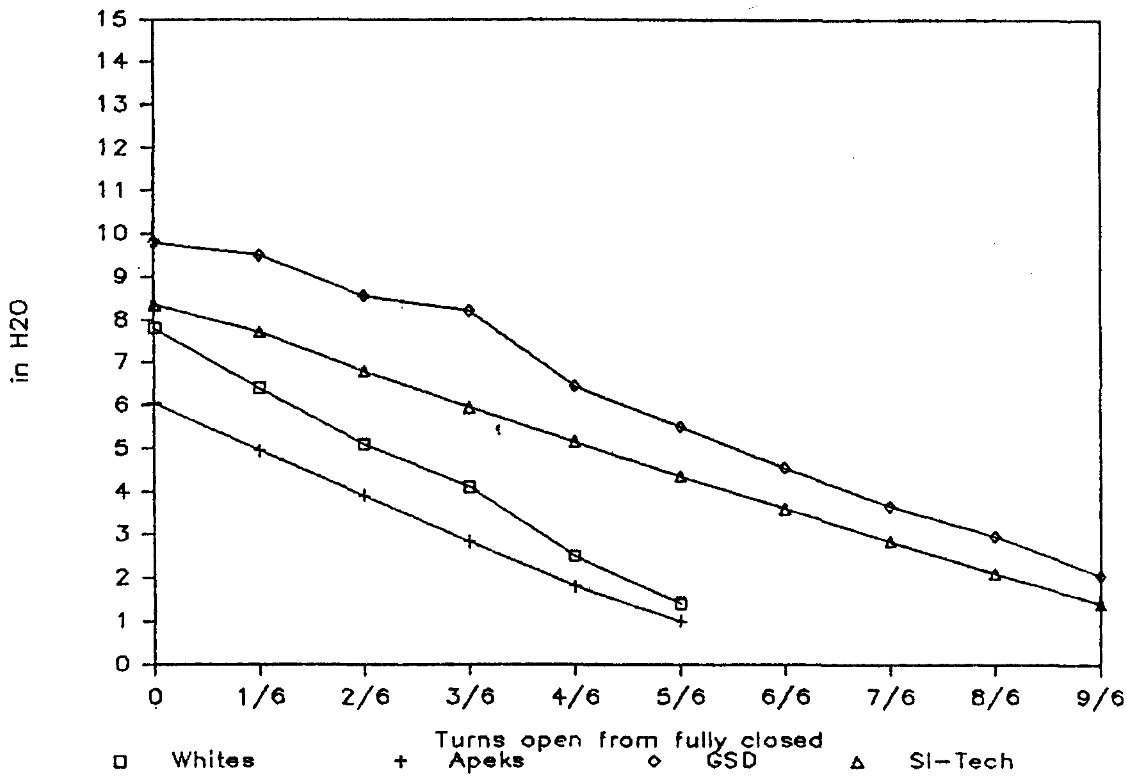
The results of these tests is presented in figures 3, 4 and 5 below. The X axis of these figures represents the number of turns open from the fully closed (highest opening pressure) setting. The Y axis represents the pressure drop across the valve in inH_2O. In comparing figs. 3, 4 and 5 when the valves are fully closed (highest opening pressure), from 1 cfm to 5 cfm the pressure drop across the valves increased approximately 33%. In the fully open position (lowest opening pressure), the pressure drop across the valve increased approximately 400%. This means that in high flow situations the bubble behind the valves is larger.

Figure 3. Pressure drop (inH_2O) at 1 cfm



The bar chart in fig. 6 provides a comparison of the four A2OP valves at 1, 2 and 5 cfm *in the fully open position* and the two manual valves. This is the position the valve is in during most diving situations. It is quite obvious that the two manual valves have much lower pressure drops at all flow rates. The Delphi valve has the lowest pressure drop of all of the valves at all flow rates.

Figure 4. Pressure drop (inH_2O) at 2 cfm



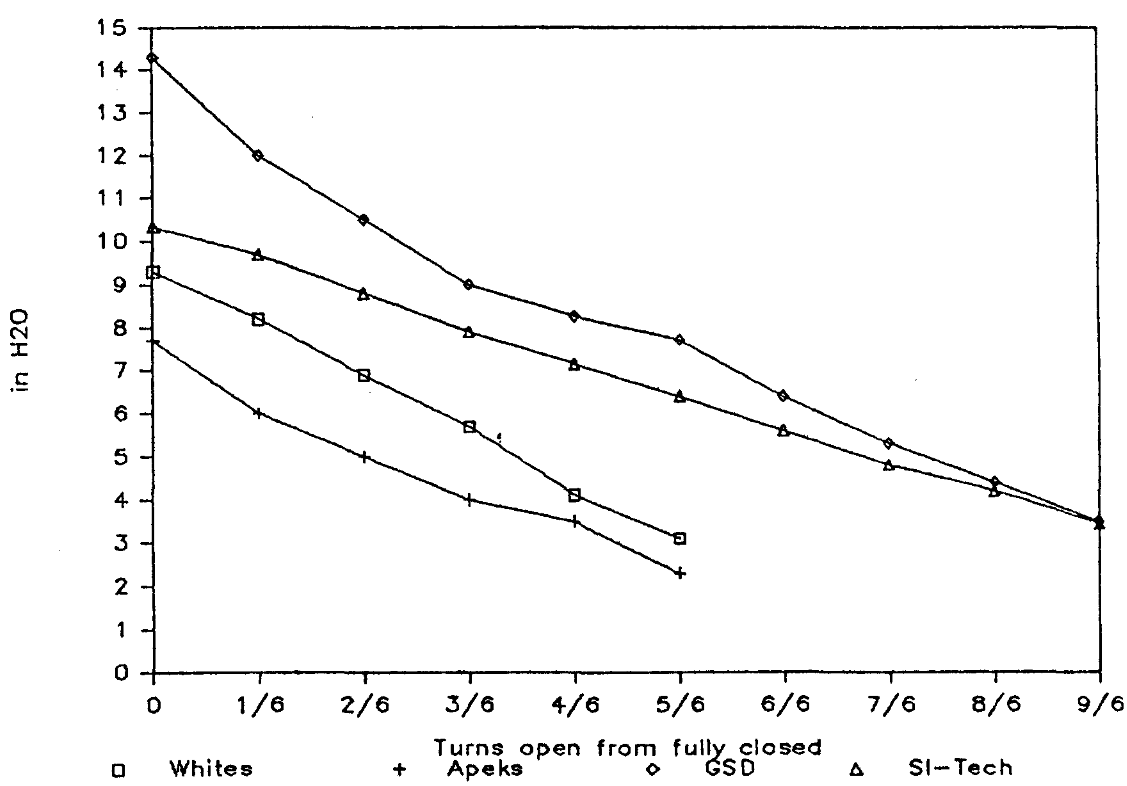
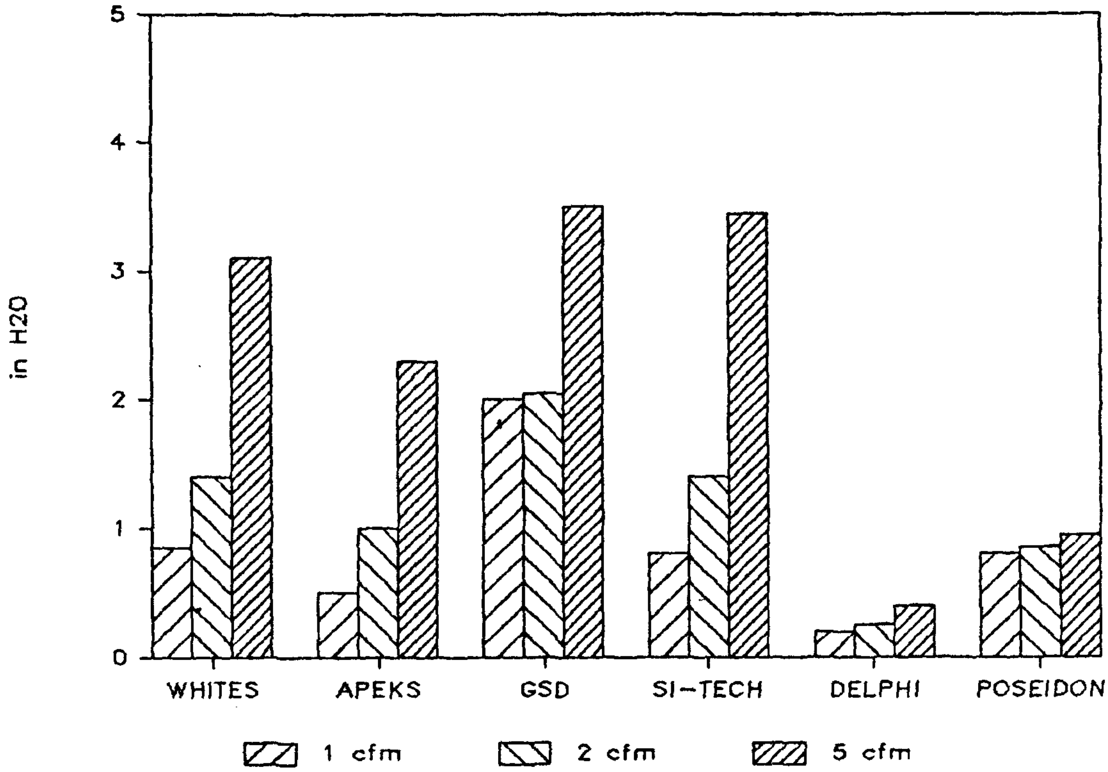


Figure 5. Pressure drop (inH_2O) at 5 cfm

Figure 6. Pressure drop (inH_2O), set at minimum opening pressure



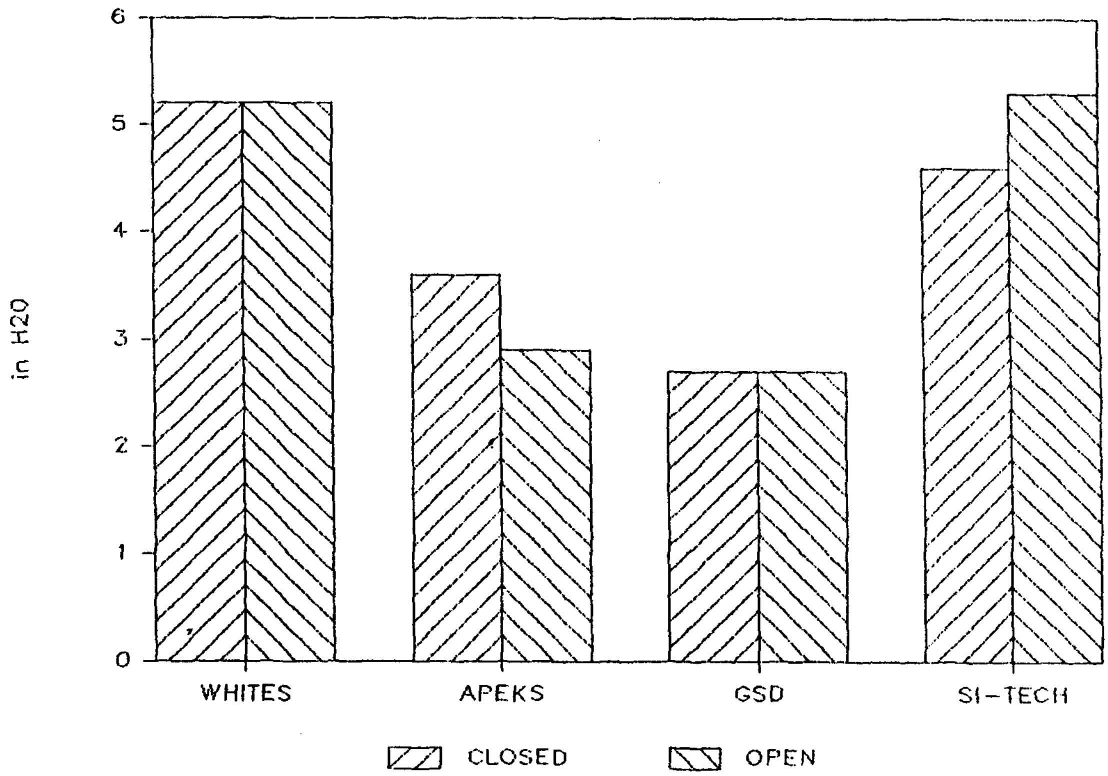


Figure 7. Pressure drop (inH_2O), 5 cfm min/max opening pressure

The flow rates of the A2OP valves were tested in the manual modes. The valves were first tested in the fully closed modes, then in the fully open mode (fig. 7). The interesting thing is that only two of the valves, the Whites and the GSD, have the same pressure drop at the fully closed and open positions. The Apeks valve experienced a drop in pressure from the closed to open position. For some reason not determined at this time, the SI-Tech valve showed an increase in the pressure drop from the closed to the open position.

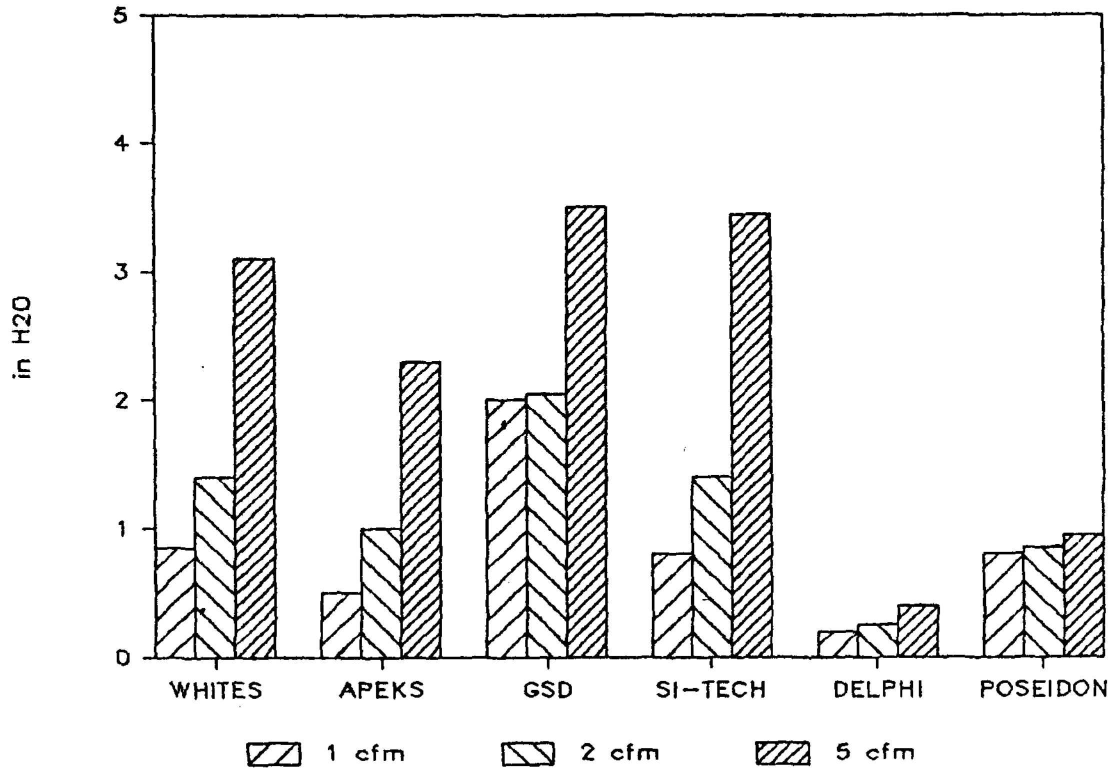
The pressure drop across the four A2OP valves were compared in two modes: In the automatic mode (fully open) and the manual mode. The results are presented in fig. 8. The most interesting result is that in all A2OP valves except the GSD, the fully open automatic setting produced a lower pressure drop than when the valves were operated in the manual mode.

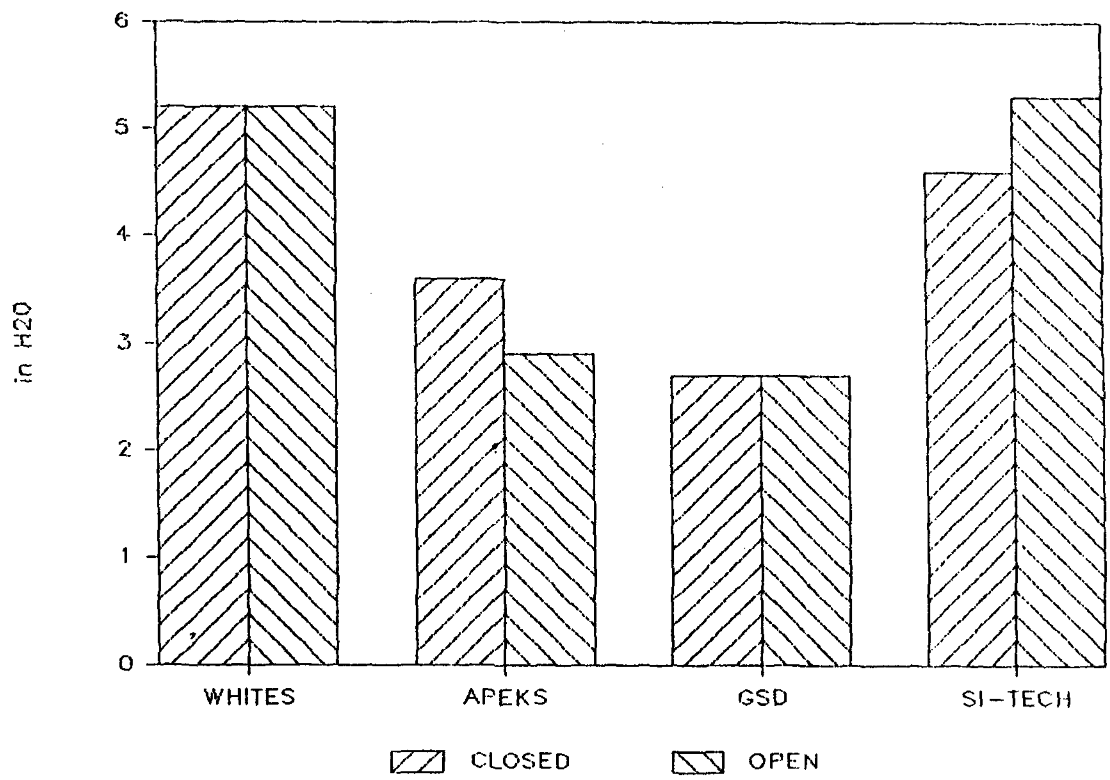
Figure 8. Pressure drop (inH_2O), 5 cfm auto and manual operation

A comparison of the four A2OP valves and the two MPD valves was also made figure 9. The A2OP valves were fully open and the flow rate was 5 cfm. As one would expect from the previously reviewed data, the two MPD valves have a much lower pressure drop.

The question has always been asked what effect the underwear has on the operation of the valve. In the case of the A2OP valves in the automatic mode of operation, it is believed that the underwear will have less impact on the performance of the valve. This is because the valve in the automatic mode floats up off the underwear. Because the MPD valve must be pushed in to activate the valve, the valve is pressed into the underwear. At this point we have only evaluated the MPD valves. Figure 10 shows the performance of the Delphi valve with (pile) and without underwear at 1, 2 and 5 cfm. As can be seen in fig.

Figure 6. Pressure drop (inH_2O), set at minimum opening pressure





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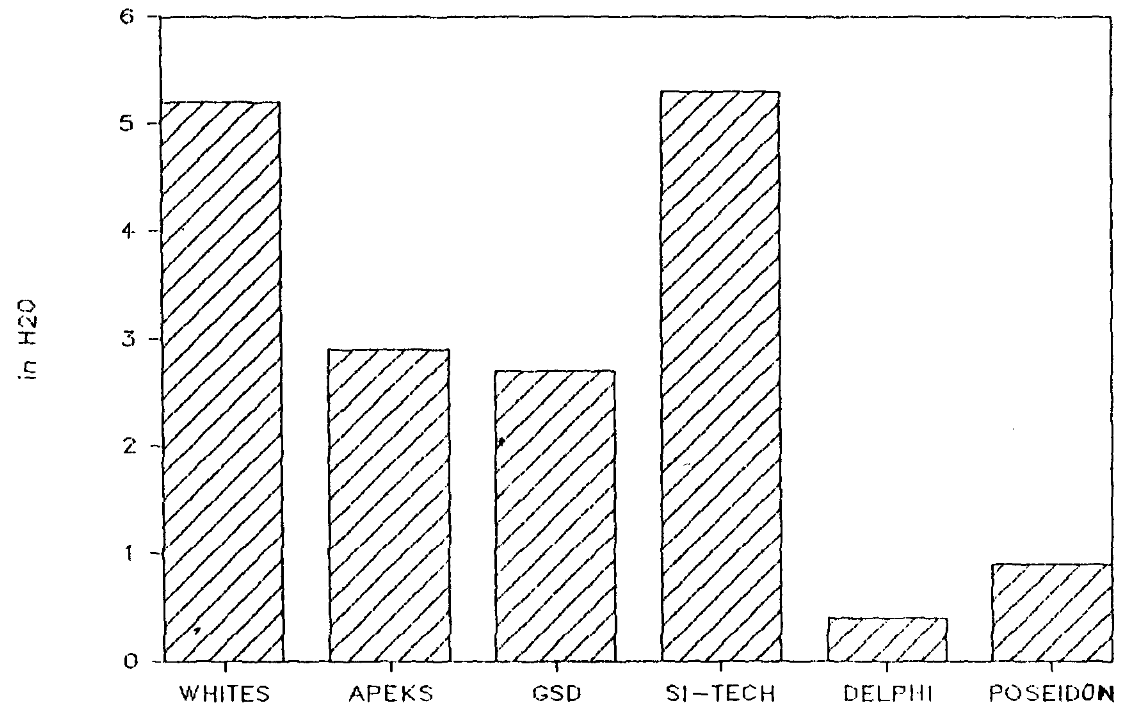
10, the underwear has a major impact on the performance of the valve. Additional testing will have to be performed to fully determine the impact the different types of underwear have on the performance of the dry suit valves.

Figure 9. Pressure drop (inH_2O), 5 cfm

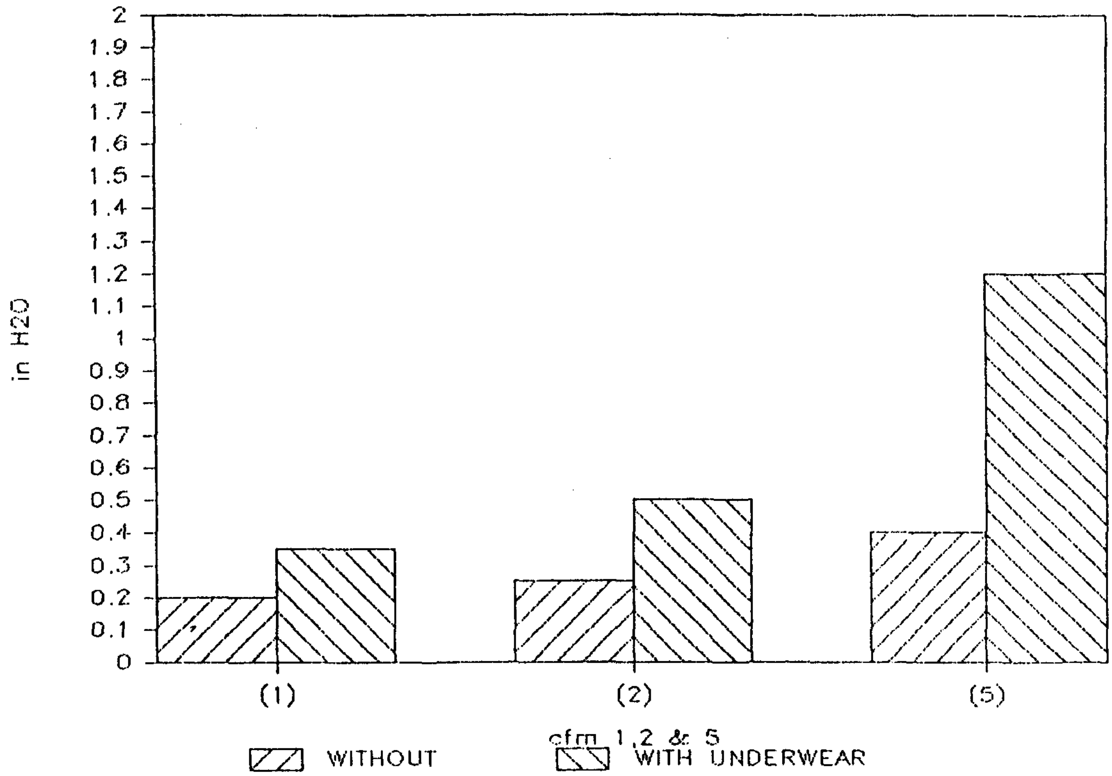


The force that is required to activate the valves is shown in figure 11. The two manual push to dump valves required the greatest force to activate. Although all the valves are grouped in a close range, I think we may consider that the MPD valves are near the upper limit for the force required to activate them.

In the case of the MPD's being mounted on the upper arm, a 112 lb. small female experienced some difficulty in activating the valves. This difficulty was not experienced when the valves were mounted on the front chest area. This shows that the force required to activated the MPD valves and the positioning of the valve should be taken into consideration in the layout of a suit.

The last item examined was the flow rate of all of the inlet valves. This is of interest because some manufacturers claim the inlets and exhausts are of a balanced design and that the flow rate of the inlet valve is less than that of the exhaust valve. The flow rates were determined using a flow restricted auxiliary hose (most auxiliary hoses in the diving market have flow restricting mechanisms). As can be seen, the flow capacities of the inlet valves are grouped in a small range (fig. 12).

Figure 10. Pressure drop (in H_2O), Delphi valve with and w/o underwear behind valve



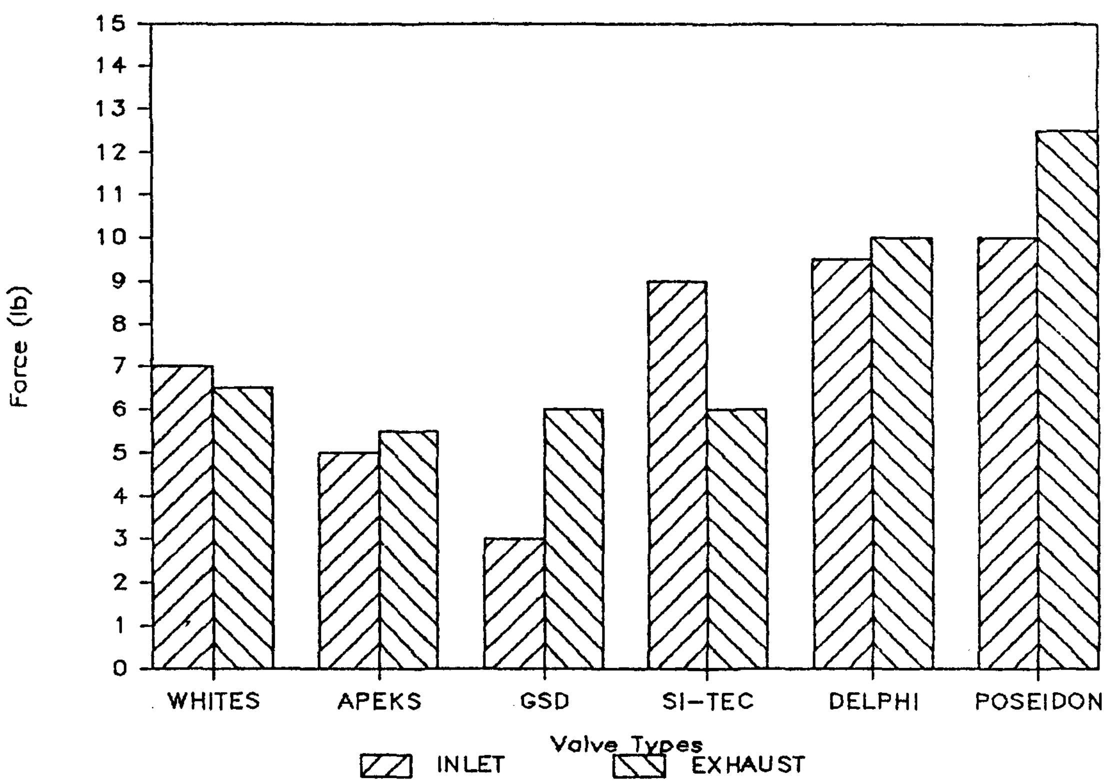
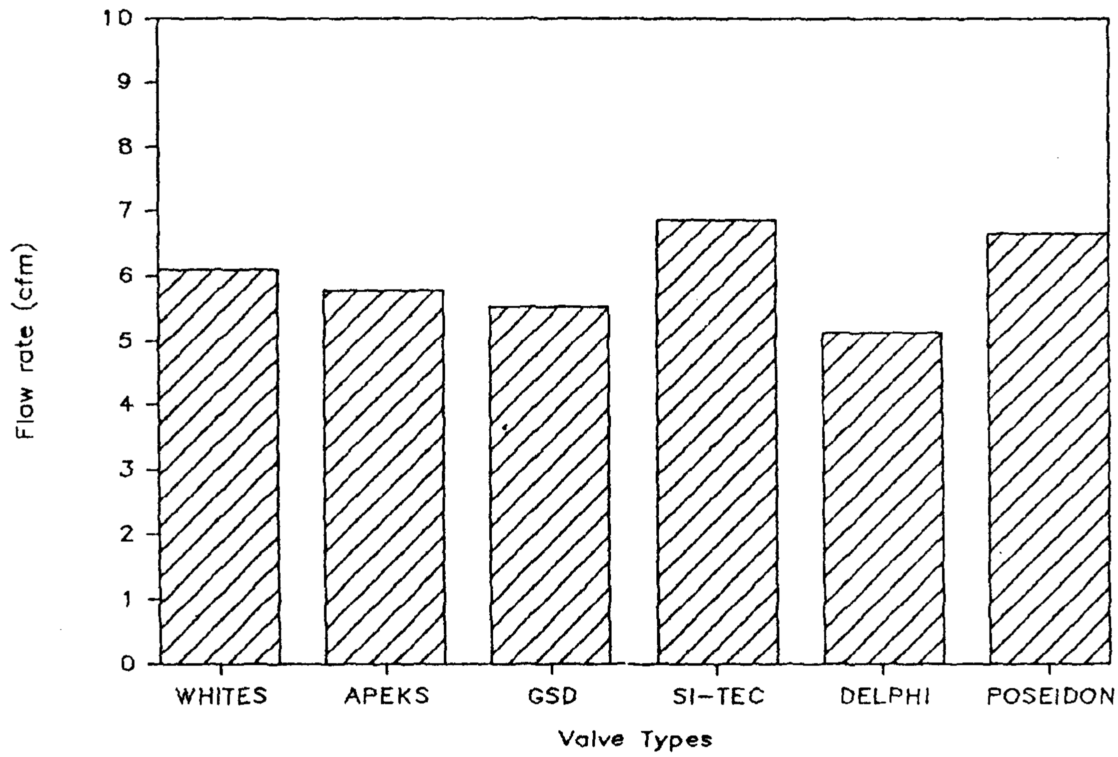


Figure 11. Force required to activate valves (lbs.)

When these rates are compared to the flow rates of the exhaust valves, the exhaust valves can pass these rates. In actual use under some conditions the claims are supportable, however, in normal everyday diving where the conditions are not always ideal, this may not always be the case. For this reason, in the event of a failure of the inlet valve in the open position, disconnect the low pressure hose if possible, while continually dumping air from the suit using both the exhaust valve and the seals and flaring if needed to check the rate of ascent.

Figure 12. Inlet valve flow rates (With restricted flow hoses)



Conclusion

The six exhaust valves reviewed in this paper all show different performance levels, and what the ideal level should be has not been determined at this time. Faster is not necessarily better because the possibility of overcontrol exists. We do know, however, that both ends of the performance ranges presented here have passed the test of time in the field, and the valves presented here, when operated by a trained individual, can all meet the current maximum rate of ascent of 60 ft/min called for by the U.S. Navy Decompression Tables and the slower rates of ascent called for with the new dive computers. In the case of the slower ascent rates, less demands are put on the performance of the exhaust valves.

Recommendations

1. Always follow the Dry Suit Manufacturers Association Guidelines, (See R. Long's paper, this volume) DEMA 89.
2. The dry suit valves should be cared for in the same manner as the diving regulator. The valves should be cleaned after each dive and serviced annually or more often if diving conditions dictate it.
3. During the ascent phase of the dive, the diver is heavily tasked with things to do and to monitor. Because of this task loading, when properly used, an adjustable automatic exhaust valve provides the advantage of hands-free operation during the ascent phase of the dive, when hands can be in short supply.

BIOMECHANICS OF BUOYANCY COMPENSATION AND ASCENT RATE

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A concern for the effect of buoyancy control devices on ascent rates has resulted in the measurement of ascent rate changes as a function of the placement of the buoyancy, the size of the buoyancy envelope and the capability for neutralizing buoyancy during ascent. Average ascent rates over distance are compared with ascent rates through the last four feet. While average ascent rates for the devices tested are significantly faster than the recommended 60 feet per minute, the average speed through the last four feet is markedly higher. While ascent rate and buoyancy are clearly related, there is evidence that the placement of the buoyancy "bubble" can become a significant factor in ascents where diver control is lost. Buoyancy devices which permit levels of buoyancy which result in rapid ascent rates result in a nearly vertical ascent. Smaller "bubbles" which are front mounted above the center of mass result in slower ascent rates due to a turning moment. This can develop a planing action resulting in lift and drag forces being applied in a manner that results in a slower vertical ascent. The implications for training and work effectiveness are also presented.

The early observation that a body immersed in water will be buoyed up by a force equal to the weight of the volume of water that is displaced has clearly benefitted the diving community while also providing frustration, amusement and occasional hazards to health. Generations of divers have learned that the key to proper buoyancy control lies in the ability to achieve neutral buoyancy relative to the depth that the diver is working. The achievement of proper buoyancy and the ability to maintain it throughout a dive is a skill that is fundamental to comfort and the ability to work effectively underwater. Divers weighted themselves so that they were slightly positive on the surface in order to become neutral as they descended. Breath control was used for fine tuning the neutral state and as the complexity of the activities divers performed increased, so did the awareness that adjunctive buoyancy control was needed. Flotation devices entered the scene and divers were able to inflate bladders of various sizes and shapes in order to increase buoyancy as needed for some of the activities. The use of flotation bladders, including vest type bladders, did little to complicate the rate of ascent at the time because the bladders were generally small with 15-18 pounds of lift. While this amount of lift force was sufficient to increase the rate of ascent, the problem was not significant since the divers were skilled in the use of the devices which were only to be used to maintain neutral states in the water column.

As time passed, the development of several problems associated with buoyancy evolved in concert with changes in equipment technology and teaching techniques. The development of larger bladder configurations which could hold the bubble in a variety of positions depending on whether the bladder was front mounted, back mounted, over the shoulder or around the body became commonplace with buoyancy potential up to 80 lbs or more in some extreme cases. These large bladders offered yet another potential for divers with weaker water skills in that they could be used with significantly greater amounts of weight so that the diver could, by inflating or deflating the bladder, move up or down in the water column with considerable speed, eliminating the need to develop surface diving skills to overcome the slightly positive state which normally existed on the surface at the beginning of a dive.

"Push button diving" permits the diver to constantly adjust buoyancy throughout the dive and the ascent, but it requires careful attention to the size of the bubble since larger bubbles lead to larger scale changes in buoyancy with changes in pressure according to Boyle's Law. These larger scale changes become particularly dangerous during the final phases of the ascent when the diver nears the surface.

A concern for this problem of varying ascent rate due to the buoyancy compensation devices led to an early 1980 study at the UCLA Underwater Kinesiology Laboratory. Since the wisdom of the time indicated that ascent rates were never to exceed 60 feet per minute and that this rate was considered to be the maximum safe ascent rate, the results were evaluated in terms of that rate. The rate of 60 feet per minute was also associated with following the "small" bubbles to the surface while maintaining an open airway and exhaling constantly. In actual fact, there was a wide variation in ascent rate with few ascents being slower than the recommended 60 fpm. It was commonplace to witness divers engaged in ascents two to three times this rate who, when questioned, would indicate they were travelling at the rate of their smallest bubbles as they did on all of their ascents.

A study to determine the effect of currently available buoyancy control devices was conducted in fresh water with the diver in full ocean gear placed horizontally at a chest depth of 9'4" from the surface, holding the sides of a weighted box while the bladder was filled until the overpressure relief was activated. The diver was then signalled to exhale fully, relax and release the handhold. The ascents were video taped and timed and average ascent rates were calculated for the 9'4" ascent as well as from 4' to the surface. The latter measure was made because of the observation that the trajectories of the divers during ascent became more vertical as the amount of buoyancy was increased.

The following data were derived:

Bladder configuration	Vol/l	Lift/lbs	Ascent/9'4"	Last 4'
20x17" Single bladder HC	5.1	11.2	68 fpm	43.3
23x18" Single bladder HC	12.7	27.9	122 fpm	147.8
23x19" Bladder in bag HC	15.5	34.1	132 fpm	185.8
24x19" Bladder in bag HC	17.2	37.8	138 fpm	187.8
24x18" Bladder in bag HC	17.5	38.5	143 fpm	205.7
25x20" Bladder in bag HC	17.3	38.1	149 fpm	208.7
19x16" Bladder in bag HC	21.6	47.5	156 fpm	213.3
Large size, jacket type	21	46.2	149 fpm	225.9
26x10" Backmount w/bag	24.9	54.8	168 fpm	245.3
Over the shoulder w/bag	21.2	46.6	150 fpm	254.7

*HC denotes horsecollar type and w/bag indicates bladder in bag
**Wetsuit expansion was assumed to be constant

It is of interest that volume alone does not predict the rate of ascent. The configurations that permit the bubble to locate high on the chest cause a flaring type of ascent. This passes through the last four feet with a significant horizontal component at slower ascent rates which contrasts dramatically with the configuration which locate the bubble over the shoulder resulting in a nearly vertical ascent with no horizontal component.

This alteration of ascent rate can also be initiated even at relatively high speeds by utilizing the body parts to generate a lift component to the trajectory. Lift forces always act at a 90 degree angle to the drag forces which in most cases are the resultant of buoyant force less the resistance encountered with the water. Lift forces can be very powerful and result in significant changes in trajectory as any sailor, pilot or kite flyer can attest.

This data indicates that increasingly rapid ascent rates are probable as the size and configuration of buoyancy devices are maximized. Additional problems which are related to changes in the equipment are seen in the development of thicker, more flexible wet suit materials, neoprene dry suits and dry suits which utilize a waterproof shell over thermal underwear. The thicker wet suit materials result in larger buoyancy changes as a result of suit compression. The changes follow Boyle's Law and consequently create greater problems near the surface than at depth.

The neoprene type drysuit offers the potential for an enormous bubble growth inside the suit before the seals at the neck and wrist will open. If the diver becomes inverted, the bubbles in the leg compartments (assuming enclosed feet) will expand with no outlet and cause the classic diver "blow up" which hardhat divers can encounter. There are techniques which can result in the diver in this circumstance regaining control of the ascent but they must be applied immediately in the early stages of the development of the problem if they are to affect the rate of ascent. The shell configurations have a generally similar problem although the shell will not expand beyond the limit imposed by the non-elastic suit.

In any case, it is clear that the dry suit manufacturers and instructors who are advocating significant instruction prior to the use of the suit are providing fundamental knowledge and skill to the diver who would use these devices. The management of buoyancy is clearly fundamental to the matter of ascent rate and if ascent rate is judged to be a factor in decompression sickness as well as lung overexpansion injuries it is also clear that increased attention to the development of knowledge and skill in the beginning and continuing education of divers is necessary. It is my belief that the modern diver must be concerned with the specific buoyancy characteristics of his or her equipment. This includes but is not limited to the control techniques and the location and operation of fill and dump systems. The admonition that one must equalize early and often on descent becomes no less important on ascent. In both instances the diver must stay ahead of the problem in order to maintain control. The loss of control identifies an accident and the ability to regain control can become as important as preventing the loss of control if one wishes to avoid injury.

DIVE COMPUTER MONITORED ASCENTS

Discussion Leader: Michael A. Lang

Panel: Mark Walsh, John Lewis, Ron Coley and Karl Huggins

Michael Lang

Michael introduced the dive computer expert panel: Mark Walsh (Design engineer, DACOR Corporation), John Lewis (Principal designer Datascan II and Datamaster II), Ron Coley (Product Manager Suunto/SeaQuest Dive Instruments), and Karl Huggins (Co-Designer EDGE, U. of Michigan). I've discussed this session briefly with the panel members and we agreed to follow a tentative format. What we're interested in right now in dive computers is the manufacturers recommended ascent rate with some background as to why, how is the ascent rate indicated or monitored on the different dive computers and is there any kind of ascent rate violation procedure?

Mark Walsh

We have the MicroBrain and the MicroBrain Pro Plus dive computers. The algorithms are P3 and P4 from the Bühlmann/Hahn series. On both of them we have an ascent rate indicated at 33 ft, the tolerance zone goes to 40 ft. We have an ascent rate warning indicator, an arrow which flashes at you and continues to flash until you slow down back within the zone. For ascent rate violations, there are none, so you get into the range of omitted decompression, which we'll be taking care of later.

John Lewis

I can speak to at least three dive computers: The Oceanic Datamaster II and the Datamax Sport, the U.S. Divers Datascan II and III. The recommended ascent rates are 60 fpm. The indicator is that the depth display flashes. Also, all of those dive computers upgrade every second and so independent of the depth flashing at you, if you get more than a one digit change at a time, you know you're exceeding 60 fpm and there's no ascent rate violation overrides. The reason for the 60 fpm, as I commented yesterday, is that's where the database is. There's no database that supports any other hypothesis.

Ron Coley

I will probably amaze some folks and say that there are really three variations of the SME dive computer. The first was the SME-USN, which was a table reader and essentially eliminated the need for you to calculate the tables. It didn't give you any kind of credit for times spent at shallower depths. If you went to 61 ft, it jumped to the 70 ft table and if you exceeded the 60 fpm ascent rate, upon surfacing, it would go into the error mode. It would lock you out of decompression information from that point on. It was replaced by the SME-ML, which I affectionately call the blue nose, which was the first version of the multi-level tables in the SME. It has nine mathematical compartments, three of which are in addition to the six compartments that are found in the U.S. Navy tables. Those six compartments have all been reduced, their M values have been lowered, trying to get lower no-d times. In the same light, the mathematical models have been expanded in its range and reduced in its capacity to hold nitrogen upon surfacing. A 33 fpm ascent rate is programmed into it. Very simplistically, 1 atm/min. The computer operates with that 33 fpm ascent rate at all depths throughout the entire range. Once you exceed that rate it flashes the word "slow" at you. I noticed that Glen Egstrom mentioned a flashing light that got his attention when he violated the ascent rate program in his dive computer. You can eliminate the word "slow" from flashing at you very simply by stopping and allowing the average time over the depth you've ascended to equal out to that 33 fpm. Interestingly enough, in effect, what you get is a series of safety stops or varied stops that look very similar to a lot of the dive profiles that we watched being drawn on the board yesterday. There's been a great deal of concern over whether or not operationally that it is possible to maintain slower ascent rates. I guess I'm a little bit at odds as to that information that's coming back, because what I've found is that initially, many people were terribly shocked at how often the dive computer flashed slow at them. Over the years that complaint has virtually disappeared. If you surface with the slow ascent rate warning flashing at you, it will continue to flash through your entire surface interval. Within the last 18 months I inspected 720 DC's upon surfacing. In that sample, I would say that initially, I found that about 50% of the divers had the slow ascent rate flashing at them, and that within the last 6 months, it has become a very rare phenomenon for me to see slow ascent rate flash. With the revised version of the SME-ML, which we call the R1, there's a three second damper so that you have to violate the ascent rate for three seconds. The "blue nose" will actually flash slow at you if you raise your console quickly. For every foot that you exceeded, it will flash at you twice. For you to look at your console and see slow, slow flash for something that happened, we put the three second damper in there so that wouldn't occur. Immediately I received phone calls from diving instructors saying it wasn't as sensitive as it used to be and I don't like that. "As I train my students, I really like to have that sensitivity there, and especially in the last 10 feet of water column. Now, because it takes three seconds receiving this thing, everybody will stop, they'll perform the safety stops, but now in the last ten feet, some people will bounce to the surface. When I go around and check all my students gauges, the slow won't be flashing and I can't scold them. So I'm kind of upset you made that modification."

There's another thing that comes across from the instrumentation that would provide that I see the results of. We ask everyone to fill out a 12 dive dive profile log. When they purchase the instrument, they send it in to us and we send them a luggage tag that says they're a computer assisted multi-level diver. I would say that the sample that is returned is very disappointing, but at the same time, by reviewing this literature, I've seen a lot of different dive profiles. The trend for people to take safety stops is definitely on the increase. Safety stops can vary at depths and is a function of the diving terrain. If you're diving on a coral reef that happens to be at 23 ft, you'll find people taking 23 ft safety stops. If you're diving on a boat with an ascent line, you'll more than likely find people stopping in the 10-15 ft range.If you're diving by using the dive profile recorder, you'll learn very quickly that it takes and records a maximum depth in each three minute block of time so that if you want your safety stop to appear on your dive recorder profile, you'll need to make the stop in excess of three min to make sure it gets recorded. If you're only spending thirty seconds at 10 ft, you may show that last plot on that dive profile at 40 ft or 60 ft, so that as I review these logs as people apply more and more knowledge, that they become more familiar with the technology, the number of safety stops appearing on these logs are on the increase. The length of the safety stop time is also on the increase. The complaints about a slow ascent rate warning flashing after they surface are on the decline. There are a lot of people out there who are following these ascent rates and feel very comfortable with them. I couldn't tell you whether they're diving with dry suits or BC's, but I do know from the information that I see come across my desk, that these are things people no longer complain about, and that the safety stop is definitely something that's becoming more and more common.

Karl Huggins

The ascent rate for the ORCA Industries units is a variable ascent rate. From depths deeper than 120 ft, the recommended ascent rate is set at 60 fpm, from 120 ft to 60 ft the recommended ascent rate is 40 fpm and from 60 ft to the surface the ascent rate is 20 fpm.

The rationale behind that was the concept that they wanted the change in pressure over the total ambient pressure remain constant as much as possible to put less stress on the diver as he's ascending. As you can see on the graphs (Appendix) if you have a constant dp/p, you would have a continually changing ascent rate going from a depth of 200 ft at somewhere around 78 fpm to being around 11 fpm when you finally hit the surface. The .33 dp/p is just an average taken over a 200 ft depth range of the ORCA ascent rate. The dp/p on the other side is graphed against the depth showing that following a 60 fpm ascent rate that value increases drastically as you get closer towards the surface whereas if you continually change your ascent rate, it stays down at a lower level. Whether this has anything to do with the decrease of stress on the physiological and dissolved gas factors in the body, I don't know if anybody had any information on that when they made that decision. It wasn't a decision that I was involved in. In terms of the display, the SkinnyDipper and DELPHI flash a LED whenever your ascent rate is violated. They do have an 8 ft buffer zone, so you can basically zoom up at any speed you want for 8 ft and it won't indicate anything. Once you get past that point, it will then start flashing at you. It's sort of a cumulative counter so that the amount of time that you violated can be counted down by stopping at the depth so that the ascent rate, the required time to ascend that depth, once it's counted down, the light will stop flashing. That's the way that information is displayed, also with the depth display flashing on and off along with the LED. In terms of ascent rate violation basically all it will do on the SkinnyDipper and the Edge, is continue to flash at the surface until the time of ascent has been caught up so there's no real penalty programmed back into the algorithm or anything that really displays once it has caught up its normal ascent time that will indicate that you have violated the ascent rate once you hit the surface. The DELPHI will stick an indicator in the recording mechanism that it has so when you pull out the information, it sets a flag indicating that the ascent rate was violated.

Mike Emmerman: Have the manufacturers received comments from the users regarding ascent rate violations and the indicators thereof? John Lewis: No. The only indication that we have when the unit comes back has to do with violations and ascent rate is not one of them. We can read the log if you took decompression, or omitted decompression. There is no log maintained with respect to ascent rates, and I have heard no anecdotal comments from users. Mark Walsh: When the MicroBrain comes back, we cannot retrieve an ascent rate violation but in talking with dealers, instructors and consumers, at first there was hesitancy to accept the ascent warning, it bothered them, they didn't like it. Then, when they realized they were looking at their DC anyway, they slowed down. The other side of the coin are the complaints I have received stating: What does the unit do for me to prevent me from ascending too quickly? They feel it should be hardwired into their system as a cattle prod.

Karl Huggins: I can relate a story for Paul Heinmiller who is not here because he is working on the production of the DELPHI at this time. He just returned from a California trip with a huge dive club where he equipped everyone with DELPHI dive computers. He indicated that at the end of the first day of diving, all indicator lights were flashing after the dives. By the end of the week, divers were monitoring their ascent rate indicators, with hardly any ascent rate warnings flashing. I believe that there is the ability to feed that information back to the diver and allow him to monitor the ascent rate as long as they have control over the ascent. Another example of misinformation is I ran into a new diver at a quarry once who blamed the dive computer for his dry suit blow-up. People will take a new piece of equipment and blame it for anything that could go wrong. John Lewis: I would like to add a comment to what Ron Coley said regarding the safety stop. I just returned from a trip where people were doing serious, multiple, deep repetitive diving and everyone there was making a long safety stop. The top of the reefs were typically at 15-25 ft, so the divers were stopping there and returning to the boat with about 100 psi in their cylinders. Bill Hamilton wondered how much larger the dive computer battery had to be to build in a cattle prod.

Bill Hamilton asked Ron Coley, since the Suunto was currently the only DC with a logger and the DELPHI from ORCA soon would, do divers flash that information and copy it into their logs? Are we getting better retrospective data as a result of this? There is such a huge spectrum out there making it difficult to give a real short answer. We have dealers who, when using the DC for the first time after having sold it for two years say: It does that? On the other hand some people are overwhelmed by divers bringing them their dive profiles, some of which were used to map caves some for mapping shipwrecks. Some people find it a useful tool and use it extensively, some not at all. There were certain limitations in the original model. It would record ten hours of underwater time before you filled up the memory. We got a lot of calls from divers who were spending more than ten hours in repetitive series. Recently, a group from Houston, Texas returned with the new model which overwrites the oldest so that you always have the most recent ten hours worth of time. They had spent 35 hours underwater in one week on a Honduras trip. The majority of those people had each and every dive profile plotted. Bill: When they come up from a dive, they log their most recent dive and keep doing that. Mark Walsh: The MicroBrain doesn't give a dive profile, but the Pro Plus has enhanced information now. There are three levels of logbook information. Six dives in a 48 hour period indicated by log 1 through 6, you go into 7 or 8, it cancels out the first dive. It also gives surface intervals between those, time to flight as far as the number of desaturation to an 8,000 ft altitude and it will give desaturation time until you're completely washed out against your controlling tissue. we won't give the profile, but what divers are doing is using the additional information, time to fly, desat time, indicate it in their log book after they get out. Bill: They do get a reading of what kind of shape they're in? Mark: That's right. The second level is the transitional log. You will always have your three last dives and surface interval in the unit, and then the permanent log book is your maximum decompression, total number of dives, total of dives, total hours spent underwater. Bill: Can the diver access that? Mark: They can. It's not erasable, retrievable by the user. Bill: Earlier you said it's only retrievable by you. Mark: This is on the MicroBrain Pro Plus. On the MicroBrain it is limited information.

Woody Sutherland asked how long you could exceed the programmed ascent rate before being warned? Mark Walsh: The MicroBrain updates every second. The envelope is 7 ft from 33 to 40 fpm, then the ascent warning arrow comes on. John Lewis: I think with the exception of ORCA which are 3 second upgrades, and Karl can correct me, all the rest are 1 second upgrades. Karl: Yes, for SkinnyDipper and EDGE. I don't know what the DELPHI does in terms of upgrades.

Bill Hamilton: The Suunto logs the deepest point every 3 minutes. As a physiologist playing around with decompression, I see that as a whole lot better than not any information. I wonder what other people think about that, should we demand every minute or more often than that? Karl Huggins: The DELPHI can be programmed into more rapid data collection, you can take it down to 15 seconds if you just wanted 4.8 hours worth of data. I don't know what is involved with that, but it is a software condition that could be solved. Bill: That might be very useful if you want to map a cave or shipwreck or such. Bill, you know that's not long enough for cave dives. Ron Coley responded that he did have a unit that was Suunto's original simulator, which had to be pneumatically activated and exposed to pressure. It was a diveable computer, very conservative, because every 15 seconds, it counted it as 1 minute. The people who were interested in getting very precise dive profiles would then have something that gave them a plot point every 45 seconds. It was totally useless as a decompression computer. I've loaned that unit out several times to people who wanted very precise information for that reason. They put it in the error mode by exceeding all of the parameters that are validations of the computer, but they still maintained that dive profile recorder and used it. You did an interesting experiment with one where you tried to trick it into thinking 90 fsw was the surface. Bill: We used it for excursions from saturation and it took some tricks for our purpose.

Bob Stinton pointed out that divers become preoccupied and distracted by watching the indicator, which invariably pulls their attention away from other things they must also do while ascending. There should be a type of indicator you can look like a speedometer, saying you're at the right speed, so that you do not have to concentrate so thoroughly while processing that information. Mike Emmerman thought that was really a training aspect of using dive computers. Phil Sharkey said his divers thought of a five pixel display, where the middle pixel would display the correct ascent rate and those to the left or right would indicate too fast or too slow.

Dennis Divins mentioned that he understood that 60% of dive computers were sold to new divers and was interested in hearing from the manufacturers if there should be training courses for these individuals, especially with regard to ascent rate and proper use of the dive computer? Mark Walsh stated that Dacor had that problem because they do sell USN tables (60 fpm ascent rate) and dive computers with a Swiss algorithm based on 33 fpm ascent rate. I've gone on record that dive computers belong in the advanced certification and above, not available to basic divers, but from a corporate standpoint it is the choice of the dealer and their morel obligation to their customer/client. I think full understanding of the tables and repetitive dives and being able to calculate them are a necessity before a person enters into computer use. By levelling off at the advanced certification, you hopefully have achieved this in one way or another by the timespan they stay in that certification. Of course, people can walk in off the street, buy a dive computer, get basic knowledge and go dive with it. We are a little slow right now in preparing our specialty course. I've talked with training agencies about it and have draft copies. When we went into the new generation of the dive computer, I have to upgrade all that information to satisfy the new generation. I applaud Suunto/SeaQuest, especially Ron, for producing excellent training and audio visual materials for dive computer training.

Dennis Graver: We do have a body of instructors here, and if we say to them: This is what we want you to teach your entry-level students during their beginning class, what would you want them to know? Mark Walsh: Follow the manufacturer's recommendation because the algorithm, the mathematical model, is based on that computation. Dennis: Are there any procedural steps you would suggest? Mark: How to follow 33 fpm? Dennis: No, I'm thinking more about what Phil Sharkey commented about holding the display up while you're ascending, etc. John Lewis: I don't think anyone advocates not teaching tables and I think it has a very important role. I used to think no one should be allowed to scuba dive any deeper than they could free dive, and I still sort of believe that up to a limit, as long as it doesn't apply to me anymore. Instruction of the tables acts as an introduction. It gives the student familiarity despite the fact that it looks somewhat overwhelming until you get a degree of confidence. It's not a bad first step towards using a dive computer. Further, you can't really do that without at least having a flavor of decompression theory and its history, which is particularly important as well. Finally, it's a backup. If the electronics break down, you can still use tables. I wouldn't presume to tell anybody how to design a training course, but it seems to me there's a lot of merit in maintaining the teaching of the tables. Mike Lang: I recall us agreeing last year at the Dive Computer Workshop that continued teaching of the tables was in fact a good prelude towards teaching dive computer use and procedures.

Ron Coley: I would like to see emphasized that you work with a procedure that is only a mathematical approximation, regardless if it's table based or it's a device, and that once you understand the basic concept behind that procedure, that you should try to follow those rules. You must also have the good judgment to understand that you personally can select how far you want to push that limit, whether it's an ascent rate limit, a No-D limit or repetitive diving limits. There is not a device or table that will ever relieve the diver, ultimately, of being in charge of his own safety. I hope basic instruction gets across that there is no piece of black magic out there that will relieve you of that responsibility. No one is going to create technology to replace your common sense and water skills. No matter how advanced, expensive or elaborate dive computers become, they will still require a knowledgeable user to take full advantage of them. If our dive computers are presented in that light, then I think instructors and training agencies are giving us a real fair break. That is all I would like to see come out of the instructional part of a basic training course.

Karl Huggins noted that in order for the divers to have responsibility for themselves, they have to acquire the understanding of why we ask them not to ascend at 200 fpm, why they need a good control of their buoyancy to maintain control. To talk about ascent rates, you have to talk about buoyancy, because those two items are inseparable. Whatever ascent rate they go at, a variable one, whether if be 60 fpm, 33 fpm or the BSAC procedure of 15m/min up to 6 msw, then 1 minute to the surface. I like that procedure, because you have a relatively rapid ascent rate up until about 20 fsw, then you have to stop to make that final adjustment, so you need the control on your buoyancy to make those last 20 feet in 1 minute. John Lewis: Is a stop equivalent to the 1 minute final ascent time? Karl: You can stop, but they still want you to take 1 minute to the surface.What it all boils down to is getting across to people why you want them to follow a specific ascent rate or ascent within a specific range, and being able to control it.

Glen Egstrom agreed 100% with Karl's observations. The field of diving has been getting away, over a period of time, from telling people the why's of what we want them to do. There is a significant issue today that you are obligated to give them enough information so they can make an informed decision about their behavior. If you don't explain to them why you want them to do things, I have no notion of how you can then get to the point of where they understand enough to make an informed decision. That's the kind of idea that really has to be recognized in the instructional communities.

Glenn Boden wondered how far away we were from seeing a heads-up display on the market? Mark Walsh: That's a valid question I couldn't answer right now, especially with Bill Oliver and Ron Coley sitting there looking at me!

Bill Hamilton: My comment has more applicability to a dry suit question that was brought up a moment ago than it does to tables, but the Air Force has trained an awful lot of pilots that have never piloted a propellered airplane. You don't have to absolutely start with the primitive. John Lewis: If you're willing to take the task, you could teach decompression theory and introduce the database. I have a feeling that is a pretty formidable task. Bill: The thing is you still need to be able to use the tables, you can't get around that. John: One doesn't preclude the other. Bill: But particularly with the display level you get with the EDGE, you can get a feeling for what the models are doing.

Drew Richardson: Is there any trend towards a maximum depth indicator light or warning light with a 130 fsw ceiling for recreational diving applications? Mark Walsh: On the MicroBrain and the MicroBrain Pro Plus, being an international distributor and dealing with the European market where they have deep diving occurring daily and they believe in decompression, we have an availability of 270 fsw on both units. We caution, for domestic use, to follow the recommendation of 130 fsw. There is no shunt in the unit that can give you a choice. Maybe the next step is to have a domestic and foreign market unit. Right now we do have feet and metric, but have not addressed, other than precautions, to decrease that operational depth, which is fully operational against the Bühlmann series (to 330 fsw). We've retreated from that and incorporated 270 fsw. It is an economic necessity because we do sell a lot overseas. John Lewis: The Datamaster II and the U.S. Divers Datascan II both have overrides that effectively give you zero time below depths of 130 feet. The override on the sport units and Datascan III have been relaxed and let you go to about 170 fsw, and the Datamax Sport has an explicit provision for decompression so you can even take it beyond that if you want to spend the time. Despite what is taught, there is a substantial proportion of divers that really resent that kind of restriction. Mark: The altitude compensation feature of Bühlmann's research provides No-D limits that are quite restrictive: 130 for 7 min, instead of 10 min, so operationally it's going to prevent a lot of domestic divers from doing anything beyond 130 fsw anyway unless they dedicate themselves to decompression, but we do not teach decompression diving. That is what brought about the Pro Plus. In 1988, we came out with the MicroBrain and we were told flatly we did not provide enough information, we want decompression profiles. It was not enough to give a bail-out schedule. Ron Coley: The operational limit of the SME is 200 fsw. At 201 fsw it becomes a digital depth gauge and dive timer. Karl Huggins: The EDGE has a maximum depth of anywhere between 165 to 170 fsw depending on the pressure transducer and the adjustments made to it. The SkinnyDipper has maximum depth of 199 fsw and the DELPHI will have that maximum depth also with the condition that the DELPHI Pro unit goes down to 300 fsw. Those will only be sent to people who sign their life away. Bill Hamilton: That's a very good point. I sometimes deal with people who are making dives slightly beyond that depth range, but they're doing it for recreation, they are "sport divers" if you will. We actually have several issues that aren't really part of what we're trying to settle here, but just to mention the fact of nitrox-enriched air diving, trimix diving, as you've mentioned the European deep diving, cave diving, sort of defines a second level of recreational diver that is not diving at the training agencies' recommendation of 130 fsw maximum depth. I don't take issue with that recommendation, I'm simply saying that there is a category here that exists that is not being totally addressed but getting fringe attention. Maybe we should just bite the bullet and recognize that there are scientific requirements and recreational requirements for diving in those ranges and let's do what we can to make it work right. Mark Walsh: I've had at least three requests for a nitrox algorithm in the dive computer. Karl Huggins: I don't think there's that much scientific diving at those depths, I know there is a little bit. Bill: As people begin to realize that they can use that capability, they're beginning to ask for it, reluctantly. Karl: In Michigan they're not so reluctant to ask for it and do dive at those extreme depths on shipwrecks in cold water. Bill: The guys in the Great lakes go down to 250 feet to play with the wrecks. I'm not trying to bless that, I'm simply saying it happens. Drew Richardson: That is an informed choice, they understand the consequences.

Ray Scharf: For the purpose of reporting data for scientific diving, how close are we to downloading capabilities to personal computers. Mark Walsh: The downloading capability has been addressed. It's not accessible to Dacor now, but will be in the future. The DELPHI will be able to dump it's information optically through one of the LEDs. You have an optical coupling unit (reader) that you put over the LED that feeds into your serial port into your computer and will be able to dump that information directly. Ron Coley: Many functions have been discussed: Reprogrammable computers, computers that will dump directly to the PC, ultimately heads-up displays, which divers recently asked me who would want their vision cluttered up while diving and trying to see the underwater environment. Anyhow, these accessories are certainly on our research and development list and there are items we want to have the capacity to do. The development and delivery of those products to the diving public, are usually connected to other industries (*i.e.* pressure transducer) with much larger budgets and require much higher volumes of individual units. When these other people started manufacturing, we rode on their coat tails. We can use our ingenuity to reapply technology developed by other industries and make huge leaps in months or years, depending on how fast that technology becomes available to us. We are not the driving force though. If you tell me you can sell 10,000 units per year, there are not a lot of manufacturers jumping up and down, ready to drop everything to redesign an electronics package to fulfill your needs, because we are a very insignificant market. I think everyone wants a direct PC dump, application for mixed gases, each individual should be able to set an alarm for how close he wanted to approach the No-D limit and how deep he wanted to dive. We can design these things, but how soon they become affordable is a question determined by other industries. Bill Hamilton wants to see a little key on the dive computers that can be turned to the next notch by the instructor when a diver passes the next training level, so he can go deeper, etc. Karl Huggins liked the idea of a small button that comes with a liability and release form on the side, with the only way to get past that is to accept the liability.

Glen Egstrom: It is important to realize that because of the rapid advances in technology, we have a rapidly increasing amount of information that we have to transmit to our students from day one. What that implies to me is we have to take a serious look at the information content of the scuba course, because all of the things a diver has to know about equipment selection, buoyancy control, decompression, dive computers. There is very little time to address that in a basic course. What we might be looking at is sequentially laying this out in some way so that it will now be addressed through the continuing education program, through the first year of training a diver, if you will, versus through the first few days. You can't get that amount of information into the student in the time we have available to do it in. Mike Emmerman: We have to go back to making the course what it should be, for however long it takes, to train a basic diver and there may be limits. Dick Long: I think that in reality we have many different kinds of divers. We need to separate divers out, some divers will never take continuing education. Karl responded that those divers want to take advantage of the technology, but do not want to put the time in to learning it. Glen reinforced that it is really quite serious and if you're paying attention to what's happening in our society today. If you can't demonstrate this issue of informed consent, you are on extremely soft ground.You have to able to do that for whatever it is you do. I think realistically, that the only way to do that with that current attitude is to block out the kinds of things you are going to require as you go through these various stages of training. If you choose not to go to stage two, you don't have that information, but you don't come back later and cry saying you didn't know that. The issue is that if you want to go to stage two, then you have to know that you have to get that information.

Ron Coley: There's a way to follow the analogy of having a license to drive a car, while it's very true that you don't need to know how to fix a Cadillac, the licence to drive does not allow you to compete in the Indianapolis 500 and you would very carefully have to stop and think about whether or not you were qualified to contend in the Paris-Dakar road rally. I like to use the analogy of walking. The ability to scuba dive is like being able to walk. You can walk around the park, you can walk to the zoo, you can take an extended trip into a remote area, or you can climb Mt. Everest. Walking in itself is not where you need to suit down and decide whether or not it is truly a dangerous activity or whether or not it is one that requires specialized equipment or skills, it's where you choose to walk and when you choose to walk there that requires the decision and knowledge. Perhaps what Glen describes as continuing education is basically mapping out to people where they are qualified to take a stroll and where they really need serious equipment and skills.

Andy Pilmanis remarked that in the final analysis, if you look at the accidents and what causes them, the vast majority you can trace back to violations of the rules. They are not accidents. They are violations of the existing rules. If everybody was adequately trained we could eliminate the problems. However, what is adequately trained? Mike Emmerman mentioned the near accidents one sees in the field that don't make it to the chamber.and felt that the continuing education has to be brought back to the basic training. Mark Walsh: In the Pro Plus we dedicated ourselves to one mode: the planning mode. You can plan your next dive profile and dive it prior to the dive. I've not yet been able to put into accelerated time though except for compression and ascent. This is also to familiarize the user. When they're not diving and want to familiarize themselves with the displays, they can actually be playing with their unit, with no debt to the memory. In the next generation we'll reach for more.

Chris Wachholz felt that the learning curve in the operation of the dive computers must play a role. You could teach a student to use the tables, and could evaluate that. As dive instructors became more aware of the limitations of the tables, they started taking safety stops, slowing their ascent, building in safety factors. Now we have dive computers. Lots of people believe that we now have the answer and have forgotten the safety rules. People are now diving severe profiles and have forgotten the basic safety rules that apply to both DCs and tables. I think it would be very important for the basic diver to understand that DCs need to be taken with a grain of salt. If people would dive that way, a significant number of accidents would not occur. Mark Walsh: It does come back to training, and I agree with those of you who mentioned common sense. Glen Egstrom and Eric Kindwall looked at the first draft of our manual and we incorporated on site at that time certain specific language that dealt with following your deep dive first, never returning to your same dive depth if at all possible, when you are expiring your no-decompression limits, always try to ascend within the last 2-4 minutes remaining. Plan it that way. Granted, as with tables, you can run the red line.

Drew Richardson agreed that thorough training was good and essential, but it didn't actually remain in the diver's behavior pattern forever before it needed to be brought up again and renewed in the memory banks

Mike Lang concluded the panel discussion by thanking the manufacturers representatives for their input, candid discussions and continued support of AAUS endeavors in the diving safety arena.

DIVE EQUIPMENT SESSION DISCUSSION
Discussion Leader: Michael A. Lang

John Lewis inquired as to the length of time it took to train someone in dry suit diving. Dick Long: Let's say we talk about a current scuba diver, a competent person with decent watermanship skills. A two day course involves two classroom sessions (4 hrs total), two pool sessions (4 hrs. total) and three ocean dives. You can teach them the fundamentals of how to use the suit. The first three dives will be under the control of an instructor. After about ten dry suit dives, the diver becomes acclimated to the environment in a dry suit.

Phil Sharkey posed the question as to whether we should be focusing on the standardization of the controls on BC's and dry suits and their operation and location on the diver, a procedure that could work on both systems. Glen Egstrom: I touched on that. In the first place, it's always been with a certain amount of sadness to recognize that at a point in time DEMA had the ways for developing that standardization. That is to say there were criteria for each of these routines, such as location of the oral inflator hose. Right now, that committee has not been active for quite some time At the present time if you take a look at the proliferation of the controls, it's mindboggling. To have the same uniform controls for buoyancy compensators, that would take a monumental effort. To match it up with the dry suit configurations would take an act of Congress.

Glen Egstrom: We've done a number of learning experiments that dealt with learning curves for different kinds of conditions and tasks that are done in the water and one of the things, it turns out surprisingly enough, is that it takes from 7-12 successful repetitions of a particular skill before the person gets it into a mindset where its going to be learned. They need to do the practice through a period of supervised exposures rather than just lecture, and they have to go through the repetitions of skills. Bob Stinton: Two years ago there was a meeting at DEMA where the dry suit manufacturers got together and talked about the establishment of basic standards. Some of the people from the northern latitudes immediately said we don't want you establishing some standard that says a person to be trained in dry suits has to be a certified basic diver. Where we live, we train students in dry suits, because it's immoral to teach somebody in a wetsuit. The people from the southern latitudes felt dry suits were too complicated. The northern folks said that if you take our students, they think wetsuits are antiques. A new guy who walks in learns the skills and assumes that is the way it's done. The 10 dives came from the fact that Dick used to have a wetsuit and wouldn't try a dry suit, so we took his wetsuit away and told him he'll get it back, if he wants it, after he's made 10 dry suit dives. This was just prior to lobster season opening.

Brian Hartwick: There are really some problems with sticky valves. Dick: Sticky valves are a great concern of mine. We see people take care of their regulators after the dive, but don't rinse their valves. As long as you keep them clean, we don't see problems. It is an awareness and maintenance problem, which is why I put washing the valves in the recommendations for maintenance of dry suits. Mike Lang: Steve Barsky always said to be careful using woolly bears or other lint producing underwear, because his major concern was that they interfered with valve operation. Bob: Many valves have silicone valve components. The SI-Tech valves had rubber components, and when they were brand new, were heavily lubricated with silicone, so everything that went through there would stick. To him that was an issue, to others it wasn't. In reality, once the silicone wore off, I've never seen a valve stick or leak because of that. Chris Wachholz mentioned that of 175 accident reports, DAN received four cases where problems with dry suits were reported.

Drew Richardson: Do you see any improvement on the horizon for flow efficiency in valves? Bob Stinton: When you talk about flow, you talk about valves sticking. That could be an inlet valve. The only time I've ever blown up was the BC inlet valve sticking. You push the dump button, but all the air won't immediately go out. That is a potential problem. You have to keep them clean and not let them sit for a long time without using them. Higher flow valves with a suit that doesn't contain any air, you can put an air volume in it, keep putting it in, but it won't stay in the suit. The only air space you need to maintain is that of the insulation. Once that is there, any other excess air automatically goes away all the time, so that there is not a flow rate issue or valve issue, the air just goes out the hose. The question is does the suit become attitude dependent? I've seen people with valves mounted on the wrist say the valve failed and they didn't know it was a manual push-to-dump valve. What Glen said is true about BC's that if you go up rear first, you can push the button all day, but won't get the air out of the BC. So all the guy knows is he got to the surface and there was an accident. What you read in the reports is that they never know. The valve sticking or the valve not working, accessory hoses are possible explanations. An example is a guy jumped off the boat, was overweighted, sank straight to the bottom. The fact that the hose was kinked, never totally coupled with the quick disconnect, and he never pushed the button before he hit the bottom, was irrelevant; he said the valve failed. With the valves we're diving with now, the flow rates are very adequate. The question follows are they adequate enough for every conceivable accident? No. For all conceivable conditions? No. I'm not sure you can ever attain that.

CHAMBER PERSPECTIVE OF DIVING ACCIDENT INCIDENCES

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The thought did occur that before you discuss problems, you need to know what the extent of the problem is and if it exists. I assembled some notes from our experience at the Catalina Chamber, at the receiving end. What are the causes of diving accidents and how often do they happen? This workshop is aimed at ascent. As far as a problem, decompression sickness (D.C.S.) is minuscule compared to cerebral arterial gas embolism (C.A.G.E.) from my standpoint as an ex-chamber administrator. With cerebral air embolism, we're talking about life and death, with decompression sickness we're talking about a little pain and maybe some disability, and usually not even that. If indeed this workshop is directed at ascent and what medical safety problems exist, I would hope that CAGE is not forgotten in that area.

Table 1 is a summary of what we've seen at the Catalina Chamber, with +++ being a maximum and + a minimum indicating relative frequencies. The correction I've noted is an attempt to solve that particular problem in a general fashion.

Table 1. Cause, frequency and correction of CAGE and DCS

CATALINA CHAMBER

Disease		Cause	Frequency	Correction
C.A.G.E.	1.	Out of air	+++	Ed., Eq.
	2.	Buoyancy Control	++	Eq., Ed.
	3.	Panic	+	Ed., Sc.
	4.	Non-panic breath-hold	+	Ed.
	5.	Pulmonary blebs	+	Md., Sc.
D.C.S.	1.	Violation of DC limits	+++	Ed.
	2.	Rapid ascent	++	Ed., Eq.
	3.	Instrument error	++	Eq.
	4.	Repetitive diving	++	Ed., Res.
	5.	Shallow dive first	++	Ed.
	6.	DC limits error	+	Res.
	7.	Multi-day	+	Res., Ed.
	8.	Altitude	+	Ed., Res.
	9.	Susceptibility	+	Res., Sc., Ed.

Ed.: Education; Eq.: Equipment; Sc.: Screening; Md.: Medical; Res.: Research

The out of air situation is number one and has been for some time as far as CAGE. To me, that is primarily an educational problem. Training divers to monitor their air supplies or if the dive computer can activate that cattle prod at the right time, then you can perhaps, to a large degree, get rid of that. Buoyancy control, which has been discussed, causes both of these illnesses, sometimes simultaneously. By far though the most serious problem is CAGE where lack of buoyancy control has been a major contributor. The panic aspect, was the number one cause of air embolism in the 1950's and 1960's. That doesn't exist anymore. Rarely do we see the diver go out to the kelpbed, freaking out and shooting to the surface. That's rare, where it used to be a predominant cause. Non-panic breath-holding applies to very experienced divers such as underwater photographers taking pictures while holding their breath from 10 fsw to the surface. This is due to a lack of awareness of what you're doing and, of course, in the last 10 fsw is where you have the largest volume expansion and that's where it happens. Pulmonary blebs occur in a very small number. It's a medical screening problem which does occur. People like to lump incidents into that category, when they can't pinpoint a cause. It's very hard to prove.

In the last fifteen years, out of 600+ cases, we've seen about 50% CAGE and 50% DCS occurrences. As far as DCS, violation of no-decompression limits is by far the largest cause. Whether these divers do it knowingly or unknowingly, whether they're educated enough or not, those are clear cut violations. Nobody is going to argue, theoretically or otherwise, that they shouldn't be. They deserve what they got, sometimes to the extent that you wonder why they're still alive. It's phenomenal what the human body can tolerate. We had an abalone diver once who made 12 dives to 135 fsw in an 8 hour period. The bottom time was unknown in each dive but it had to be significant, such as an hour duration or more on hookah, not scuba. He made no stops on any dives. His ascent rate was as fast as he could get his load to the surface and yet he came in complaining of a little disorientation. In any event, it's phenomenal what the human body can tolerate in some instances.

Rapid ascent is related to buoyancy, to a large extent of what we see, but in addition to that, people come in swearing they followed the tables until you get to the ascent part. Did you come up at 60 fpm? The answers amount to: Was I supposed to? Others say: Of course I did, that's what you're supposed to do. If you question them a little deeper, there's no way. They are coming up at 120 fpm, 180 fpm, that's what you're talking about. As far as we could determine, in many of these cases, they did follow the rest of the procedure, except for the final ascent. Until these dive computers start spitting out the logs to us, which I feel is one of the greatest developments ever to come along from the chamber's standpoint, because you never believe a diver regarding his profile. That will then determine what is going on. Otherwise it's all this very loose information, we really don't know. That has been in the formula quite a bit, where divers do follow the rules until the end of the dive, but then come up too rapidly.

With instrument error I refer to depth gages and watches. Not in the sense that the equipment always malfunctions, but non-monitoring of the equipment also. With depth gages I've over the years gotten to the attitude of saying plus or minus ten fsw. I have a very low opinion of the accuracy of divers' depth gages.

Repetitive diving is high on the list. Many patients we get were doing repetitive dives. I think the DAN information shows the same thing. In many cases you're talking about 6-8 dives, unknown whether they were within the limits or not. During a six hour treatment you ask the diver the same question six times and you get six different answers. You then go outside and ask the dive buddy, who gives you the seventh different answer. Again, the greatest thing to come along for chamber people is even the idea that dive computers will spit back the information. Divers don't know what they've done. We don't know how many repetitive dives you can do in a series and how it changes procedures in the tables.

The deep dive first rule is violated constantly. This a high number item. People start diving, make some shallow dives then go down deep. Some of you may have heard the incident with the divers aboard the Russian vessel in the Indian Ocean, where the U.S.

Navy assisted with the treatment. The scenario we got back was the way they dive was to make short, shallow dives followed by longer and longer, deeper and deeper dives.

Regarding No-D limit errors, when a patient comes in with a particular profile, there's a constant argument as to where he fits, the Navy tables, Huggins tables or Canadian tables. A lot of times, he's in between several of the tables. Based on the questionable information the diver supplied, he wouldn't fit on any table you came up with. That' where the japanese fishermen fit as well.

The multi-day problem is not common, but it is more of a concern in the scientific diving community. we have gotten a number of patients who have been diving for seven days, a series of dives every day, all following good procedures. At the end of that series they were bent, even though they followed the rules. The idea here is that the tables did not take into account the very slow tissues that might be involved here. That is an observation.

Altitude primarily involves people, at least in the Southern California area, not with respect to flying after diving, but driving over mountain passes on their way home, usually hours later. To get out of the L.A. basin, you essentially have to go over a pass of 4,000 feet. They may have made the dive within shouting distance of the Catalina Chamber, but when they go across the channel on the boat, get into their car and drive over the mountains, then call us at the chamber. It's that critical in some cases.

I can't find any other category so I'll call the following cases "higher susceptibility" which I'm not about to define. The saying goes that some people are more susceptible than others, which is probably true, but we don't have a good handle on what the variables are. There are some people we've treated with good records of their dives who have bent when they should not have been. That is a very small number, maybe 3 or 4 in 15 years. The gas loading problem is enormous compared to the susceptibility problem. However, I have no doubt that people have different thresholds of when they bend, but I don't think it's that big of a factor.

As far as ascent goes, it is obviously involved in all of the above, but the most important is the air embolism part and that's really an out of air situation. As far as DCS, ascent is very much involved in the situations where people simply ignore the ascent. Often that is in combination with an air embolism in an out of air situation also. They did everything right until they ran out of air and now they have to get to the surface. That is a common occurrence. The highest danger of using scuba is that you're free swimming and you're not supported, such as in the military or commercial fields, by the surface.

THE DIVERS ALERT NETWORK (DAN): DIVING ACCIDENT DATA AND ITS IMPLICATIONS

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The U.S. National Divers Alert Network (DAN) was started in 1980-81 to provide access to information regarding availability of recompression chambers and other facilities for treating diving accidents. A detailed report on 270 diving accident cases representing 48% of the total 1987 cases (564) was published in January 1989. The 570 total included 127 decompression sickness Type I, 340 Type II and 97 AGE diving accidents. The results of the report indicate a significant need for diver education to counter the myths and misinformation surrounding diver injuries. For example, 58% of DCS accidents occurred within the U.S. Navy tables but the individuals appeared unaware of other contributing risk factors such as type and frequency of diving, rate of ascent, diving too deep, exertion level, fatigue, currents, etc. Some 50% of all injured divers had consumed alcohol the day of the dive or the night before adding to contributory dehydration. The average time delay for DCS affected divers to telephone for assistance was 15 hours, due primarily to the failure of symptom recognition or denial. Only 36% of all injured divers received oxygen, the well proven first aid measure. These and additional factors contributing to DCS or AGE will be discussed. The collection of this data is continuing and it is hoped that the publication of this annual accident report combined with training and education programs will lead to a decrease in the 570 or so injuries per year in the diving population.

Introduction

Recreational scuba diving is unique among recreational sports. It requires a training course and certification to participate. Training consists of the testing of physical abilities, a brief review of math, and a basic understanding of the interaction of human and gas physiology. At its best, scuba is an evolutionary process for the participant who continues to grow in experience and knowledge after certification.

Unfortunately, the knowledge gap between what a diver or instructor believes and the science and physiology upon which scuba is based is often quite large. This lack of knowledge and understanding can lead to injuries in scuba and many questions arise about diving and safety as a diver gains more experience. The Divers Alert Network has attempted to meet these needs since its beginning.

The most dramatic example of the knowledge gap is when injury or death occurs. DAN is instrumental in assisting many injured divers to treatment yearly, however, there is also a strong desire in the medical and diving community to minimize injuries. This goal can only be accomplished through the comparative analysis of dive accident cases and the accumulation of data. This will result in the recognition of certain trends and unsafe practices in recreational scuba diving that increase the likelihood of injury.

The need for assistance

Two ways in which recreational scuba divers can get quick assistance are through the use of the DAN Emergency and Medical Advisory phone lines. The emergency line provides immediate assistance and answers for the injured diver as well as a hyperbaric physician consultation for the local physician. The medical information line provides the caller with a quick response on a wide variety of safety and dive medicine topics. It also provides a physician referral service.

The Divers Alert Network emergency line is perhaps the most unique service offered in any recreational activity. Because there is inherent risk in scuba diving, DAN maintains a 24 hour, seven days a week emergency assistance service. Except for the cost of the call, this service is free to the caller. Divers are referred to emergency rooms, physicians, and hyperbaric chambers on an almost daily basis for evaluation and treatment.

The use of the emergency line has steadily increased since 1980. The 1987 line use was up 22% over 1986, and increased 18% in 1988 for a total of 871 calls. In 1989 the line had already been used 34% more in the first quarter which is a traditionally slow usage period. In a review of 1987 emergency calls, the line had been used appropriately 87% of the time (DAN emergency line use, 1988). The emergency line is also being used by medical professionals for the referral of carbon monoxide poisoning, iatrogenic embolisms, and clostridial myonecrosis cases.

The breakdown of callers' questions to the DAN non-emergency line shows that it is being used to fill the existing knowledge gap. The number of calls concerning diver qualifications, contraindications to diving, and general safety, suggests a growing awareness by divers of problems that can be encountered in the sport. Divers are also becoming aware of information beyond the level of their basic diving education (Williams *et al.*, 1989). Usage of the line was up 66% in 1987 over 1986. A similar increase of 67% was reported from 1987 to 1988. The first quarter of 1989 showed an increased usage of 91% over the first quarter of the previous year.

This unique service is not only meeting divers' needs for assistance, but minimizing the potential for injury by exposing divers to additional information.

Data collection

DAN collects dive accident cases primarily from the DAN network chambers who support the data collection effort. DAN does not receive 100% of all cases as it is dependent on the efforts of volunteers at each facility to make sure an accident form is filled out and mailed in. Cases are also collected because DAN is the first contact for many of the injured divers who are then referred to these same facilities.

All injured divers are contacted whose reporting form was not complete, or to confirm the accuracy of questionnaire data. Every effort is made to insure that the analyzed group of divers were involved in recreational diving at the time of their injury. Scientific, military, oil field, or any sports diver who is diving for purposes of profit are excluded from the study. Incomplete cases and any cases where the final diagnosis is in dispute are also excluded.

The injured diver

The injured divers represent a broad range of diving experience, age, physical stature, and health. In 1987 24.1% of the injured population were females (DAN, 1988). This figure compares favorably with the 1987-88 combined percentage of 23%. In 1986 and 1987 the percentage of female callers on the medical advisory line was 30%. This figure is probably higher than the percentage of participating females in the sport since it represents any female caller with a question, such as a diver's mother.

In a 1988 survey of the DAN membership, 24% of the respondents were female in a population of 2,633 diver members (Wachholz *et al.*, 1989). Although the exact number of females in diving is not known, it is very likely that the percentage of injured females in the sport is a representational sample. In a comparative analysis there were no indications that women were any more susceptible to decompression sickness than their male counterparts.

Risk factors

There were common risk factors in both decompression sickness and gas embolism. These factors occurred often enough when compared to all known risk factors that they were considered contributory to the injury (see Table 1). The complete list of risk factors for the 270 divers analyzed is contained in the DAN Report on 1987 Diving Accidents.

Table 1. Diver Risk Factors

52 AGE cases reported

# of Cases	Condition	Ascent	Fatigue	Current
24	Rapid ascent	--	9	8
18	Fatigue	9	--	8
16	Current	8	8	--
14	Buoyancy problem	11	4	3
11	Exertion on dive	7	4	7

47 Type I DCS cases reported

# of Cases	Condition	Ascent	Fatigue	Current
22	Current	--	12	6
20	Exertion on dive	12	--	11
18	Fatigue	6	11	--
11	Cold	6	7	6
11	Alcohol	8	5	4

171 Type II DCS cases reported

# of Cases	Condition	Ascent	Fatigue	Current
73	Current	--	28	37
64	Fatigue	28	--	31
58	Exertion on dive	37	31	--
42	Rapid ascent	17	18	20
31	Cold	17	18	22

This list of individual and environmental conditions is shown in numeric significance for each final diagnosis in the column on the left. The numerical columns to the right represent the number of times any two factors occurred together.

Dive day conditions and risk factors are listed by the diver in the following manner:

1. A strong to moderate current is considered a factor because of the increased exertion required.
2. Fatigue is a factor because the diver said he was physically tired or had missed some sleep the previous night.
3. Exertion is considered because of the increased muscle activity, but the diver specifically mentioned this factor for the dive(s) preceding his symptoms.
4. Cold is a factor because the diver said he was cold during the dive as compared to being comfortable.

These same risk factors obviously also appear in the dive profiles where individuals are not injured. What is their significance to the injured population? We are left with two assumptions about the people injured.

1. Several risk factors generally occur together in dive injuries. Accident forms generally show more than a single risk factor (except rapid ascent in AGE).
2. Divers who are injured apparently plan their dive, but do not modify their plans when physical or environmental conditions necessitate that they do so.

There is inherent risk in scuba diving as there is in many other recreational activities. A reduction in dive injuries is possible, however, by enhancing the education of the diver through such studies as the risk factor occurrences shown in the DAN data. The prevention of dive injuries through the avoidance of the circumstances which can create an accident has been a cornerstone of the Divers Alert Network education programs.

Safe Limits

DAN is often asked, "Do the U.S. Navy dive tables apply to recreational divers and are they safe?" If you are using the Navy tables as they are intended to be used, then they apply to you and are relatively safe. The Navy tables were meant for single dive, single day diving and that is how they were tested. Only certain repetitive schedules were tested on a limited basis. One can only say that the incidence of DCS is low in recreational divers using the Navy tables because the exact number of divers is not known or how many dives they make yearly. The Navy reports a DCS incidence of 1.2% to 2.2% for divers in the 50 fsw to 190 fsw no decompression limits (Berghage and Durman, 1980).

One estimate of the average risk of recreational decompression sickness in a population of two million divers doing 10 dives yearly with 1,000 injuries was .005% (Wachholz, 1988). This would be from all dive depths and times. There are many other dive tables in use today in addition to the U.S. Navy tables, but no table can guarantee that decompression sickness will not occur as a result of its use since we still know very little about decompression.

We cannot make a valid comparison of Navy and recreational divers. Navy dives are working dives made to a given schedule. Recreational dives are done for pleasure without as much exertion required and may not follow the given time limits of the U.S. Navy dive tables.

Among the decompression sickness cases studied in the 1987 report 58% (126) of 218 diver profiles were within the U.S. Navy tables. Only 26% of dive computer profiles were within limits, but the majority of dive computer users favor a multi-level or multidepth profile. In order to determine the reason for the table failures we examined each DCS case for a technical or recreational diving violation.A list of 7 disqualifications involving 107 divers is shown in Table 2.

Table 2. Technical and recreational diving violations

Rapid ascent	28
Decompression dive	22
Multiday diving	48
Previous DCS	4
Medical disqualification	2
Flew within 24 hours	2
Dive depth > 140 fsw	1
TOTAL	107

The remaining 19 divers were single day, single or repetitive divers and within the limits of the Navy tables. Thirteen of these 19 divers had at least three of the risk factors shown in Table 1 involved in their dive day. Additional frequent risk factors also included diving at 80 fsw or greater, pushing the no stop limits to within one letter group of a decompression dive, diving repetitively, using alcohol, or a medical history of spinal cord surgery. Seven divers had 4 or 5 risk factors involved and one had 6 risk factors on the causative day of diving.

Environmental and physical conditions are the most commonly associated factors in a diving injury even in this small population of 19 divers where one would expect to find the safest group of DCS victims. This is further evidence that divers do not make appropriate adjustments in their dive schedule based on the conditions at the time of their dives and this is most likely due to the relative lack of information that divers have concerning the nature of dive accidents.

Individual susceptibility in DCS cannot be ruled out, but as cases are looked at more carefully, there seems to be very little chance occurrence of recreational decompression sickness. Only 6 divers (2.7%) had 2, 1, or no risk factors at all in our DCS study population. In this group of six divers, four were diving at 80 fsw or greater and two of these were unduly extending their time at depth.

Rapid ascent

The 1987 and 1988 National Divers Alert Network reports on diving injuries contained a total of 538 non-fatal injuries. One hundred fifty-three or 28.4% of these injured divers experienced a rapid ascent. The breakdown of these rapid ascent injuries were 49 arterial gas embolisms, 81 Type II decompression sickness, and 23 Type I decompression sickness. Arterial gas embolisms are the dive injury most often associated with rapid ascent. In 1987 48% of all embolisms studied involved a rapid ascent. The 1988 figures show that 54% of all gas embolisms stated they had a rapid ascent. One of the most common reasons for rapid ascent is equipment failure. In 1987, 29 rapid ascents were made because of equipment problems. Seventy percent of equipment problems involved rapid ascent. Equipment problems and rapid ascent combined resulted in 8 air embolisms. In the 1988 population, 32 equipment problems were associated with 16 rapid ascents and 8 arterial gas embolisms.

New divers are particularly at risk for rapid ascent because they are still developing skills in buoyancy and ascent control and do not yet have the appropriate responses for sudden underwater problems. Lack of experience may lead new divers into having a rapid ascent. In the total population of 538 studied divers, 163 had one year or less experience. There were 60 divers (37% of the total inexperienced divers who had an injury) who experienced a rapid ascent problem.

There is a direct relationship between rapid ascent which causes over-expansion of the lungs and arterial gas embolism. The relationship between rapid ascent and decompression sickness is not clear. In 1987, 23% of the decompression sickness cases involved a rapid ascent. The 1988 figures show 24% of all DCS injured divers had a rapid ascent.

Rapid ascent often occurs in combination with other events. The most common conditions occurring in the population of 153 divers are listed below in the table. Some of these conditions were present during the dive and others may have initiated the rapid ascent.

Table 3. Rapid ascent risk factors

Condition	Percentage
Dive 80' or greater	56
Single dive	51
Buoyancy problem	40.5
Experience equal to 1 year or less	39
Low or no air	31
Equipment problem	29

Diver experience

Diver experience is a difficult quality to determine. It involves more than just the number of dives or the number of years a person has been diving. Experience also involves the understanding and practice of safety habits. Time and experience is important in developing both of these traits.

The 1987 Report on Dive Accidents provides some clues as to the role of inexperience in diver accidents. Suppose a diver is arbitrarily assigned an inexperienced status if the number of dives is less than 20 times a year or if the number of years diving is 1 year or less. Fifty-five percent of all diver injuries fall into this one year or less, twenty dives or less category. Fifty-two percent of all males and sixty-six percent of all females are inexperienced by these standards. This is the only area where women seem to be more susceptible than men, but this could just be an artifact of the small female population size.

Lack of experience is a factor in diver injuries because (1) it is the principle reason for the information gap, and (2) inexperience can lead to a loss of control in the diving environment resulting in panic, a rapid ascent and possible injury. Sixty percent (31) of the gas embolism cases fit the inexperience criteria (20) or were injured in training (11). Inexperience may also have played a role in the more experienced divers because 12 (57%) of 21 more experienced divers were involved in spearfishing or photography which focus the diver's attention away from maintaining depth or an open airway. We do not know how experienced the divers were in these activities.

Dive computers

One of the latest technologies in diving is the use of dive computers (DC's). The use of DC's is becoming more popular and more cases are showing up in the accident reports. In 1987 there were 41 computer cases in 270 total injuries (15%) and in 1988 there were 83 dive computer cases in 268 total injuries (31%). Some of the cases from both years were the result of misuse of the DC's and some injuries such as gas embolism were unrelated to the use of the dive computer.

It is not yet clear if the increase in dive computer accidents is due to a more aggressive diving population buying computers, by divers justifying the purchase of an expensive dive accessory with maximum use or by the simple increase in total dive computer purchases (Scheer, 1988). It is clear from the 1987 DAN Report that most DC divers who are injured dive more often, start their dive day deeper and do more decompression diving than table divers who are injured. Repetitive multi-day diving was a common associated risk factor for divers using both computers and the U.S. Navy decompression tables (Vann *et al.*, 1989).

The risk of injury with dive computers may be no greater than with the use of the Navy tables, but their ease of use allows a higher risk style of diving.

Delay to call for assistance

The signs and symptoms of gas bubble disease are perhaps the most misunderstood aspect of diving injuries by divers in general. The lack of information adds to the validity of myths and anecdotal stories which are told as fact to the inexperienced.

Very few divers or instructors actually come in contact with DCS or AGE. Divers learn about DCS or AGE from a list of potential signs and symptoms, but few remember more than pain, paralysis, and seizures. Anything less than what a diver may feel represents DCS symptoms is subjectively dismissed as "something else". The gradual onset of pain and numbness, or a light tingling sensation are overlooked because these symptoms are quite tolerable and do not match the diver's perception of what a dive injury should be.

This subjective view of symptoms and lack of information results in an average delay to calling for assistance of 15 hours after symptoms have started. Not only do the divers not realize they are hurt, but the subsequent delay to treatment lessens the chance of a complete recovery after therapy. Only 56% of the treated divers had symptom resolution after a single hyperbaric treatment.

It is interesting to note that only 56% of the accident population received any first aid at all. Only thirty-six percent of all divers received oxygen as a first aid measure.

In a review of the combined DCS cases for 1987 and 1988 some interesting data on recreational DCS signs and symptoms are noted.

In 70% of all cases, the first recognized symptom of DCS was reported by the diver to have occurred in 2 hours or less after the last dive. Another 23.5% of the total population reported the occurrence of their first symptoms between 2 and 23 hours post-dive. This means that 93.5 percent of the total accident population had a recognized symptom occurring within the first day post-dive.

The most prominent first symptom is pain; this supports military data which suggests that most DCS is pain only (Elliott and Kindwall, 1982). The most prominent second symptom is also pain, but nervous system signs and symptoms such as numbness/tingling, weakness, and fatigue are more frequent as a secondary symptom. This may account for the fact that recreational divers have more Type II DCS than pain only Type I. They wait much longer to seek help, giving time for secondary symptoms to arise.

Conclusions

The systematic collection of diver data by DAN and its network of volunteers is creating a great deal of information for analysis on recreational diving injuries. Many conditions exist within a diver accident profile that may be factors which contribute to an individual injury. A causal relationship between these conditions and diving injuries has not yet been established and the relationship remains statistical, but the DAN data indicates a strong relationship. Even though this data remains associated with diving injuries, it is a better basis for safe diving practices than the use of anecdotal information.

In order to validate the DAN data, a prospective study was begun in May 1989. This study will follow a randomly selected group of divers in an attempt to determine the individual diver demographics, physical health, abilities and experience. It will also attempt to establish the risk associated with recreational diving and to determine if there is individual susceptibility. Such actual information will eventually form the basis of scuba diving safety education.

"The most severe injuries occurred during or shortly after training" (Dick and Massey, 1985) reported one retrospective study of neurological decompression sickness. The recent DAN data also reflects a similar finding, but would add the infrequent diver to this group.

The evidence of a relationship between dive accidents and the lack of experience is strong, but difficult to define. The inexperienced diver has accidents for many different reasons. Individual susceptibility to dive injuries may be influenced by a diver's physical ability, behavior, and response to the physical risk and stress present in diving (Dembert, 1987). Stress, and the diver's response to stress play an important role in new diver accidents (Bachrach and Egstrom, 1987).

The analysis of inexperienced diver accidents can prove to be of short and long term value in the prevention of dive accidents. Accident avoidance is a strong incentive for the new diver to develop safety habits that take dive day conditions into consideration. These safety habits will carry over into a continuing dive career. The more information gained by accident reporting, the more accurate the safety recommendations will be in the future.

The presentation of gas bubble disease represents a broad spectrum of disease symptomatology. This is one reason why a more intensive study of symptomatology was begun by DAN. A severity code classification scheme was devised by DAN to generate data on symptomatology for research purposes. The six level coding system classifies divers by the severity of their symptoms. Severity code 1 would be a pain only, limb DCS, while a cerebral embolism would be classified as a code 6. The presentation of peripheral and central nervous system symptoms are represented by codes two through six.

This coding system has proved beneficial in determining the extent of diver injury in our accident population and provides a basis for comparison in cases with residual symptoms (Bond *et al.*, 1989). It has also pinpointed symptoms which require greater diver awareness.

Summary

Recreational scuba diving is evolving as a leisure activity and there is still much to learn about safety and accident prevention. In order to obtain an accurate database on recreational diving accidents, a wide variety of information must be analyzed. It is impossible to get a clear picture of this problem if study is confined to limited or single aspects of dive accidents. It appears from this study that dive accidents are the result of the interaction of many factors and in general are not caused by a single condition.

There are approximately 600 treated dive injuries a year, making it difficult to convince a diver in a population of one to two million divers that he may be hurt. Divers rely on their traditional diving habits until they stop diving, are injured, or better information comes their way. The first step in unraveling the speculation and myths associated with recreational diving is to establish solid information based on the accumulation of actual statistics. This data will be the basis for safer diving habits in the future.

DAN is indebted to the treatment facilities and many physicians who assist in the collection of accident data. This paper would not be possible without their efforts and cooperation.

References

Bachrach, A.J. and G.H. Egstrom. 1987. Stress Indicators (Chapter 2). *In:* Bachrach, A.J. and G.H. Egstrom (Eds.). Stress and Performance in Diving. Best Publishing Co., San Pedro, CA. pp 11-22.

Berghage, T.E. and D. Durman. 1980. U.S. Navy Air Recompression Schedule Risk Analysis. Naval Medical Research Institute, Bethesda, MD.

Bond, J.G., R.E. Moon and D.L. Morris. In press. Initial Table Treatment of Decompression Sickness and Arterial Gas Embolism. Submitted to Aviation, Space and Environmental Medicine. 1989.

DAN Emergency Line Use. May, 1988. A Review of DAN Emergency Calls on Pagers. From: Divers Alert Network Preliminary Report on Diving Accidents.

Dembert, M.L. 1987. Individual Factors Affecting Decompression Sickness. *In:* Symposium on Decompression Sickness, Duke University. November 1987. Sponsored by Duke Medical Center, NOAA and UHMS.

Dick, A.P. and E.W. Massey. 1985. Neurologic Presentation of Decompression Sickness and Air Embolism in Sports Divers. Neurology, Vol. 35, No. 5, pp. 667-671.

Divers Alert Network. December, 1988."Report on 1987 Diving Accidents",

Elliott, D.H. and E.P. Kindwall. 1982. Manifestations of the Decompression Disorders. *In:* The Physiology and Medicine of Diving, 3rd edition. Bennett, P.B. and D.H. Elliott (Eds.). Bailliere Tindall, London, pp. 461-471.

Scheer, T. 1988. Computer Diving Style - Diving into the 1990's. *In:* DAN In-House News, Vol. 1, No. 1.

Vann, R.D., J. Dovenbarger, J. Bond, B. Bond, J. Rust, C. Wachholz, R.E. Moon, E.M. Camporesi and P.B. Bennett. 1989. DAN's Results and Perspective of Dive Computer Use. *In:* M.A Lang and R.W. Hamilton (Eds.) Proceedings of AAUS Dive Computer Workshop, USC Catalina Marine Science Center, September 26-28, 1988. USCSG-TR-01-892. USC Sea Grant Publication.

Wachholz, C. 1988. What Is the Incidence of Nonfatal Diving Injuries? *In:* Alert Diver, Vol. 4, No. 3.

Wachholz, C.J., J.A. Dovenbarger, G.P. Fowler, III, J.S. Rust, and L.D. Thompson. 1989. Comparison of Accident Data vs Survey Data of Uninjured Divers of DAN Membership June 1988. (Abstract). UHMS Annual Meeting, June 7-11, 1989. Hawaii.

Williams, J., R.E. Moon, E.M. Camporesi, G.Y. Mebane, J. Dovenbarger, C. Wachholz and P.B. Bennett. 1989. Utility of Divers' Alert Network Non-Emergency Telephone Information Service. From: Diving Accident Network Preliminary Report. Hyperbaric Center, Duke University, Durham, NC.

A REVIEW OF ASCENT PROCEDURES FOR SCIENTIFIC AND RECREATIONAL DIVERS

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An ascent procedure consists of three distinct elements. It has a beginning, which for most scientific and recreational divers occurs when a no-decompression limit has been reached. It progresses at some defined rate or rates of ascent, and if a safety stop is included, it ends with a stop at a shallow depth for a prescribed period of time. The issues are the prevention of air embolism and decompression sickness. The options are reduced no-decompression limits, a safety stop, and a reduced ascent rate. The test data of Spencer and Powell are referred to as a basis for reduced no-decompression limits, and the tests of Pilmanis are presented in support of a safety stop. The absence of experimental evidence that a reduced ascent rate is necessary for the prevention of air embolism is noted, and calculations are are presented that quantify its effectiveness as a means of decompression. These calculations demonstrate that the maximum effect of reducing the present rate of ascent by a factor of two is equivalent to a safety stop of less than 0.6 min at 15 ft.

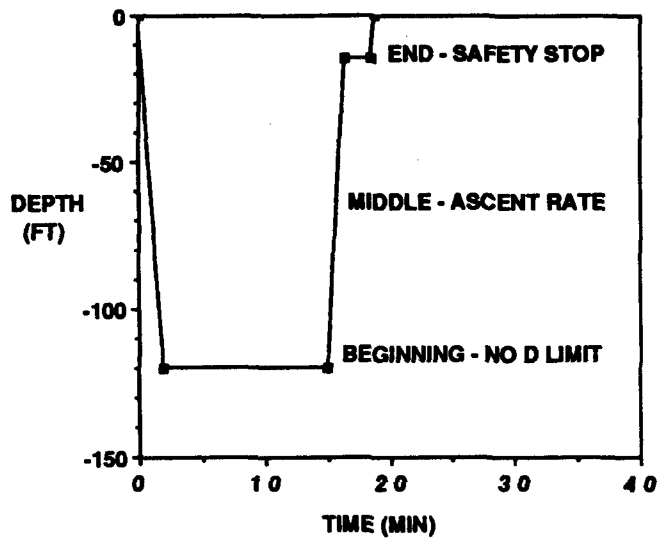
Introduction

The Underwater Diving Manual published by DAN describes two "life-threatening conditions" that are directly related to ascent: air embolism and decompression sickness. Both are a result of gas bubbles but with differing origins. Air embolism is caused by "ruptured lung tissue releasing bubbles into the circulation", whereas decompression sickness occurs when "(absorbed) nitrogen comes out of solution and forms bubbles in the tissues and blood stream." The purpose of this paper is to quantify the net benefit of differing ascent procedures in order that an informed decision can be made by the American Academy of Underwater Sciences (AAUS) as to what ascent procedure is best suited for both scientific and recreational divers.

What are the issues and options?

As illustrated in Figure 1, an ascent procedure consists of three distinct elements. It has a beginning, which for most scientific and virtually all recreational divers occurs when a no-decompression limit has been reached. It progresses at some defined rate or rates of ascent, and, if a stop is included, it ends with a stop at a shallow depth for a prescribed period of time. The issues are as stated previously: the prevention of air embolism and decompression sickness. The options under consideration are reduced no-decompression limits, a safety stop, and a reduced ascent rate.

Figure 1. Basic elements of an ascent procedure



No-Decompression Limits

There are three relatively recent experiments that deal with no-decompression (NoD) limits that are relevant to our discussion: Thalmann (1984), Spencer (1976), and Powell (1987).

Thalmann attempted to increase the Navy NoD limits, and he tested a total of 107 exposures without any occurrences of decompression sickness (DCS) to the following limits:

- 60 feet for 66 minutes
- 100 feet for 30 minutes
- 120 feet for 24 minutes
- 150 feet for 14 minutes

However, a careful reading of his report indicates that these experiments actually included a short decompression stop at 10 feet, although the actual time spent at 10 feet is not documented. More important is that during a second trial of 100 feet for 30 minutes, 4 cases of DCS occurred out of 20 exposures. Thalmann did not use Doppler monitoring of his test subjects, and this result leads me to conclude that if clinical symptoms of DCS is the only diagnostic, what does not work is far more important than what may work on occasion.

Spencer performed tests to the Navy limits. He also Doppler monitored his test subjects for nitrogen bubbles as well as recorded clinical symptoms of DCS. Each of the following examples produced high grade bubbles and at least one case of DCS:

- 60 feet for 60 minutes
- 70 feet for 50 minutes
- 25 feet for 720 minutes

The one example of a bottom time he tested that did successfully exceed U.S. Navy NoD limits was 150 feet for 10 minutes.

Powell tested reduced NoD limits that closely resemble Spencer's empirical formulae for 15% VGE. These bottom times closely resemble the U.S. Navy Dive Tables with the addition of 10 feet to the actual depth of a dive, and thus they do not differ greatly from the admonition in the U.S. Navy Diving Manual to "always select the next depth greater than the actual depth". Powell also Doppler monitored his test subjects. These experiments produced no DCS and at most low grade bubbles.

DEPTH	BOTTOM TIME	DECOMPRESSION TIME
50 FT	100 MIN	7.9 MIN
60	60	3.2
70	50	6.5
80	40	5.3
90	30	3.5
100	25	3.3
110	20	1.8
120	15	0.7
130	10	NoD
140	10	0.3
150	5	NoD

Table 1. Decompression required by Oceanic DataMax Sport when diving to U.S. Navy NoD limits.

It seems probable that diving to the U.S. Navy NoD limits has worked so well for so long because a large percentage of diving was performed well within these limits. Lately, the diving community seems to be besieged with well meaning but poorly founded new rules. Reduced NoD limits do not fit into this category. They are well documented and, in my judgment, should be adopted by scientific divers as well as recreational divers. For scientific divers that have a need for bottom times closer to those of the U.S. Navy, most dive computers can still be used for this purpose, despite the fact that they are based on reduced NoD limits. They will require a decompression stop, but as can be seen in Table 1, the required decompression stops are quite modest and are not unlike a "Pilmanis safety stop", which is discussed in the next section.

While we are on the subject of NoD limits and dive computers, presently available dive computers seem to fit into three distinct groups (Table 2). We have already discussed the Spencer NoD limits. The so-called "Bühlmann limits" are considerably more conservative for intermediate depths, *e.g.*, allowing as little as 12 minutes at 100 feet. In view of Powell's extensive testing of 20 minutes at 100 feet, Group 3 would appear to be unnecessarily restrictive, particularly for scientific divers.

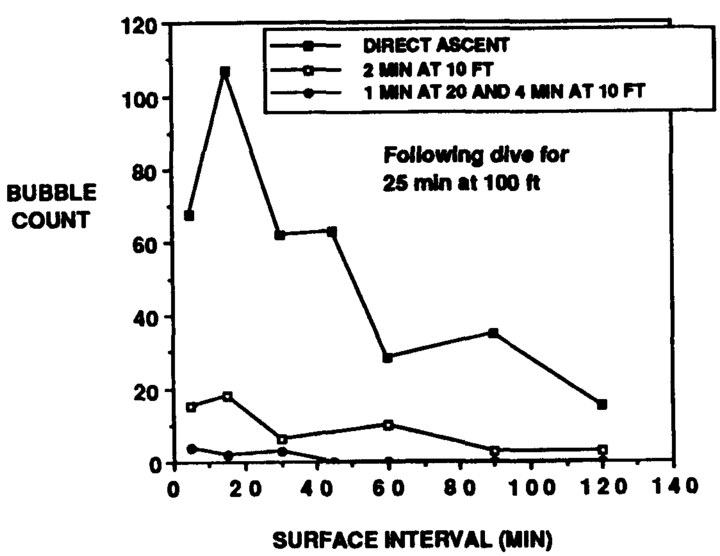
The Pilmanis Safety Stop

The effectiveness and importance of a safety stop, *i.e.*, a decompression stop that is not required by either a dive table or dive computer, was dramatically demonstrated by Pilmanis (1976). As can be seen in Figure 2, following a dive to 100 feet for 25 minutes, as little as 2 minutes at 10 feet was shown to reduce the Doppler monitored bubble count by a factor of 5, and a 5 minute stop virtually eliminated any trace of measurable bubbles. No one who has seen these data can seriously argue with the decision to include a stop in the ascent procedure recommended for both scientific and recreational divers.

Group 1.	U.S. Navy limits	Suunto USN
Group 2.	Spencer 15% VGE	Oceanic Datamaster II
		Oceanic Datamaster Sport
		Oceanic DataMax Sport
		ORCA EDGE
		ORCA Skinny Dipper
		Suunto SME-ML
		U.S. Divers Datascan 2
		U.S. Divers Datascan 3
Group 3.	"Bühlmann limits"	Beuchat Aladin
		DACOR Microbrain
		DACOR Microbrain Pro
		U.S. Divers Monitor

Table 2. NoD Limits of Presently Available Dive Computers.

Figure 2. Pilmanis experiments on ascent procedures



Most Dive Masters, some much less politely than others, insist that divers **"never get back on the boat with less than 500 psi in their tanks"**. An admirable rule that has been conceived to prevent drowning. However, I believe that there are times when the rule should be changed to **"never get back on the boat with more than 100 psi"**. I am referring to situations where serious repetitive multilevel diving is involved, and the avoidance of decompression sickness is an issue. Finding the boat with an ample air reserve is absolutely necessary, however, having done so, the proper procedure should be to use this reserve for as long a stop as it will permit. Stops are the diver's best friend, and

I believe that burning air in a safety zone makes much more sense than surfacing with an unnecessary reserve.

Ascent Rate

The sole remaining element of our ascent procedure is the selection of a proper rate of ascent. The U.S. Navy Diving Manual specifies a rate of 60 fpm. The question is whether a reduction in this rate is necessary and of value.

Intuitively, the probability of an air embolism caused by a ruptured lung is bound to be decreased as the rate of ascent is decreased, since a slower rate of ascent provides the diver with a greater time to react to the discomfort of lung overpressure. On the other hand, with the possible exception of some individual medical problem such as lung damage or disease, thirty years of Navy experience coupled with the carefully controlled and monitored experiments of Spencer, Powell, Thalmann and many others leads one to the conclusion that with normal breathing a 60 fpm ascent rate can reasonably be expected to produce ascents that are free of air embolism. If this conclusion is correct, a slower ascent rate can only be justified by its effectiveness as a means of decompression.

Is slower better?

Unfortunately, intuition is of little value when it comes to the evaluation of the effect of a reduced ascent rate on the decompression status of a diver. Instead, it is necessary to descend into the depths of decompression theory and deal with compartments, half times, nitrogen loading, etc. Having taken this journey, I will spare the reader considerable pain by presenting only the results of this exercise, preceded by a brief review of the theoretical basis of the U.S. Navy dive tables.

The Navy model is comprised of 6 compartments. Each compartment is assigned a half time and an allowable nitrogen loading like that illustrated in Figure 3. The faster compartments have greater allowable nitrogen tensions, and as it turns out they control deeper dives, an example of which is presented in Figure 4. Here, for a 110 foot dive for 20 minutes, the 10 minute compartment is seen to control the dive. By contrast, as illustrated in Figure 5, for a dive to 70 feet for 50 minutes, the controlling compartment is the 40 minute compartment. Note that the 5 and 10 minute compartments have both nearly saturated, however, neither can control this dive since neither can ever reach its allowable nitrogen loading at this depth. As the depth becomes progressively shallower, the control passes to slower and slower compartments.

We are now in a position to evaluate the effectiveness of a slower ascent rate, and for this purpose I have chosen to contrast 3 distinct ascent procedures:

1) a direct ascent to the surface at 60 fpm
2) a reduced rate of 30 fpm beginning at a depth of 60 feet
3) a 60 fpm ascent followed by a 3 minute safety stop at 15 feet.

The results of 3 representative examples are presented in Figures 6, 7, and 8. As can be seen, in every example the 30 fpm ascent rate produced a reduced nitrogen loading, but this gain was dwarfed by the reduction achieved by a 3 minute stop at 15 feet. As a final example of the ineffectiveness of a slower ascent rate, I calculated the time at 15 feet that would produce nitrogen loading that was equal to or less than that produced by the 30 fpm ascent rate. The **maximum** benefit of a 30 fpm ascent rate when diving to the Navy NoD limits is equivalent to 0.8 minutes at 15 feet!

Figure 3. U.S. Navy theoretically allowable nitrogen loading

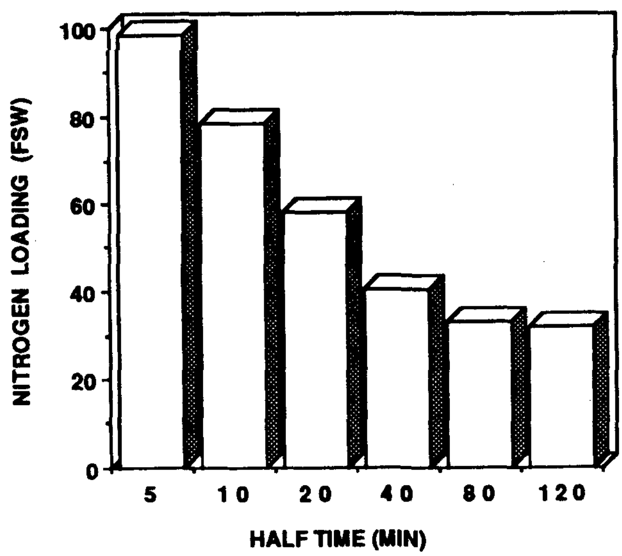
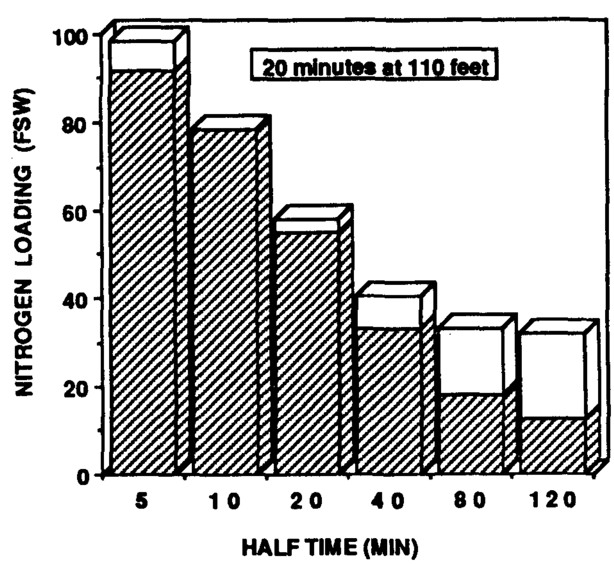


Figure 4. Example of U.S. Navy theory



If you are puzzled by these results, let me suggest that you think about the effect in the following way. The reduced ascent rate is approximately equivalent to a stop at one half the depth from which it began for a time equal to the increased ascent time. Our example of 30 fpm from 60 feet is equivalent to a 1 minute stop at 30 feet. No wonder it is ineffective when compared to a 3 minute stop at 15 feet.

Figure 5. Example of U.S. Navy theory

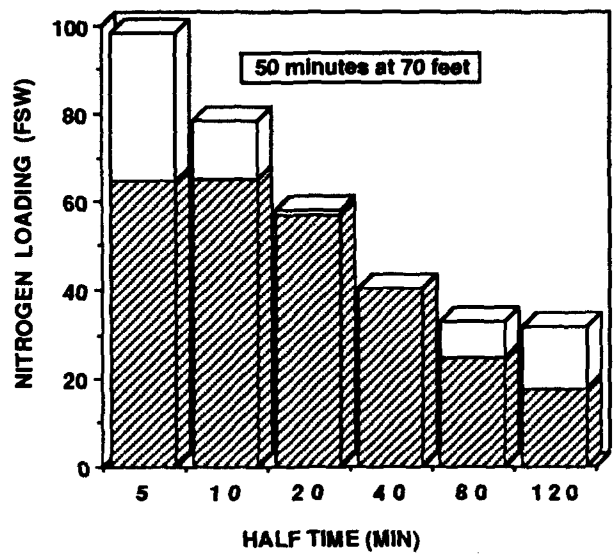
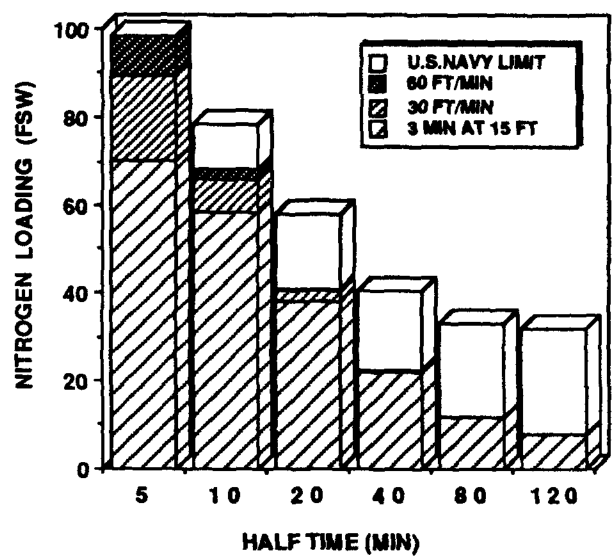


Figure 6. Differing ascents following 5 minutes at 190 feet



Are all safety stops the same?

It is important to note that while the 3 minute safety stop is always a much more effective means of decompression than a reduced ascent rate, as can be seen in Figure 9, neither is particularly effective when diving to the Navy NoD limits at shallow depths. The fractional nitrogen loading (referenced to the Navy NoD limits) achieved by our two modified ascent procedures has less than a 5% effect for depths shallower than about 60 feet. Upon reflection, the reason for this is obvious. For dives greater than about 100 feet, the 5 minute compartment controls the dive, and thus the relevant time scale for decompression is 5 minutes. However, as stated earlier, as the depth becomes shallower, control shifts to slower and slower compartments, thereby rendering the 3 minute stop increasingly less effective.

Figure 7. Differing ascents following 20 minutes at 110 feet

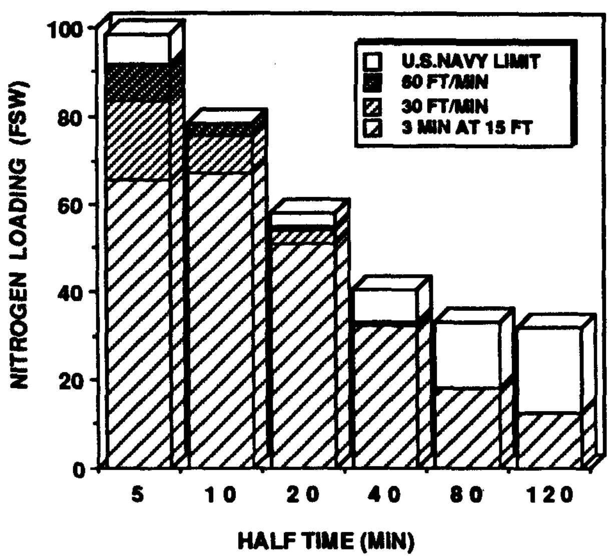
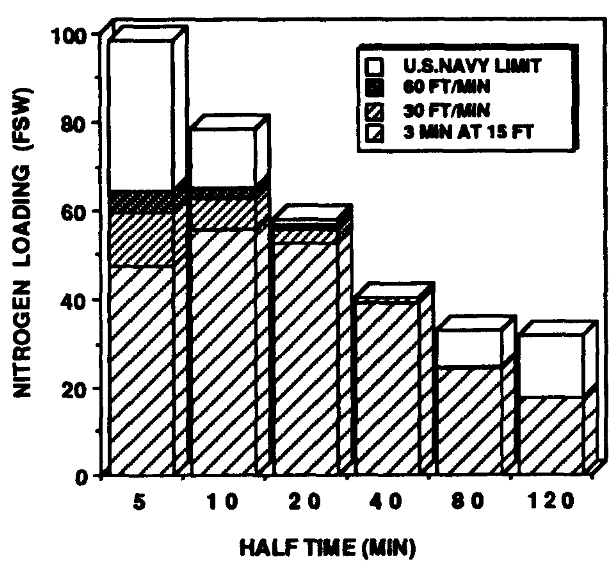


Figure 8. Differing ascents following 50 minutes at 70 feet



If we turn the problem around and ask what safety stop is required to limit the fractional nitrogen loading to 90% of the Navy limits (a value that is comparable to Spencer's reduced NoD limits), the result is the strong depth dependence shown in Figure 10. A safety stop of as little as 1 minute following a NoD dive to 190 feet is quite effective, but a comparable result following a NoD dive to 40 feet requires over 20 minutes. Also shown in Figure 10 is a curve that represents 10% of the bottom time, which is seen to be a reasonable approximation. Keeping in mind that this is a purely theoretical evaluation, it would seem that a proper safety stop should be the greater of 3 minutes or 10% of the bottom time.

Figure 9. Depth dependence of modified ascent procedures

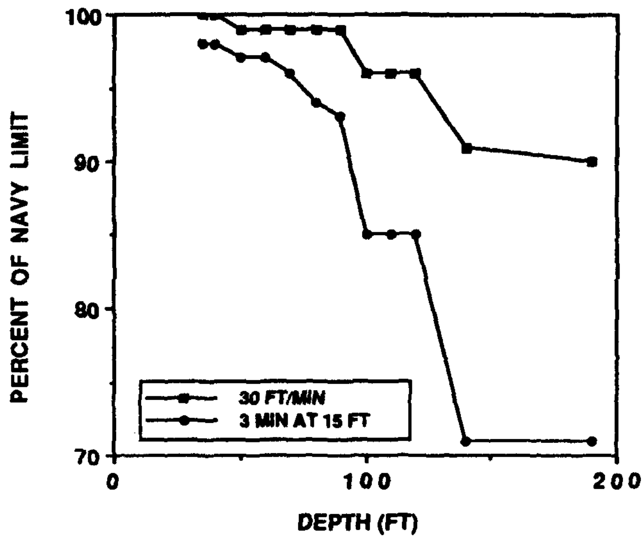
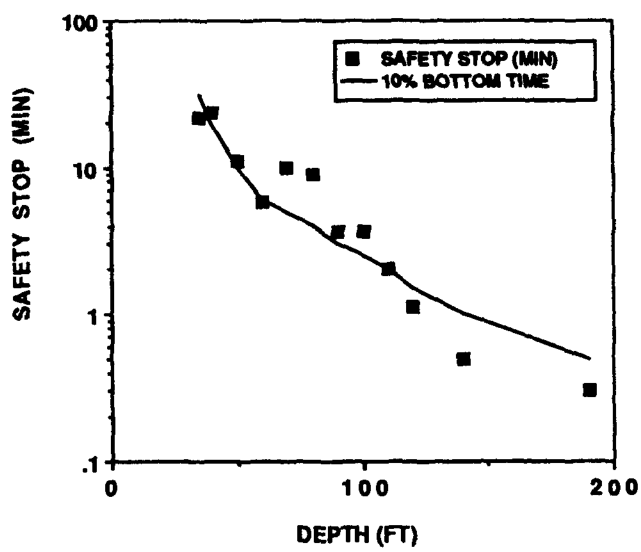


Figure 10. Safety stop required to produce 90% of Navy limits



Summary

In my judgment, the reduced NoD limits that were tested by Powell and are incorporated in at least 8 presently available dive computers are appropriate for both scientific and recreational divers. However, a reduced ascent rate is unwarranted. It is not necessary for the prevention of air embolism, and as a means of decompression it is theoretically ineffective and has no experimental basis. Is it harmful? Not directly. However, if divers are allowed to believe that it is an effective means of decompression, they are likely to skip a stop. Pilmanis demonstrated that a stop is as valid a concept as Newton's Laws of physics, but a slower ascent rate is more properly associated with alchemy; an even bigger hoax than cold fusion has turned out to be.

References

Mebane, G.Y. and A.P. Dick. 1982. "Underwater Diving Accident Manual". Published by Divers Alert Network.

Pilmanis, A. 1989. "DC's, Tables, and No-Stop Diving Discussion". *In:* M.A. Lang and R.W. Hamilton (Eds.). Proceedings of Dive Computer Workshop, American Academy of Underwater Sciences, Costa Mesa, CA. 231 pp.

Powell, M.R. 1987. "Recreational dive planning...the next generation", PADI publication, Santa Ana, CA.

Spencer, M.P. 1976. "Decompression limits for compressed air diving determined by ultrasonically detected blood bubbles". J.Appl.Physio. 40.

Thalmann, E.D. 1984. "Phase II testing of decompression algorithms for use in the U.S. Navy underwater decompression computer". U.S. Navy Experimental Diving Unit Report 1-84.

Thalmann, E.D. 1986. "Air - N_2O_2 decompression computer algorithm development", U.S. Navy Experimental Diving Unit Report 8-85.

BUOYANCY CONTROL AND ASCENT RATES

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New decompression tables and dive computers incorporate rates of ascent ranging from 20 to 70 fpm . Some prescribe 60 fpm in deep water and 20 fpm in shallow water. In practice, recreational scuba divers do just the opposite. They ascend faster as they approach the surface than they do at depth. At depth they are either neutrally or negatively buoyant. Consequently, they use their fins and not positive buoyancy to initiate their ascent. But due to expanding wet suits and buoyancy compensators, which can increase a diver's buoyancy by 30+ pounds, ascent rates near the surface range between 120 to 300 fpm. Unless a diver is trained to maintain neutral, negative, or less than a pound of positive buoyancy during the entire ascent, it is virtually impossible without the use a weighted ascent line to ascend at 20 fpm. A diver with excellent buoyancy control may not be able to determine how fast he is ascending without a visual reference or a sensitive depth gauge and a watch, or an "ascent meter." Linear ascents at these prescribed speeds are incompatible with the way contemporary recreational divers are trained, and how they dive as certified divers. Either diver training needs to be modified or different ways to ascend and decompress need to be described.

Introduction

Ascent procedures prescribed in relatively new dive tables and dive computers, which are rapidly being adopted by recreational and scientific divers, and those long prescribed by certifying agencies are significantly inconsistent. Some prescribe constant ascent rates, regardless of depth. The No-Bubbles Table ascent rate is 40 fpm. The Suunto SME-Ml computer uses 33 fpm. ORCA dive computers, on the other hand, incorporate varying rates of ascent, 60 fpm for depths exceeding 100 ft, 40 fpm for depths between 60 and 100 ft, and 20 fpm for depths between 60 ft and the surface. Certifying agencies, for the most part, instruct entry level divers to ascend slower than 60 fpm, which can be interpreted to mean that all ascent rates, ranging from one fpm to 59 fpm, are acceptable, regardless of depth. The DCIEM Sport Diving Tables prescribe 50 to 70 fpm.

Excluding the non-specific prescription of ascending slower than 60 fpm, there are finite variances in the above prescribed ascent rates of 50 fpm in shallow water and 37 fpm at depths greater than 100 ft. The purpose of this paper, however, is not to compare or challenge the underlying principles or physiological validity of any of these ascent procedures, but to demonstrate that in addition to their fundamental differences and ambiguity, some of them may be impractical for tens of thousands of certified divers, and that all of them are dependent upon the diver's ability to accurately determine ascent speed and exercise precise buoyancy control.

Determining ascent rate

If it is essential for scuba divers to ascend at the specific speeds incorporated in whichever decompression model they elect to use to prevent decompression illness, then it is essential that they have the ability to determine with accuracy the speed they are ascending at. When using weighted, perpendicular ascent lines, divers can determine and control ascent speeds. *i.e.*, 20 fpm = four inches or approximately one hand width (four fingers) per second. But ascent lines can only be used for certain kinds of dives, and it is a tedious procedure to ascend hand over hand for 60 ft at three seconds/foot. It requires great patience and self discipline, and it should be anticipated that only a minority of recreational or scientific divers, if any, will ever adopt and consistently use this method.

In general, scuba divers make free swimming or buoyant ascents, and ascend slower at depth than they do near the surface. Some monitor watches and depth gauges, and make mental calculations to estimate ascent speeds, or rely on dive computers to display flashing signals when maximum ascent rates are being or have been exceeded. Some claim they can estimate ascent speed by rising slower than their smallest exhalation bubbles, or by eyeballing neutrally buoyant particulate matter in the water. Some correlate the number of fin kicks with the number of feet traveled/minute, but this can only work when buoyancy is constant. Many simply ride buoyantly to the surface at unknown speeds that accelerate maximally as they approach the surface.

The realities are:

1) Very few divers have the ability to consistently determine with acceptable accuracy the speeds at which they ascend.
2) Everyday myriad divers during portions of their ascents inadvertently descend, or ascend 100% to 300% faster than 60 ft/minute.
3) Divers may log two minutes for total ascent time from 120 ft to the surface, when deep water portions of their ascents were significantly slower (too slow) than prescribed speeds, and shallow water portions were significantly faster (too fast).

Buoyancy control

Assuming that all scuba divers suddenly acquired the ability to accurately determine ascent rates, they would still need the ability to control ascent rates, which requires precise buoyancy control. Three lbs of buoyancy can propel a diver to the surface faster than 60 fpm, and divers with as little as one pound of buoyancy may rise faster than 20 fpm. However, it is well documented by dive masters and diving instructors, who guide hundreds of thousands of certified divers on underwater explorations every year, that recreational divers, especially the newly certified, are notoriously lacking in buoyancy control skills. They tend to overweight themselves and use excessively large buoyancy compensating devices (40+ pints of capacity) which they untimely over- and underinflate as they shift periodically from being too heavy to being too buoyant. They are rarely buoyant at depth. Most likely they are heavy. They stand, sit on and bounce along coral reefs. When not standing on the bottom or hanging onto or breaking and destroying fragile, precious corals, they undulate and use their fins and hands incessantly in futile attempts to establish and maintain stable positions. When they ascend, they lack the necessary skills to effectively compensate for expanding wet suits and buoyancy compensating devices that compound buoyancy control problems. Consequently, they frequently overvent BC's and inadvertently descend when they think they are rising, or undervent and escalate upward at accelerated speeds.

Certified divers commonly "pop" to the surface and float head high out of the water, which indicates they are at least 10 lbs buoyant and that their ascent speeds probably exceeded 200 fpm. Walt (Butch) Hendrick, President of Life Guard Systems, and members of his staff, have trained thousands of certified divers in rescue techniques. They state that their major problems with trainees are improper weighting (usually overweighting) and lack of buoyancy control skills, and that these problems are becoming progressively worse. Dennis Graver, Director of Education for NAUI, stated in the September/October 1989 issue of Sources, The Journal of Underwater Education, "The problem of incompetent divers is readily apparent to resort operators, who no longer accept a "C-card" as proof of diving ability. The resort professionals are crying out for better-trained divers".

Next to breathing, the most important skill in scuba diving is buoyancy control. It is also the most neglected (Hendrick, 1988). In fact, gathering and compiling information for this paper has heightened my own awareness of the importance of precise buoyancy control, and that controlled ascents are virtually impossible without it. The major point is, entry-level divers and certified divers in general do not have the ability to exercise the precise buoyancy control that is necessary to execute ascent procedures prescribed in dive tables and computers.

Patience and self discipline

After practicing various ascent procedures and observing experienced, skilled divers with dive computers who should have been ascending at 20 ft/minute, but were, in fact, ascending MUCH faster, I have come to believe that the majority of recreational and scientific divers, including myself, don't necessarily have the patience and self discipline to consistently ascend from 60 ft to the surface at four inches/second, even if they have the ability to do so. It is a tedious and difficult task, and I find that it is easier for me to stop and hover periodically than it is to maintain a constant slow rate of ascent. And unless I exercise constant control, my ascent speeds tend to vary from 40 to 100 fpm.

Summary

The purpose of controlling ascent rate is to potentially prevent decompression illness. If it is essential for diver safety that divers ascend at finite speeds prescribed for whichever decompression model they are using, then it is essential that they have the ability to:

1) determine with accuracy their ascent speed;
2) control that speed over a given vertical distance, where changes in diver buoyancy due to variable buoyancy equipment compound buoyancy control problems;
3) consistently exercise the patience and self discipline that is required to ascend constantly at the slowest speeds advocated.

It is virtually impossible for scuba divers not using weighted, perpendicular ascent lines to consistently determine with accuracy how fast they are ascending. Dive computers can be helpful, but they only flash visual displays when prescribed speeds are being or have been exceeded. There is a real need for reasonably priced digital ascent meters (DAM's) that every diver can afford to own. Divers equipped with DAM's would have no difficulty in determining ascent rates, regardless of diving experience.

If scuba divers were provided with digital ascent meters, or should they utilize unique methods of determining ascent speeds not described in this paper, they would still have to have the ability to exercise precise buoyancy control to control ascent speeds. One of the premises of this presentation is that the vast majority of certified divers lack buoyancy control skills necessary to implement ascent procedures prescribed, without using ascent lines.

Unless it is demonstrated by physicists and/or physiologists, and/or case histories of decompression illness that ascending at 60 fpm is a major contributor to "Bends", the possibility of staying with 60 fpm maximum ascent rate is worth consideration. It would be consistent with past diver training and knowledge. It would eliminate inconsistencies which exist and have the potential to increase. It would be more compatible with diving practices, and easier for divers to execute.

Whether the best "bends prevention ascent rate" proves to be 60 fpm, 40 fpm, 33 fpm, 20 fpm, or some combination of all of these, certified divers need to develop better buoyancy control skills than we are seeing today. I personally believe that the fundamental problem is lack of buoyancy control skills, and that certified divers all too readily exceed 60 fpm by 100% to 300%.

If it is demonstrated that all divers should ascend linearly at controlled speeds, including 20 fpm, we will need a revolutionary change in diver training. If varying rates of ascent, 60 fpm being the maximum, complemented with stops proves to be viable, training agencies should be encouraged to beef up and modify buoyancy and ascent training and certification standards.

A principal cause of buoyancy problems is the wet suit. It is buoyant and compresses and expands with changes in surrounding pressure. The thicker the suit, the more weight the diver has to wear. The greater the compression and expansion, the more difficult it is for the diver to control his buoyancy, especially during the ascent. More weight + more compression = bigger buoyancy compensators, which compound buoyancy control problems. If it were possible to produce a wet suit with adequate thermal protection that required less weight, and compressed and expanded less with changes in surrounding pressure, buoyancy control would be significantly easier. Divers could wear less lead. They could wear and use smaller buoyancy compensators. They would experience smaller changes in buoyancy as they changed depths.

Nonetheless, with or without less compressible wet suits that require less weight, it is apparent that entry-level divers need more instruction and training in buoyancy control. Buoyancy control problems are minimal in tropical waters when divers are without wet suits. However, a myriad of certified divers without wet suits continue to overweight themselves and power inflate buoyancy compensators that subsequently mimic wet suits and compress as they descend. More air is injected at depth....

Recommendations

1) Manufacturers could work to create wet suits with less buoyancy and less variability in thickness with changes in depth.

2) Start a trend in diving - wear less rubber - wear less weight - wear smaller buoyancy compensators - Grade divers by their ability to use the least amount of air in their BC and to demonstrate precise buoyancy control, not by how deep they have dived.

3) Encourage certifying agencies to incorporate more and better buoyancy control and ascent training. The overweight - compensate - with - inflated - buoyancy compensator system has got to go. Student divers in pool training need to physically experience the sensation of diving with no or little air in the BC and how breathing affects buoyancy. They need to understand that selecting the optimum amount of weight for a dive is a thoughtful task, and that changes in equipment, or depth need to be considered.

I have dived with and observed experienced divers using dive computers that regularly exceed prescribed ascent speeds. They seem to lack the patience and self discipline, as I do, that it takes for a diver to consistently ascend from 60 ft to the surface at 20 fpm. I tend to believe that most divers will experience similar problems. Ascending at varying speeds, not to exceed 60 ft/minute, adding "extra ascent time" to bottom time, making a stop and taking 30 seconds to ascend the last ten feet, has been a viable system for me.

And finally, I would like to take this opportunity to thank the American Academy of Underwater Sciences (AAUS), the Diving Equipment Manufacturer's Association (DEMA) and the NOAA Office of Undersea Research for organizing and making this Biomechanics of Safe Ascents Workshop possible, and for inviting me to participate as a speaker.

References

Hendrick, W.F. 1988. Buoyancy Control. November/December issue of Scuba Times magazine.

Recreational SCUBA Training Agencies' Ascent Training Policy Statements

Discussion Leader: James R. Stewart

Panel: Dennis Graver, Jon Hardy, Jay Hytone, Drew Richardson.

Jim Stewart introduced the panel and asked Dennis Graver to start off with the training agency's policy statement on ascent training.

Dennis Graver - National Association of Underwater Instructors (NAUI)

I am the Director of Education for NAUI, a Headquarters staff position. For the past two years, the NAUI Training Department has been working with an ad hoc committee of dive table experts to update and modernize the NAUI Dive Tables. Several aspects of this project relate to ascent practices. There are two primary types of ascents - swimming and buoyant. NAUI's policy is that all non-emergency ascents are to be swimming ascents.

Problems associated with ascending include gauging the rate, controlling buoyancy, arresting an ascent, maintaining buddy contact, avoiding entanglements and obstructions, and potential physiological problems including air expansion injuries and decompression sickness. The problems convert into training goals. A capable diver should be able to control and arrest an ascent at any time, to monitor and gauge correctly the rate of ascent, to maintain neutral buoyancy and buddy contact throughout an ascent, and to avoid entanglements, overhead obstructions, and physical injury.

The NAUI Openwater I Scuba Diver Standards for confined water state that the diver must be able to, "Perform proper techniques for surfacing." This requirement becomes specific only when supported by descriptions of proper techniques in other NAUI literature. NAUI Openwater I Scuba Diver Standards for open water training are more specific, however, and specify that a diver must be able to, "Ascend at a steady rate of approximately 60 feet per minute while controlling the buoyancy compensator to maintain neutral buoyancy." This is what the diver must demonstrate to meet the requirements for certification. "The NAUI Textbook" (page 112) states the following procedures for a normal ascent: 1) "maintain neutral buoyancy"; 2)"rate should not exceed 60 feet per minute"; 3)"should not pass smallest bubbles"; 4) "time ascents and compare to gauge"; 5) "look up and around"; 6) "extend hand overhead"; 7) "maintain buddy contact".

The following recommendations are included on page 89 of "The NAUI Textbook":

1. Perform a three-minute safety stop at a depth of 15 feet during any dive approaching the Maximum Dive Time (previously called no-decompression limits) and at the end of all repetitive dives to depths of 60 feet or greater.
2. In the event required decompression was omitted from a dive, refrain from further diving, rest, breathe 100% oxygen if available, watch for symptoms of decompression sickness, and proceed to the nearest treatment facility if symptoms are suspected.

The following training methods have been developed by NAUI Instructors, and are recommended. Students need to learn to perform slow, controlled ascents in a pool, but most pools do not have sufficient depth to provide realistic training. By tethering a float placed in the center of a pool to the shallow end and stringing a line diagonally from the float to the deep end of the pool and having students follow the line to the float while learning ascent procedures, the distance and the learning are increased. Students are asked to swim the length of a pool horizontally simulating an ascent and to surface at the opposite end. The instructor times the swims, informs the students of their rates - which are usually nearly twice as fast as they should be - explains the correct rate is one foot per second, and asks the students to repeat the exercise in the opposite direction. The students swim more slowly, but even then usually swim the length of a 75 foot pool in about one minute. This exercise impresses upon the students just how slow the maximum rate of ascent is. During the first normal ascent performed in open water, the students are instructed to ascend with the instructor, to mimic his or her activities, and to observe carefully and match exactly the instructor's rate of ascent. The instructor ascends at precisely the correct rate by carefully monitoring instrumentation. This gives the students an opportunity to both witness and experience a proper ascent.

The first time students perform normal ascents where they gauge the rate themselves, their ascents are timed by the instructor or his/her assistants and compared to the depth to determine the actual rate versus the correct rate. This information is shared with each student. For subsequent normal ascents during open water training dives, an ascent line flagged every five feet provides a useful reference for students. As a student passes a flag, he/she can count "one-one thousand, two-one thousand", etc. and should not pass the next flag before reaching "five-one thousand". Students should be taught and required to perform hovering stops at a depth of fifteen feet for at least three minutes. As part of the training for the NAUI Openwater II Scuba Diver rating, students should learn to perform continuous neutrally buoyant ascents as described in "The NAUI Textbook II", pages 11-12.

NAUI's current requirement and recommendations for normal ascents include neutral buoyancy throughout ascents, a maximum rate of 60' per minute, the need to carefully gauge the rate, the ability to arrest an ascent at any time, a stop at 15 feet for three minutes for all dives where excessive nitrogen may be a concern, and a new policy to stay out of the water if required decompression has been omitted. Input regarding NAUI's ascent policies and recommendations is requested from the experts present at the AAUS Biomechanics of Safe Ascents Workshop.

Jon Hardy - SCUBA Schools International (SSI)

I am representing SSI and besides being an instructor with SSI and all these other agencies, I am a consultant to SSI, not a Headquarters staff member. First, a little bit of philosophy on SSI's position on this whole ascent question and skills in general. The interests of the student/customer come first, before the interests of the store, instructor or the agency. Next, in any skill there are two criteria the association has used to decide whether those skills will be used or not. Those two criteria are: Is it a real function of open water diving and does it work under difficult conditions. Therefore, no skill is in the regime for training unless it's a real function of open water diving, and it will work under difficult conditions. The final piece of philosophical position is that the instructor has flexibility even though there is a prescribed teaching program, the instructor is told that there is flexibility within that and given examples of it.

Not quite so regimented, but to parallel some of what Dennis has provided you with for NAUI, normal ascent procedure includes the following things with SSI: A regime of classroom that includes both the spoken word and required audio visual materials, taken to the pool in which only open water skills are practiced, and those open water skills are then taken to the open water training. I see a little bit of concern where some of us seem to differ on the next one. SSI pushes a combined BC use / swimming ascent. That does not mean it is a "buoyant ascent" as we would talk about buoyant in emergency ascent training. What is prescribed in the manual is that you achieve neutral or slight positive buoyancy on the bottom and then you start your ascent. I would suggest that is in the one to three pound range Walt was talking about. You thus control the ascent rate by venting on the way up. This is what the instructors are to achieve with their students. The ascent rate is done at 60 fpm and there are phrases in the instructor manual very similar to what Dennis has extracted from the NAUI materials. It says in one place not to exceed 60 fpm. It does not deny any slower rates. The slower ascent rates are in the instructor training courses, but not in the student materials. There are references to small bubbles, to using a watch and to using a dive computer. The current revision of the student study guide has a safety stop at 15 fsw for 3 min. when you dive in excess of 60 fsw.

All of the SSI tables, which are reproductions of the U.S. Navy tables, have the decreased no-decompression limits indicated on them. They also have a warning published on them that you may get bent using these tables and that they should be used conservatively.

Normal ascent training is done in a series of steps during open water training. The first two dives are not to exceed 40 fsw. No dive is to exceed 60 fsw during training. All the agencies agreed on this maximum of 60 fsw. SSI is just a little more conservative, you can't go past 40 fsw on the first two dives. During ascents in openwater training, students are not to orally inflate BCs. They can deflate, but are not to orally inflate. Students use a power inflator to inflate and then either the oral or rapid dump to deflate.

All ascents are to be started at a normal state with 500 or more psi and, one that I don't see in many textbooks, is a pause before you initiate the ascent. You stop, make contact with your buddy, communicate in some manner, then initiate the ascent from a pause. Then, the usual: Look up, turn around, hold your hand up, hold the mechanism for deflation of your BC in your line of site and, of course, stay with your buddy. I've tried to cover all the points Dennis covered.

Jay Hytone - YMCA SCUBA Program

I represent the YMCA. I am not an official staff member of the Y, I'm a volunteer as the majority of the Y board and field coordinators are. The YMCA, being an inherently conservative organization, appears to have standards that are also very conservative. We've been advised by counsel because of the threat of legalities all the time, that we need to be very careful when establishing firm figures in our standards. Therefore, you will not see anywhere in our standards that we recommend 60 fpm, because the position is if we say what you should do, then we're also obligated to make sure the instructors do it. We know that's not possible, because we know that is not happening.

The following YMCA policy statement was prepared by Frankie Wingert, National Scuba Director: Recreational diving is to be no-decompression diving. Safety decompression stops as a safeguard against decompression are encouraged, but planned, required decompression is not condoned for any reason. The U.S. Navy dive tables are recognized as the basis for dive scheduling, but studies have shown the no-decompression limits of the Navy tables can result in decompression sickness. A modified no-decompression limit which is two repetitive group designations less than the Navy limit is recommended for all depths. Multi-level dive table calculations are not condoned. The use of electronic dive computers to permit multi-level diving is permissible, but only if such instruments are used strictly according to the manufacturer's instructions and recommendations and only for no-decompression diving. The computers should be monitored and the dive controlled in a manner that will permit a direct ascent to the surface at any time. The YMCA Scuba program stresses that with the vast unknown areas of human physiology, teaching of scuba diving students in the area of decompression theory must include practical conservative adjustments to the tables we are provided.

In training, we have buoyant and swimming ascents called for both in the pool and in open water. We do have prescribed a specific way in which the instructor will obtain this. We do give our instructors extremely wide latitude in meeting the standards. The YMCA felt that was very important because of the wide variety of training conditions we run into around the country. There are holes, shall we say, that need to be met, and I can suggest from what we've gotten here this weekend I'm certainly going to be making some recommendations to expand the intent of our policy on ascent. We spotted the fast ascent rates approximately ten years ago when we were doing the scuba life saving and accident management research and other than develop flaring practices and things like that as part of the scuba life saving program, and requiring all of our instructors to become certified in that, it was simply our presumption that this would therefore filter down to the students being trained. We have unfortunately done no specific research which would communicate whether that has or hasn't happened.

Drew Richardson - Professional Association of Diving Instructors (PADI)

I am the Director of Training and Education for PADI International. Physiologists have reason to believe that many diving accidents resulting in the need for recompression therapy are caused by too rapid an ascent, not excessive tissue pressure. These accidents often result in neurological decompression sickness (Type II) and are treated as such. I present a discussion of the ascent-rate issue for your consideration as a diving educator. While it is not important that students understand the physiological rationale behind the ascent rate, in the interest of improving diving safety, it is important to focus public attention on this area, since it appears to be ignored by many divers. **The time has come to encourage all divers to slow down on ascents.** During the past several years, statements have repeatedly been made that many divers ascend at rates well in excess of the recommended maximum rate of 60 feet per minute.

In a recent Skin Diver Magazine editorial, Bill Gleason published the results of his casual personal observations of divers ascending during several dive trips he was on. His observations support the concern that divers may not be making slow, safe ascents. He observed that while all of them started up slowly, they didn't finish slowly; some individuals were ascending at almost twice the prescribed maximum (60 feet per minute) rate. Only two buddy teams took longer than the 60 fpm rate, and both of them stopped for a safety stop. The conclusion is that many rapid ascents appear to take place from 30 feet to the surface. It is at this depth that a diver needs to be most careful, since the relative pressure change to the surface is great and overexpansion injuries are of the highest concern. "The greatest danger from gas expansion in the lungs occurs near the surface, where the rate of volume change for a given range of ascent in the water is greatest," wrote Dr. Alfred Bove (Skin Diver Magazine, April 1988). PADI has always insisted on strict adherence to an ascent rate not exceeding 60 fpm, and that a slower ascent rate is always acceptable. To ascend more rapidly is potentially hazardous. Many experts are calling for ascent rates slower than 60 fpm, yet this ascent rate works quite well **when practiced.** Unfortunately, it appears as if recreational divers are not practicing this rate. While slower ascent rates certainly will help, it does not mean the maximum ascent rate of 60 fpm is flawed. The problem lies not in the theory, but in the practice. In an effort to further promote slowing the ascent and diver safety, it is PADI's recommendation to make a safety stop of three minutes at 15 feet on every dive.

A classic example of a cause of a pulmonary overpressurization accident: A diver who is ascending to the surface comes up too fast, breathes improperly or holds his breath. A typical medical example: In some cases, no evidence can be found of improper exhalation. It is thought that the diver may have a congenital defect or other lung problem. For this reason, it is crucial that the Medical Statement be thoroughly screened to identify asthma, emphysema, chronic bronchitis, any gas-filled cysts in lungs or chronic obstructive airway disease. Any history of these problems can cause parts of the lung to trap air. Refer all such indications to a physician familiar with diving medicine before the student uses scuba. A theoretical example might be: Any local airway obstruction can trap air during ascent and increase the risk of gas embolism.

Let's suppose a diver ascends too rapidly to the surface. Between 30 feet and the surface, he experiences a dry mouth. He swallows. If he happens to have a full lung of air when he swallows, he has, in essence, closed off his epiglottis - the same physiological response as holding his breath while ascending. Take a moment to swallow. Think about the physical effect. Now, take a deep breath and hold it. Physically, the response of closing off the epiglottis is similar. If the diver were asked if he held his breath, he would answer, "no". Nevertheless, closing the epiglottis constitutes holding your breath if combined with a fast ascent, and could prove damaging. While it is not reasonable or practical to encourage divers not to swallow while ascending, it is practical to encourage them to slow down. The simple act of swallowing during a controlled slow ascent would not pose such a serious concern. In a psychological sense, a diver who begins ascending slowly from 90 feet may feel he is just about on the boat by the time he reaches 15 feet. If the ascent is not controlled and too rapid at this point, and the diver swallows with a lung full of air, it may pose serious consequences. Pulmonary overpressurization accidents are not accountable in the Haldanian scheme of things. They become a function of Boyle's law. Decompression theory deals with dissolved gas in the blood and tissues. When you get a rupture of alveoli, you can get gas injection into the arterial circulation. Then you have what is, in essence, a "non-Haldanian" decompression incident. Some diving physiologists are concerned over what they see as a trend in the recreational diving community: a relatively large number of divers who have some type of neurological decompression sickness (or Type II) relative to bends (or Type I). The number of Type II occurrences are thought to be far more than what should be there from the design of tables alone. In the testing of a table, you seldom see neurological decompression sickness. One of the prime postulates or axioms in decompression table calculation and testing is that if you avoid Type I decompression sickness, you will almost always avoid neurological decompression sickness.

In the design of the Recreational Dive Planner, the ascent rate of a maximum 60 fpm was deliberately chosen due to the fact that it has met the test of time well when practiced. If anyone wants to go slower, they should be encouraged, as it won't interfere with the operation of this particular model. Slower ascents were calculated for the Recreational Dive Planner model by Dr. R. Rogers, and it was his determination that they would not have any adverse effect, and probably would have a beneficial one. The critical issue then becomes one of getting divers and ourselves to control our ascent rates during all ascents (including Emergency Swimming Ascent training), and never exceed 60 feet per minute.

PADI is a worldwide agency, reaching over 80 countries and certifying over 400,000 divers through our 24,000 members. With this size comes strength. Through our worldwide membership, we deliver the PADI message of safe diving practices and quality education. Along with this strength comes a responsibility to continually take a leadership position on diving safety. The significance in reestablishing these truths lies within our ability to deliver a worldwide message. If there is a significant message to deliver within diver education, there is no single instructional agency better equipped to do this than

PADI. PADI has a mission to accomplish, and the PADI Instructor has a message to deliver to those they influence. In an effort to address the issue of rapid ascents, the PADI Training Department announced the Slowly Ascend From Every dive (**S.A.F.E.**) campaign in 1988. The message was simple: Rise slowly and level off. Encourage all divers to: Rise slowly. Think about slowing down on ascents by controlling their buoyancy, timing their ascents and going at a maximum rate of 60 fpm or slower. **Level off:** Make a safety stop after every dive for three minutes at 15 feet. By "imprinting" this practice on divers, they will have a natural tendency to vent BCD's on ascents and slow down in the most critical zone - 30 feet to the surface - knowing that they must control their buoyancy to stop for three minutes at 15 feet. This time will also increase diver safety in the event that the diver misjudged maximum depth of the dive either through error or an inaccurate depth gauge. It will also compensate for ascending too fast. If divers are conditioned to take a safety stop on each dive, they will have a tendency to slow down and stop, avoiding the danger of rapid pressure reduction during the last 15 feet.

As an individual, you can't influence the whole world, you can only influence yourself, your students and your dive buddies. Over 24,000 of us in over 80 countries can join forces by promoting the PADI S.A.F.E. diver campaign to at least two thirds of all new divers certified annually and several hundred thousand certified divers whom we dive with and around. You have a message to deliver. Promote the PADI S.A.F.E diver campaign in your area. Together, let's all do our part to improve worldwide diver safety. Let's all help each other to slow down and **slowly ascend from every dive**.

Frequent questions and answers regarding the S.A.F.E. Diver campaign are: **Q.:** Why create a campaign around such a well-established diving safety guideline? **A.:** One could ask the same question about recent safety campaigns to discourage drunk driving or smoking. The dangers of these practices have been publicized for years. However, people still engage in these activities, just as many divers ignore the 60 ft per min or slower rule of ascent rate. Also, this issue now has even greater significance because of recent theories that point to lung expansion injury as a possible consequence of rapid ascents, even if the diver is exercising proper breathing techniques. **Q.:** Why 60 ft (18m) per min? Wouldn't it be wiser to recommend an even slower ascent rate? **A.:** As always, PADI's position is to promote the safest recreational diving guidelines available, based on the most up-to-date information. Hyperbaric research and testing conducted by PADI and DSAT indicates that the 60 ft (18m) per min or slower rate of ascent is still conservative enough to be considered safe. (*i.e.* Powell, Thalmann). Also, remember that 60 fpm has been the rate of ascent recommended by Navy-based tables for a number of years, and has stood the test of time rather well. Note that PADI recommends a 60 fpm or **slower** ascent rate. The 60 fpm limit should be considered a maximum rate of ascent, just as no-decompression limits are the maximum amounts of time a diver can stay at given depths. In both cases PADI recommends that divers stay well within these limits, as an added measure of safety. PADI also recognizes that it is more convenient for many divers to ascend at a rate considerably slower than 60 ft (18m) per min. For example, many divers who use metric gauges find that 12 or 15m per min ascent rates are easier to monitor (18 meters equals approximately 60 feet). Several of the dive computers on the market prescribe extremely conservative ascent rates; naturally, users will want to abide by them. **Q.:** How do I influence divers to heed this rule? **A.:** First and foremost, emphasize the importance of this rule to open water students, as well as to students at all levels of continuing education. Stress proper buoyancy control and ascent techniques during all phases of diver training, not just when those particular skills are being focused on. Set an example to fellow divers by demonstrating slow ascents and routine safety stops on every dive. Displaying the S.A.F.E. decal on your tank will show students, and fellow divers alike, that you are committed to this campaign.

Discussion following panel presentations

Walt Hendrick: I think the major concern is lack of proper buoyancy control, as well as improper weighting. Walt pointed out a comment Dennis Graver recently published in NAUI's Journal of Underwater Education: "The problem of incompetent divers is readily apparent to resort operators who no longer accept c-cards as proof of diving abilities. The resort professionals are crying out for better trained divers".

Dennis Graver responded that the agencies can put out good philosophy and good training materials. Getting the instructors to do it is a whole different story, especially when instructors bounce around from one organization to another. Instructors who say they know how to teach and they'll do you a favor by issuing your card without bothering to find out what the philosophy, the standard, the training recommendations and requirements are, makes it very difficult for any organization to enforce. Unless an instructor violates a specific standard and someone cares enough to report that, it becomes very difficult to become aware of the fact that someone is not training a student properly relative to ascents or buoyancy control. It would be extremely costly to get into field monitoring situations. The whole competitiveness of the training organizations takes away such things as creating a situation like they have for other types of instruction where the same instructor who does the preparatory training is not the instructor who does the evaluation for certification. I think there may be some measures that could be taken to ensure that the instructors are in fact teaching what the agency lays out but I'm not sure anyone is really exercising anything that is significant enough to impact on that currently.

Jay Hytone believed one of the big problems and obviously the problem being discussed, is ascent training. I think that all the agencies have probably only recently begun to address the problem. You are dealing with an exercise that is extremely difficult to teach and with two perceptions that human beings are very bad at: short periods of time and vertical distance through the water column without a plane of reference. It is very difficult to develop any kind of training program that can consistently improve the average diver's ability to do that without taking horrendously long periods of time and I'm not sure, even then, that we could do it. When Dennis writes and says, yes, there are a lot of bad divers out there. The conception, I cannot believe, that when the instructor certified that diver, he said: Well you're a bad diver, but I'm going to give you a card anyhow. That must be untrue. I think what happens is, the instructors, in putting together an entire course to provide "basic level scuba instruction" do as well as they can within the other things that control them (the time they have in the water, the time available for classroom, the expenses they run into in creating this class). When a problem presents itself, then everybody gets excited and says we better attack that, which is what happened here.

Drew Richardson responded to Walt that he felt we could definitely make a difference, but that it would obviously take time. One thing you look at is whatever data you can get relative to accidents, fatalities, etc. and look at trends there. Based on that data, it would appear that diving is becoming an increasingly safer sport with each passing year, as the number of divers is increasing, so generally we're doing something right. We all strive with workshops such as this to verify that and maximize that. One person injured or dead is one too many. With the data suggesting that diving is becoming safer, you could argue to the operators that are crying out about better trained divers, what their expectations are. We're dealing with a greater cross-section of our population, the general public that has choices between recreational diving and other activities. Their motor skills, although at the time of student certification most instructors are ethical, have met the performance requirements for that agency deteriorate over time. Those skills are renewed pretty quickly with the diver under supervision or back in the pool, but the expectation of some of these operators could be criticized as an attitude that is not embracing for the consumer coming to them for a service. That is one way of looking at it too. The ski industry, which may not be the best to compare the scuba industry to, does not criticize the individual who feels he is a skier but hasn't been skiing for years and snow-plows down the hill. They don't expect him to be the downhill slalom champion. On the other hand it is more of a service attitude. Some of that I would take issue with relative to what the expectation is. The other side is when we look at the data from DAN or URI, we look at trends and try to respond to those through the channels we have as trainers.

Jon Hardy: Most of you know my other business is a dive service on Catalina Island which does commercial work as well as take hundreds of tourists diving every summer. It's like a tropical resort put in cold water with full ocean gear and wetsuit. Times are changing, with many people diving only once in a while. They can't get the regulator on the valve, they can't get the BC on the cylinder to start with. They were well trained at one time by conscientious instructors in good programs. But diving is not the center of their life, they come back once in a while. We have to shift to much more supervised diving. There are a bunch of us out there who keep seeing these inept divers diving. Thank god they go with us, because if they went off on their own, we would have a higher accident rate. We constantly prevent or preclude accidents through an intervening hand where it doesn't become a near miss or a fatal accident because we have vastly more supervised diving than we did years ago. Look at the distribution throughout the industry. We have a lot more supervised diving which is making it safer for the industry. All that means is we have to redirect ourselves with how we handle things.

Walt Jaap commented that his bottom line was proficiency maintained through practice. In AAUS research programs, a diver has to make a certain number of dives per year to maintain his credibility and ability to dive with the organization. If he doesn't do that he has to return to a refresher program to make certain he has the ability to do that. In the recreational community, you're not set up to do that. Another comment is with the increasing number of divers, we're seeing more damage to natural areas and would like to minimize the impact on that habitat. That is another reason to improve a diver's buoyancy control.

Bill Oliver observed that many divers don't know what their own expectations and responsibilities are. I serve on a subcommittee for DEMA to look at ways to improve warnings on products. The bottom line is that a diver really has responsibility for his own safety. DEMA is considering initiating a campaign to make divers aware that they are responsible for their own safety. I would like to see cooperation between DEMA, AAUS and the recreational agencies to make it a united program. Drew stated that Bill made a very positive approach to it. All the agencies have in place now for safe diving projects were some documents that the student signs saying they will also assume the risk after training. We could use something stronger though.

Dick Long felt that Bill's approach was good but in addition needed to address the rank and file diver, not just the new student. It should be non-denominational, AAUS should endorse it, all of the instructor organizations, and it should raise the awareness of the diver's responsibility for their own safety in addition to their responsibility towards the environment. Jim Stewart said it was ironic we finally would come to this conclusion. AAUS has always had the position that the ultimate responsibility for safety rested with the individual diver. That statement is clearly written into the AAUS diving safety manual.

Mark Flahan posed the following equipment question to the panel: Would you recommend to your particular agency to require that when students go through training, they use a depth gauge and time keeping device or dive computer to monitor their ascent rates? Dennis Graver: I believe that it should be required and have recommended it to the NAUI BOD. Jon Hardy: SSI has already made a move in that direction. Instructors have been for two years now been required to have complete instrumentation. Mark: That was the recommendation of the Recreational Scuba Training Council (RSTC). Jon: Yes, In addition, SSI recommends the instructors do it with their students. The next step would be to make it a requirement. Jay Hytone: Essentially we have the same position. We require any instructor on an openwater dive to have full instrumentation. We keep our ratios in the water down so that the students have the opportunity to watch the instructor use that equipment properly. We don't require the student to have full instrumentation and to implement that, it would be my guess that it would have to be an industry wide move of some kind. Drew Richardson: That is what came from the industry-wide agreement in 1986 for the student and the instructor standard comes from the RSTC. I don't think you'll find any opposition. I recommend as a member of RSTC to perhaps interject that for consideration.

Don Harper: Can you isolate if your general acceptance level of student performance for certification is too low? It seems everybody passes the scuba certification courses, why are so many considered unqualified? Drew Richardson: I don't know that screaming for better divers is such a wide spread thing quite honestly. I think that in response to that perception in 1986, the agencies got together to create a consensus document as far as minimal instructional standards. As far as divers not passing, from a performance-based approach, assuming the candidate was medically fit, they could attempt forever, if they chose to become certified, they would not be released from an agency unless they successfully mastered the motor skills required to dive independently of an instructor. Dennis Graver: No comment for the record. Jon Hardy: We have a dual problem there. We have the old instructors in the field, the guys that are so proud that they have been teaching for thirty years, and haven't changed one iota during that course of time. How do we bring them on line? Some of them by the way are in the scientific community and they teach and requalify these scientific divers to do the same skills in the same obsolete way that they did for twenty years is really not appropriate either. Times have changed. I agree with Dennis, whether we're on or off the record, the quality of the instructor training is really significant and we need to somehow get beyond simple, mechanical training of people to execute skills and get inside their heads and find out what truly makes an instructor. We talk about ethics and I gave examples of some of the major ethics problems that occurred in our industry and they had to do with instructors who were top candidates in our courses, but could not perform high quality ethical operations in diving. We need to take some new incredible quantum leap in how we train instructors. We have really good instructional materials but somehow we need to take another step to how they most effectively really cause this behavioral change to experience.

IMPACT OF TRAINING ON ASCENT RATE SESSION DISCUSSION

Discussion Leader: James R. Stewart

Jim Stewart

It has been my pleasure to have been involved in diver training for quite some years now., Actually, Archimedes and I.... It has always seemed to me that anytime you start training a basic diver, you start hammering on certain concepts such as: Never hold your breath while ascending. That is one of the major items stressed in any diving class. If you forget everything else, do not forget to not hold your breath when you come up. You may have to come up in a hurry, but at least you can minimize problems. When you start teaching the slow ascent rate to basic students, it's the same as teaching them not to hold their breath when they come up. There are certain do's and do not's in diving and ascent rate violation is certainly as important from a different perspective as breath holding.

Discussion following Andy Pilmanis' presentation

Regarding the accidents on the Russian research cruise Jim Norris added that Smithsonian personnel was on board and said the Russian group didn't have dive partners or any dive tables to use. Andy: They do have treatment tables. Jim: That is probably why one diver is now crippled. Andy mentioned the treatment table of 380 fsw on air to start with. Mike Lang added that after the incident the diving operation had been shut down for a while, the Soviet Chief Scientist commented that the scuba equipment had been checked out and was not malfunctioning, therefore diving operations could resume as they were.

Glen Egstrom asked if Andy had any indications of susceptibility with regard to the patent foramen ovale? Andy responded that the Catalina Chamber really didn't have the capabilities for that kind of research.

Dennis Divins asked why "equipment malfunctions" was not listed as a cause. Andy responded that in fifteen years he could only remember two clear cut equipment failures. One was a guy who dropped to 100 fsw with a Farallon scooter, turned it on and wrapped his regulator in the prop. Then he proceeded to make a free ascent dragging the scooter at the end of the regulator to the surface. He embolised. The other one was a complete shut down of a ScubaPro Pilot regulator when it was a prototype. Those are the only patients. There is a grey area though. Buoyancy control is an equipment problem. I can't remember any failure per se of the equipment, but certainly, it's been involved. The same goes for dive computers. The diver always comes to the chamber saying: "That damned thing bent me." Then you ask him if he looked at it during ascent and he asks if he was supposed to. Even to the extent of the boat skipper who told us he didn't think much of those dive computers: "When I see these divers come to the surface, climb on the boat, look at the thing and swear, then tie a string to it and lower it to 10 fsw..." I don't consider those cases equipment failure.

Mark Walsh pointed out that on the new Pro Plus you do have access to the dive profile and if you do violate the DC limits, it will replay that for you. The only trick is, because it's still operating, it needs to remain wet. In the instruction manual we tell users to either moisten their fingertips or keep it in a mask. Andy: Considering that a larger number of patients arrive by Coast Guard helicopter, it's lucky to get any equipment there, much less a wet dive computer. That's going to be a problem. Mark: That's as far as we've been able to take that one, but it is recallable.

Woody Sutherland: How much of a multi-day problem do you think the susceptibility versus a change in risk factor of the tables? Andy: I don't know.

John Lewis: When you put up the category of multi-day diving, is the presumption that problem happened on the first dive of the day in a series or could it be anywhere? Andy: It could have happened in the middle of the week and they continued diving. Oceaneering's experience in the commercial field is they had a job once where they were diving every day for two weeks on air. They were diving beyond that and noticed that at about ten days they'd get a hit. They solved it very simply by shifting the crews. It has eliminated the problem. There is some additional evidence out there that multi-day problems exist. Walt Jaap commented that a lot of the scientific programs are very mission oriented. We go out on these activities where we have a window of fifteen days in which to work. Would you say it's good to go for four or five days, then take a day break? Anything I say is strictly arbitrary and a guess, but what we did at our lab is say for every three days of diving, take one day off. If you plan your activities around that, then no one really gets upset. But that's arbitrary. Jim Stewart made the observation that when you have a ship scheduled for a two week cruise and you get out there on station, the diver's will take advantage of the ship time, especially when you're paying about $12,000 per day for ship time. Andy wondered what it would cost to treat them? In addition, they may not be able to finish the project.

Discussion following John Lewis' presentation

Glen Egstrom stated he would have to presume that the reduced ascent rates would reduce the problem of embolism. John Lewis: It started out at zero. You don't get negative numbers. You have going in for you thirty years of Navy experience using that procedure. If you don't like that because of lack of control, I can give you every controlled experiment that I can name, all of them with a 60 fpm ascent rate, and absolutely no incidence of air embolism. Glen: I didn't realize you were talking about a 60 fpm. John: This is all based on the presumption that I have to defend the 60 fpm rate of ascent, which I think is a fine place to be. Bill Hamilton: Also, if you do the safety stop, then you force buoyancy control. Therefore, reduced ascent rate is not the only way to reduce risk of embolism. John: I should have brought that back and started with the premise that the Navy 60 fpm rate of ascent could rule out an air embolism and, given that, I could focus on decompression sickness as the issue.

Bill Hamilton: I think you brushed Thalmann under the rug too abruptly, or maybe you have access to different numbers than the ones I'm thinking about. In the North Sea, Tom Shields did an analysis of some 25,000 commercial dives, of which 6,000 were no-stop. This doesn't mean they were all to the limit, but they were listed as no-stop dives and there were only six cases of DCS in that group. However, the were all type II. What has been read into that at the Physiology of Decompression workshop at Duke University last year, is that there's something peculiar going on in some cases. We've mentioned the patent foramen ovale, the heart defect which allows blood to go from the venous side to the arterial side, which might be one explanation or maybe just pulmonary failure of the lung to stop the bubble. The case has been made that the limits as they are written work. Andy Pilmanis: Bill: There may be another explanation in that lots of commercial divers don't report type I for reasons totally unknown to me. Bill: In that analysis, I can't argue that. The data are not firm hard data that you can back up, but as in Chris' data, he gets a whole lot more type II DCS, not because it happens a lot more often, but because that's all that comes in. Andy: I understand, but I think that kind of information is hard to super impose to make the jump to the limits. John: Bill, you were going to focus on Thalmann and then got off track. Bill: That is some of the evidence. Thalmann defends rigorously the Navy no-stop limits as being alright as they are, with a 60 fpm ascent and without reducing the numbers. John: The only point I made here is when you try to exceed them, you run into some real problems. I would say 4 cases out of 20 exposures is a real problem. Bill: He did a lot more and did show that you could extend them substantially. John: Yes, 66 minutes at 60 feet a few times. Bill: At the workshop on validation of tables this issue came up and lots of people also challenged that, but my assessment at the end was that he and others in his camp made the case that you can question, but you can't really blast. John: Take a look at Andy's experiment. Everybody tries to do it wrong. Thalmann by insisting on a direct ascent. What does it cost us to take a few minutes in that decompression zone and it works? Bill: I'm not challenging that, I personally take the safety stop, if it doesn't work good, then I reduce the No-D limits. John: There's a little bit of tradeoff, but at least qualitatively I'll agree with you. You have to be a little bit careful with this business of long exposures and shallow dives because the numbers begin to fool you a little bit. You look at Andy's data and figure 3 minutes is the world, but it really isn't if your spending 100 minutes at 50 feet. I think that's really quite a different problem. I don't think it's crazy to look at that theoretically although I'll fully accept the criticism that it's an extrapolation, but it's the best thing I've got.

Andy: Did you look at the Navy tables? John: I started with that, in fact, Ron Nishi sent me a number of experiments that they'd done with Doppler. The problem I've got with that is that they're doing a completely different mathematical algorithm, that's just so difficult for me to try to get into, it's like another PhD exercise and try to correlate them and then I don't think you'll get from here to there. They're extremely conservative, although there are dive computers on the market that are even more conservative these days, to the point that I don't think you're going to find most recreational divers accepting those no-decompression limits. In that view he took the position of let's take something that has a basis. It has Spencer's empiricism, it has Rogers and Powell's testing, let' base it on that, use that as our line and then work our way from that. If it happens to go over the line, it really doesn't cost that big of a decompression stop, which is consistent with Bill's argument.

Karl Huggins referred back to what Bill showed yesterday with the No-D times based on the ascent rate and looking at what the final outcome was. He looked at everything remaining constant so get to the surface with the M-values not violating the model. Your question is what happens when you goes past that? The question that needs to be answered with the call for data is does it make a difference how you get to those end points? From the bottom to the surface, what effect does an increased or decreased ascent rate have on the stress placed on the body as you're ascending. Will a reduced ascent rate reduce the stress there although you'll be under pressure for a longer time? John: All of these equations are based on first derivatives. None of the models have anything that resembles the second derivative, so that most that you can hope to do in the context of Haldane is to look at tensions. None of these are very large when you're at depths greater than 20 fsw. All it has to do is with relaxation. Bill Hamilton: Let me commend John. He's a theorist, but he came out with data, and that's where it's at.

Jim Stewart

We were talking about the ascent rates yesterday of submarine lockouts. I had the occasion of almost matching those one time. I found myself making the last dive on the Hannes Keller bell at Catalina. I met the bell at 180 fsw and one of the tasks I had was to cut off an old motor block they had on the bottom of the bell. When I did, that bell had a 300 fpm rate of ascent. We got sucked up with it. I had a set of twin seventies on and just a short rubber shirt and no lead. Coming up through the water column, all I could do with my mask was hold it around my face and bite down on the two hose regulator bit to hold it in my mouth. I came out of the water at the surface up to my bathing suit. I think we had only been down for 5 minutes, but that was the fastest ascent rate I ever care to remember.

Discussions following Pilmanis, Wachholz, Lewis and Hendrick

Glen Egstrom wondered if there were any parameters regarding the stop "zone" John Lewis talked about. John Lewis: While I can't give you specific numbers to the second place, my sense of it is, it doesn't make a whole lot of difference so long as you're in that 10-20 fsw zone. In fact, there is some argument that you might be better off toward the bottom of it rather than the top of it. The top of it turns out to have practical difficulties in terms of sea conditions. Intuitively, minimizing the tension is a good thing to do, therefore, the deeper that you stop, maybe the better off you are. Quantitatively, even on a theoretical basis, I don't think the effective time between about 5 feet makes a difference, I think it's down to the scatter. Glen: This is a very valuable point. If we could, with reasonable justification, recognize that stopping and holding at 10 fsw has been a problem, then if there is in fact a window in there making it good for people to come up on top of the reef, into a shallower dive pattern where they could still enjoy it and not be subjected to a lot of surge, we might be able to do a considerable amount of dive profile adjusting so that they get into the habit of taking the second half of the first atmosphere for offloading gas. John Lewis: I'd be quite happy to quantify, on a purely theoretical basis, what the effective time was spent at a stop as a function of depth in that zone. I think it will turn out to be pretty independent of the depth and you could legitimately add the caveat that it may well be a very good idea to minimize the tension in which case, the deeper the stop the better. Glen: A number of years ago, Eric Kindwall made the observation that by several means you've got very efficient offgassing. Bill Hamilton: You have two things happening here. If you stop deeper, you're going to have a lower driving force for getting rid of gas, but you'll also have less development of bubbles. If you stop later, you have more driving force, but you also have more bubbles and as Eric has shown in the laboratory, not such an efficient outgassing under certain conditions. These are not all big differences anyway, which is what you've just been saying. The reason should be based on psychology or operations rather than on what little difference you get in time in the models. Glen: What strikes me about this if you can still enjoy the dive in some shallow depth, we should assault the diver's consciousness to doing that. Bill: Right, you're better off swimming around, you'll unload more gas. John: Practicality is in this case more important than theory. If you look at it theoretically and say it doesn't matter much, that's fine because it gives you some flexibility. Now, you get down to if you restrict something, it will be violated. Whereas, if you open the window as much as possible, on some other grounds that allows the diver the flexibility to do something intelligent, for example, burn the last 500 psi on the reef you spent $6,000 to dive on for two weeks.

Ray Rogers: John, I think your observations are right, there isn't that much difference. I have done calculations regarding where in the zone you stop for the safety stop, and there isn't any apparent difference within the zone being discussed (30-10 fsw). There are minor differences in efficiency. You could argue it's more efficient at 10 fsw, but it's also more difficult. The important thing though that within this window, you're getting a very important result. The 10 foot increments are not that significant in the range. Andy Pilmanis: Ed Lanphier might corroborate this, but 10 ft was probably the only number Navy divers could remember. Jim Stewart thought Ed had probably forgotten too.

Don Harper: John, you mentioned a descent rate of 60 fpm. John said that was just the way those experiments were set up. In order to quantify the various no-decompression limits. In order to do that, you need to talk the same language. If you use Navy bottom times as time from the surface until you begin a direct ascent, even if you use a safety stop, that depends on the rate of descent too. It doesn't really influence most people though.

Andy Pilmanis asked John if the stop time at 20-25 fsw was then added to bottom time? John responded: I think it's a semantics issue. It has nothing to do with safety. As a matter of fact, in my own judgment, if you're doing anything serious, I mean diving deeply, diving repetitively, diving multiple-repets, you should most assuredly be burning all the air you have in that shallow water stop.

Phil Sharkey: Dave McLean wanted to argue for a slower ascent rate than 60 fpm. He had to leave the workshop but said: From the information from all these talks he had a laundry list for coming up: I ascend through the water column, I look up for obstructions, spin around, I hold my arm up, kick with my fins, breathe, watch my air, check my depth, wonder if I have to make a stop, make a stop, check my gauge at least twice, take a look at my buddy's position, not hold my breath, check my dive computer if I have a ceiling showing up, how much time is remaining on the computer, check my ascent rate, dump air from my BC, make sure my dry suit valve is dumping, compensate my buoyancy with my oral inflator, check my time. I'm doing all this while I'm distracted by fish or the environment, I'm tangled in kelp, there's surge, reduced visibility, I watch my buddy's antics, I'm cold, also tired, I'm thinking about my scientific task, and I'm a relatively novice diver. A slower ascent rate equals more time for me to deal with all the data. Dave wanted to show you a signal that he uses commonly which is: "Out of brains, think for me" (Slashing motion across the forehead, point to your buddy). It's clear that Dave's point about slower ascent rates gives you time to deal with all this.

Mike Emmerman commented to Andy and Chris: Regarding the statistics and accident reports of boat captains as to what they're really seeing out there, versus some of the numbers we use to define how safe this sport is, is it not a disservice to the diving community, to just talk about those cases that you've got in the chamber? Why not highlight to show how safe diving is versus "really talking about the reality", since we know those figures do not represent the true situation? Chris: All I can say is we report the numbers we have. To report anecdotal stories or hearsay would really not benefit the diving community. It's not an accurate picture entirely, but it's the best we have. Andy: I agree. Sea stories belong in the bar, they are not data. What you present to the public should be data. Mike: I agree with you. Data has to be presented, saying this is how safe the industry is, we only had 563 cases out of the universe of divers. The next comment is we're not really sure about either the cases or numbers of divers in this undefined universe. Andy: These are gross estimates, that's all we know. Chris: I think it would be equally a disservice to go the other alarmist direction and say this is only a drop in the bucket, that there were thousands and thousands of accidents out there, which would have no justification. Dick Long: Not only do we have some errors through our methods of collection of data, but so does every other industry that our data is being reported and compared against. Other occupational industries do not report near misses or some of the minor incidences. "Our industry is safe compared to..." If you take all of the potential danger that could occur, the diving industry can be proud of what we do. The fact that we realize the need for improvement and the fact that this workshop is taking place underlines that. We've done a good job so far, particularly when you consider that the diving industry is no older than it is and that it takes place in an environment that is totally uncontrollable by us. We can't go to the public with information that may very well be misconstrued, like the 20/20 deal. We should move forward with programs where we can identify areas where we need improvement and address those needs in-house. We do have the multidisciplinary resources which AAUS has gathered for us several times, from researchers to equipment engineers to training agencies, in order to accomplish that.

Don Harper: What DAN might consider are extrapolation factors to get an idea of how large the total population of incidents are. In benthic ecology, we take a sample out of water and extrapolate the abundance of organisms occurring there, whether it's real or not. You'll find that many divers may not report if they have a shoulder hit or not. Chris: I think the real serious case are being reported. People that are paralyzed or have serious neurologic symptoms are not walking around pumped up with aspirin and bottles of beer. The case we are missing are the mild cases that go away or get considerably better in a short period of time. I think we do have a good appreciation of how safe this sport is. Andy: Another way to look at it is rather than making guesses publicly, I'd rather see education get better so that those people walking around with mild cases realize that it is important and do report it.

Ron Coley: Tom Neuman, President of the Undersea Hyperbaric and Medical Society (UHMS) made the extrapolation very much like Don was suggesting, but he took another tack and said let's establish how safe we really are. Let's only measure something that we can quantify, the number of people travelling to Grand Cayman Island. Let's assume that 80% of these people are going to make the average number of dives and that Grand Cayman Islands represents 20% of the recreational diving that goes on in the America today. What he came up with, just using those numbers, there's at least 5 million safe dives being made per year as opposed to 500 ending in an accident. That is 1 in 10,000. This number is no more accurate than trying to speculate over the number of accidents. Basically, we have just as many questions about how many safe dives are being made as we have about how many accidents are actually occurring. Until you get some type of statistics to counterbalance the other, both are abstractions. My question to Chris is DAN's statistics show that 40% of the accidents are occurring to beginning divers. Is at any given moment of time 40% of the entire population of divers beginners? John Lewis: 40% is a really low number and it struck me that the training agencies are doing a really good job and that the problem focuses on divers really losing their skill levels over time.

Mark Walsh: I wish Max Hahn were here again because he could shed some light on the ascent rates by Bühlmann, whose records are established in Decompression Sickness published by Springer in 1983 and later revised in 1986. I have requested from Professor Hahn and Dr. Bühlmann the ascent rate and validation of their test program. I have yet to receive that. In 1986, those coefficients were changed because of DCS occurring in this earlier model Bühlmann had prior to when he and Hahn worked together. Why is he going for a lesser ascent rate in dealing with altitude? I want to share with you from Altitude Concepts, which puts out tables for altitude diving, every 1,000 ft of altitude, they change their ascent rate. I'll cite those: 1,000 ft (59fpm); 2,000 ft (57 fpm); 3,000 ft (55 fpm); 4,000 ft (53 fpm); 5,000 ft (51 fpm); 6,000 (49 fpm); 7,000 ft (47 fpm); 8,000 ft (45 fpm); 9,000 ft (43 fpm); 10,000 ft (42 fpm); and finish at 15,000 ft altitude at 34 fpm. Bruce Wienke: They compute those ascent rates by taking the ratio of the ambient pressure at altitude to 33 fsw. John Lewis: The Bell-Borgwardt *et al.* work at Lake Tahoe, with the caveat that they acclimatized for 48 hours, made dives to within minutes of the no-decompression limits of almost all the dive computers and agencies accepted today, albeit there are three data points. I'm almost positive those were 60 fpm ascent rates and descent rates in both chamber and lake dives.

Glen Egstrom: I'm curious about having heard several times today the descent rate being 60 fpm. I've always thought it was 75 fpm. John: The only experiments I know of quoted at 75 fpm descent rate were Leach and Barnard in that series. Glen: I believe the Navy tables were set at 75 fpm. John: Thalmann, Powell, Spencer all had descent rates of 60 fpm. It's not a big deal, but if you want to compare experiments, you have to do it with some fixed rate of ascent and I chose 60 fpm because Powell's data is what we make all of our references to. It's not of great consequence until you get beyond 100 ft, because it's within 1 minute no matter what you're doing. Glen: I always thought it was 75 fpm or as fast as you could go. John: That's probably right. It's just that these particular tests were controlled in that way and that's the way they defined the bottom times that they tested.

Bill Oliver: I'd like to compliment Walt for his presentation on buoyancy control. I think I'm the only representative here who manufactures buoyancy compensators. If you're really taught that same control in basic scuba training, it will give us a lot more latitude to build more sensible buoyancy compensators.

Glen Egstrom: As an aside, to the question of why buoyancy compensators seemed to be getting bigger and bigger, I was told that someone had done a study for the British Navy and they wanted to be able to support your head out of the water in a sea state 4.

Chris Wachholz: When table divers do these safety stops on a reef and might spend some 20 minutes between 10 and 30 fsw, the question comes up should they add that to their bottom time for calculating repetitive dives. Dick Vann felt they should. John Lewis: He's super conservative. I know what's going on theoretically and, of course, all the dive computers will keep track of it. It's a dilemma in some sense. I think the worst possible thing that could happen is if you used a hookah and stayed there all day, you could saturate at 20 fsw. I could tell you where that was in each of the tables. Walt Hendrick said that on that dive, the amount of time you spent there was really advantageous, it's the subsequent dive you need to think about. John: That's what he needs it for to get into the next repet group. The problem with that is what you're really doing is loading up the real slow tissues which haven't quite gotten there yet. If you made a really serious repetitive dive and probably beyond most scuba limitations like a hookah dive at 30 fsw, that would come into play. Most of the typical diving that I see is people are doing deep dives, coming back and making a stop. Admittedly, they're using the dive computers to keep track of that. The DCs all do keep track pretty well in those slow compartments. Bob Stinton: Don't the U.S. Navy tables have some kind of a caveat that states if you're going up and there's a disruption of the rate of ascent below 60 fsw, you add that to your bottom time? Above 60 fsw, you would add it to your 10 ft stop. John Lewis: I remember it as any increase in the total ascent time was to be added to the bottom time. Bruce Wienke: With regard to that question, I showed a slide yesterday for a 120 fsw dive for 12-15 minutes. If you add safety stop time at 15 fsw for 3 minutes to the bottom time, then you use the 120 minute compartment to determine your repetitive group and your penalty is very, very small, even for a deep short dive. I suspect that it's even smaller for dives that are shallower. John: Bruce, what Chris questioned though is if you spend an excessive amount of time in a 10-20 ft range such as 30 minutes and whether or not that has any specific role. Bruce: That would penalize you on the repetitive group. John: If you really wanted to do it rigorously, you'd have to do a computation and estimate what that did to your group and it might add a group or something. It might be important for shallow repetitive dives that are really extensive. Chris: I don't think divers are adding that to their bottom time. John: In general, I don't think they should have to. Karl Huggins mentioned that on his table, taking a safety stop at 20 fsw, you added that time to your bottom time and if the addition of that safety stop to your bottom time exceeded the No-D limit for that bottom time, then you were automatically in the largest repetitive group possible. Because at 22 fsw or so is where the 120 minute compartment would max out. If you're at 20 fsw, you're not pulling the nitrogen into your longest compartments to its maximum, towards its M-value. Basically, all I said was you would then place yourself in the maximum repetitive group for your surface interval if your going to take a lot of time at that safety stop.

SCUBA EQUIPMENT STANDARDIZATION
Discussion Leader Michael A. Lang

Panel of representatives of scuba equipment manufacturers: Dick Long (DUI), Bill Oliver (SeaQuest), Mark Walsh (Dacor Corp.), John Lewis (DC's: US Divers, Oceanic), Doug Toth (ScubaPro), Ron Coley (Suunto/SeaQuest), Bob Stinton (DUI), Karl Huggins (ORCA-Edge).

Mike Lang commenced this evening session by stating that the scuba equipment manufacturer's representatives had met over dinner to discuss a reasonable approach to design considerations and future operational conformity, to problem identification due to lack of standardization and to provide the opportunity for exchange of information between the scientists, training agencies, diving officers and equipment designers. This session is an open forum, question-answer opportunity for workshop participants and manufacturer's panel regarding use and design of dive computers, dry suits and buoyancy compensators as they relate to controlling ascent rates.

Mike Lang: This group realizes that manufacturers design equipment to specific configurations to do whatever that piece of equipment was meant to do and that for liability and economic reasons there may be resistance to change, unless a very specific need can be pointed out by the consumer, which will in addition not cause the change in design to limit any future further development of the system. One statement we keep hearing about equipment problems is that people feel we can't attain a safe ascent rate with some of the scuba equipment currently on the market. It was suggested that instead of going about in some way and try to standardize equipment and procedures, we first of all try to find out if there really is a problem in the field and who feels certain pieces of equipment, particularly as they pertain to ascent rates (buoyancy compensators, dive computers, dry suits), or combination thereof, will not let us attain safe ascent rates. The next question is whether we have decided on what a safe ascent rate was? The answer is no, we haven't at this point. For the sake of argument, let us assume a 60 fpm or slower ascent rate for the purposes of this discussion. Who has any problems with the configuration or design of the equipment that is out there right now that will not let us attain safe ascent rates?

Mike Emmerman: The large air volume that we put in these large BC's, with the poor level of training that we see in the field, they're just being used wrong. Mike Lang: Is it an equipment problem or a training problem? I would like to address the equipment problems first. Mike Emmerman: BC's have to be lower volume because it allows for divers to compensate for carrying too much weight because they have this volume to work with, so rather than being taught proper buoyancy, they use this large volume BC as an excuse. Bill Oliver: This year SeaQuest has a line of BC's that are low volume.We also have our other line of BC's that are the same volume as they've always been. What will dictate which one survives is the trained diver bias. If low volume BC's don't sell at all, no manufacturer is going to say I'm going to let my sales go the zero. That comes from training because if the instructor taught that you didn't need any more than 20 lbs. of buoyancy, there wouldn't be a market for a 40 lb BC. Karl Huggins: What seems to be the driving force in going to larger and larger BC's? What was the initial push to start in that direction and why did it continue that way? Doug Toth: The instructors are giving us the input that they want more flotation, not the diving public. The instructors want to be able to float a student with his chest completely out of the water in a comfortable position. Mark Flahan: I don't think the problem is the potential volume that the BC holds, it's how much air you put in it, which depends on your weighting. Personally, I like to have a lot of air available to float at the surface.

Dennis Graver: I feel the inflation and deflation controls should be standardized, especially with respect to locations so that each and every one of them operates the same way. I think the connectors should be standardized too. Mike Lang: Give us an example of why specifically inflation and deflation devices should be standardized. Dennis: Because I've watched people pushing the wrong button when they're trying to get rid of air on the borderline of buoyancy and they start drifting away as they're trying to let air out of the BC. Mark Flahan: Another example is one of the manufacturers has an inflator button that is down low on the side of the jacket BC. Mike Lang: Could a manufacturer respond to that question whether it would be a possibility, standardizing inflation/deflation devices? Bill Oliver: I don't think that for example putting them all on the left side there would be a problem with the manufacturers to be able to do that over a certain time period, but I'll throw out the same caution I did at the dinner meeting. You have to be careful when you start getting really specific about specifying how you want the configuration because there's a tradeoff there, which is that you lock yourself out of future possibilities for changes. I'll give you a good example: If in 1969 the manufacturers would have standardized the configuration of the BC, there wouldn't have been a jacket style or backmounted BC, we'd simply have a little 17 lb. horse collar BC.

Glen Egstrom: There really is another issue here. We're dealing a dollar short with this kind of conversation. I've heard the same position that we were in when we had buddy breathing and then we opened the door, the octopus came in, alternate air source made it awkward for a period to the point where there is no way in this world or the next we're going to regain that ground. What we have to do now is to try and functionally live with these various configurations that are packaged to doing that. I'm wondering if the same kind of thing isn't true for buoyancy compensators. If you look at this year's models, I think you'll recognize that the manufacturers have made some radical departures in terms of how you deal with things. Tekna for example has a dark blue button to go up, or a light blue, I've forgotten, the other button is the deflator. It looks a bit like the keyboard on a saxophone. The issue is that they have a very logical system, it has a pull down dump, a button you push to go up, a button you push to go down, a little thing on the end you can breath off of that is a different configuration than the Air II and some other units, but it is interesting that functionally when you look at what it is you have to do, the two are not that far apart. There are some of them that are radically departed from that. They mount the thing on the other side, or for example all of them that use Soniform valves are functionally generally the same. What we might be better served in doing would be to take a look at buoyancy compensators and see how much of this can we deal with procedurally as opposed to what kinds of things have to be perhaps standardized in terms of design. Those are really two different questions and I don't think we're going to make much progress with the design aspect because that ship has pretty well sailed downstream.

Jon Hardy: A major disservice that the manufacturers do to the consumer diver in the field are those BC's that have no rapid exhaust that is mounted high and accessible to the user of the BC. Therefore, they cannot go into controlling an out of control ascent. In addition, during the normal course of buoyancy control, the diver must go into a vertical position every time and lift the oral inflator up high. That's the only way they can dump air. I don't see that we have to controls always in the same place and always the same way, but I do think that every diver deserves a rapid exhaust that is mounted high and is accessible to the user of the BC. The lack of those create all kinds of problems in the field. Bill Oliver: When you say rapid exhaust, you don't mean power dump? Jon: Correct, I don't mean power deflate. Bill: You need the means to be able to control your buoyancy on ascent within certain parameters, right? Jon: Also the means to control your buoyancy other than strictly vertical. Glen Egstrom: Several years ago, in working with the Navy, I found that there are certain valves that, when you ascend rapidly and dump, you would stop right there. I would agree completely that with large volumes there has to be some way to rapidly dump the air. The other thing that is important is whatever flotation you're going to get, you ought to be displacing water with. The current line of single bladders with the buoyancy held closer to the center of the mass makes very good sense. The buoyancy that is put up around the shoulders buries the diver's head for starters, because the bubble gets higher and higher and creates difficulties. I believe that having the buoyancy closer to the center of mass will, in the long run, result in smaller bladders, because you don't need that much buoyancy if that is the case. Mike Lang: Glen, that, as well as the rapid exhaust valve, are thus distinct future design criteria you are pointing out.

Dick Long: I'd like to take issue for a moment with regard to making BC's a lot smaller. I understand why and where, however there are people diving dry suits who are wearing a lot of lead because they are diving in very cold places and need it. They will need 40-45 lbs. of lead. This means that they have a BC capacity that is less than that and if they have a flooded suit, that means they have to drop their weight belt. We all know that when we recover the bodies, most of them have their weight belts on. They don't want to do that because it costs money. Anyway, I think there is a call and application for large BC's and that problems can be traced to training.

Terry Rioux: I would like to see a uniform quick disconnect fitting among BC's and dry suits. That facilitates travelling with your own regulator and hoses and using other BC's and dry suits and not have all these different connectors and valves. Dick Long: I'd say that was true five years ago. With the exception of the valves coming out of Britain, all the GSD valves are the same. Bob Stinton: Poseidon are the only ones somewhat different. There is a trend to standardize. Poseidon and Viking are the only people who haven't. The British, U.S. and Canadians are the same. Terry: The ScubaPro quick disconnect has several criteria. For spare parts, if you're travelling somewhere, you can use a second stage regulator hose, just screw off the fitting. It also has a nice large barrel that divers can use. But it doesn't fit anything else in the world. Dick Long: We would prefer to have a large quick disconnect, but we had two things against us. First, the market and poor prices didn't aid the equipment, and people said there are enough quick disconnects going around. If you look at it, it only has three ball bearings. Bob Stinton: Let me comment that as a consumer, if somebody told me I had to have this BC with a high speed dump valve on it, I'm upset that I had to buy that thing for just in case because I probably wasn't trained properly. With dry suits especially, some of the larger quick disconnects were easier to dislodge. The SI-Tech QD had the little plastic wings on it for a while. We had hundreds of customers that sawed those things off. Yet, for safety reasons, even though the rationale for being able to handle the QD was good, when you brushed it, it would disengage. Doug Toth: ScubaPro has two quick disconnect designs: One is specific to the Air II and one the other quick disconnect is the standard design that fits the BC's. In a sense, we are standardized.

Mike Lang: We've addressed several items regarding BC's and dry suits, are there any questions with respect to dive computers and our abilities to make safe ascents? Steve Blair: Do the datalogging dive computers have the ability to log ascent rates? Ron Coley: We see the trend of going towards any type of serious violations being logged. Would you really like to have each and every aspect of every dive logged? Steve: How difficult and costly is it to make it a specialty item for research divers? Ron: The answer to that depends on exactly how much information and at what time increments during the dive you specify. To give you all of the options, you basically are losing some of the depth and time capabilities of the unit. Steve: I was wondering if it were more of a software consideration. Chris Wachholz: I would not want to have to sacrifice the dive profile information for the sake of the ascent rate information. Bill Hamilton: I'd be very pleased if I knew where the diver was every minute. Every three minutes is a little coarse. It wouldn't take a lot of memory. I don't think we need to know rates at all. Just, where is he every minute. You can figure out the rate from that. Anything divided more finely than that has very little meaning physiologically. Karl Huggins: I agree. At least I know with the DELPHI, what you're doing is cutting down on the total time you can record. They are able to adjust downward so you could get better resolution, but I don't know what it would cost to reprogram that information into the software.

Glen Egstrom: I want to make a general observation. The functional characteristics of any piece of equipment that is going to be involved in emergency should as far as possible at least be similar in location and function. If some of what we're discussing is not concerned with emergency procedures, then it probably doesn't make all that much difference. Because a person can learn to use and adapt to a piece of equipment. If on the other hand it is, such as diver rescue for example, then the functional characteristics should be the same. I say emergency procedures because in normal operation, I don't think it needs to be standardized.

Dennis Graver: Two ideas. First, I am of the opinion that we would be better off not having CO_2 cartridges on buoyancy compensators. I think it would help us from a liability standpoint and if not, at the very least, it be offered as an option. The BC should come without one, if you want a cartridge, you have to get it. The other idea would help with standardization, the extra second stages (octopus) have both right handed and left handed configurations. I see some problems with the left handed configuration and I think it would be helpful if we settled on one. It has to do with sharing air on ascents. Mike Lang asked the question of who had specific applications for a CO_2 cartridge that would outweigh the disadvantages. Walt Hendrick: I'm not opposed one way or the other, except for the requirements that would be placed on skin divers. Particularly on the West Coast in the kelp where they must wear their jackets which now becomes a large BC which has no possible way of deflating it below the surface. It gets in the way, it can easily be entangled and the first thing they do in a rescue the remove it from the person and tow them in without it. It serves no purpose in that framework. If, in fact, it had some means of inflation, then it might have some practicality, where a person might realize they're in trouble and could activate it. Doug Toth: If we are talking about skin diving and someone is on their way up from a dive and may be ready to black out, I think the CO_2 cartridge would be a service to him. Glen Egstrom: My difficulty with that is, if he's at that stage, I doubt seriously that would help. Dennis: We're talking about two different realms: buoyancy compensator versus skin diving vest. I was talking about BC's. It's been studied for years out on the charter boats in California that 85% of the CO_2 cartridges would not inflate. I offered to replace their cartridges if I could fire them off, people don't maintain them. Mike Lang: They were already punctured and left in the BC. Dennis: It is a maintenance problem, not training or operational problem.

Phil Sharkey: In the last five years I've been involved in three rescues of divers on the surface, flailing about, with a totally empty cylinder, unable or not bright enough to put the oral inflator in their mouth, take a breath of air and blow. I've never fired a CO_2 cartridge myself. I swam up to them and tried to fire the cartridge. If they don't really don't work and we can't solve that in terms of training and design then we should get rid of it. If we do get rid of it, let's give some thought to the kind of situation where a scuba diver needs one: out of air, at the surface, overweighted, which is not an uncommon experience. Dennis: Did you drop their weight belt? Phil: They weren't wearing weight belts in the Caribbean.

Jim Stewart: A year ago at the Dive Computer workshop at Catalina, I talked with several of the manufacturers and thought one of the things a dive computer should be able to do is be modified for a "failing mode" that might display the diver's repetitive group before it goes blank. Is there a means by which the DC will pop up a group designation with its final dying gas before it goes blank? That would be one of the kinds of things really beneficial, so if the DC dies, you don't worry about it. My second point is that divers are losing their accountability and responsibility. We come out with electronics that do many wonderful things, whatever you need. The individual person has to assume responsibility for their own safety, no one else can do that for you. We've gotten away from that responsibility in training as well. There are so many mechanical devices and technology has gone beyond the point of the diver's ability to cope with it all. Everything we're discussing here is taking the diver out of the loop and decreasing their awareness and responsibility. I certainly agree with the apparent low level of quality of new instructors. They don't have the knowledge and experience to realize there's not just their one agency's way of doing a particular skill, nor do they have any geographic experience in different environments. You should give people all the kinds of tools they need to solve a problem.

Karl Huggins: It boils down to the statement that was made earlier: Of the divers you see today, scuba is not the center of their lives, but, my concept is that for the duration of their dive, scuba is the center of their life, and they need to be aware of that. They should be very aware of the proper use of and responsible for their life support equipment.

Don Harper: For added safety in dry suit diving, can a relief valve be placed in the ankles or legs so in the event of an inversion they would help? Ed Lanphier: Historically, Cousteau's constant volume suit had valves in the legs. Dick Long: We have valves now but we have two major problems: 1) Dry suits are already outside the price range people are willing to pay, 2) The exhaust valves required would be difficult to keep clear, given the type of abuse they'd get (walking through mud, sand, etc.). If the suit fits properly, there's not a lot of space down there for air to collect.

Jon Hardy: The world has changed and there is an expectation with regards to the technical advances going on nowadays to incorporate systematizing and human engineering. Is there some way to bring buoyancy control and instrumentation together? Bill Oliver: A microprocessor controlled buoyancy compensator would go directly against what we're saying with regard to diver responsibility. That would be a technological solution to a training problem. I think that would make everything more complicated than it need be. In addition, the maintenance requirements would be equivalent to an aircraft.

Glen Egstrom: We all recognize that there is a risk associated with what we do in the water. Hopefully we are able to turn that into a calculated risk by showing where we can trade off our limitations against whatever the environment or conditions are. Anything that we can do to minimize or to clarify the nature of that calculated risk so that we can better deal with it, I think is critical. What we've done in the last few days is identify and clarify the nature of that risk. I don't believe that at this point we can come up with a solution relative to our long standing problems. I would suggest that we might make a recommendation, if you will, to put this concern into an arena that is probably better qualified to deal with it than we are, and that's back to the diving equipment manufacturers. The ability to minimize the risk falls into two categories: design and training. We've identified primarily training issues. It's a good idea to identify problems, but I'm not too sure we're the best people to identify the solutions. Mike Lang: Where does the interaction occur then between the community and the manufacturers other than in a forum like this? Glen: This forum can provide the information and hopefully, the interaction would come back where they would ask for additional clarification.

The observations were made by several manufacturers and participants that many of the design criteria were not feasible because of economics. Some areas that manufacturers perceived as needing attention in terms of design or protocol were market dependent and could not necessarily respond to the observations or needs of the scientific diving community. Bill Oliver: We try to put as much function into the equipment as possible. I personally could say I would be in the position to be able to change some design criteria, but if the market doesn't demand it, it doesn't stand a very good chance. Dick Long: I think manufacturers don't want any forms of standards because they can get sued if they change anything. I think they are not likely to pick that up unless they are encouraged to do so for a reason that is different than what they have looked at in the past. If you can identify some genuine needs to which they can respond to and generate this, then I think you have a chance of doing it. Just asking them to do it without that, I think your chances will be very slight. For an example: If you would say you'd like to have a basic uniform operational procedure on some basic pieces of equipment, so that training in one will be applicable to every other similar piece of equipment, I think they might take that as a serious consideration, because of the logic of it, it's obvious. They require some additional instruction beyond the simple matter in itself. Therefore, if you can up with some guidelines of what you'd like to see them do, for instance, that an emergency procedure should be the same. Weightbelt buckle should always be dead center in the front for example. That kind of condition We need to more here than just put out some suggestions, we need to get some action items as well. Mike Lang: You're right Dick, that's one of the first questions I asked this evening, if that's what you're saying, if there are any problems we need to identify and if so, let's get some recommendations out.

Chuck Mitchell: Andy pointed out the problems in his presentation: The top two problems for C.A.G.E. were out of air and buoyancy control, for DCS it was violation of the decompression limits and rapid ascent. The things we're talking about now are BC's and dry suits. Dennis Graver: How about an active rather than passive indicator of low air? Chuck Mitchell and Jim Stewart chimed in again that it was diver responsibility. Walt Hendrick: We should probably also talk about wetsuits because of their compressibility and resultant buoyancy changes. Glen Egstrom: Work is being conducted with new materials for wetsuits which may be appropriate. Jim Stewart: Building a BC into the top of a wetsuit with an oral inflator has been done 30 years ago. It cut down the drag 100% of anything we have today and puts you in a vertical position. I feel that should be explored further today. Karl Huggins: I believe Moray built a unit like that a few years ago with an attached BC to a wetsuit. Jim: This was not attached, you had your shirt with two layers of material with a small airspace in the middle. Of course, it was compressed to a point where when you were in the water, it didn't make any difference. Anytime you needed it, you'd blow in a little air.

SCUBA EQUIPMENT STANDARDIZATION DISCUSSION - continuation

Discussion Leader: Glen H. Egstrom

Glen Egstrom: I don't know if any of the rest of you had the same sense of frustration that Mike and I had last evening relative what we might be able to come up with as recommendation relative to equipment because we seem to kind of go from philosophy to practical problems to differences of opinion whether equipment should get larger, smaller or stay the same. One of the things I would like to do in this first morning session is to continue and see if we can in fact identify any problems or recommendations. My personal feeling is that we should probably be a little careful about putting anything out such as this is the design that we want, because we don't have that kind of insight. I do however think it is appropriate to identify the kinds of problems we see and be as specific as we can, and to be able to identify functional features that we might feel are really important that we could have consensus on. I sense that wasn't completely clear on the issue of the dump valve. The only difficulties I've seen with the rapid exhaust dump valve is its location, since some of them are located a little low so that you have to lean back quite a ways to dump and others are located high up on the shoulder, making it easier. From my experience those that have the rapid exhaust valve are able to stop the ascent almost as if you put on brakes at virtually any place in the water column where you want to stop. Is there any additional observation on that?

Jon Hardy: The observation is that there still are a number of units that don't have a rapid dump. I believe that's a real disservice by taking a tool away from the diver. The location needs to be high. The other one is some rapid dumps in existence that are high but the diver cannot utilize his own rapid dump properly. Bill Oliver: I wanted clarification as to what you mean by high. It might be better to accurately describe the diver position rather than an abstract term. Jon: Functional in the normal swimming position. Bill: I also want to clarify something. The term rapid dump or rapid exhaust is rapid in the sense that you can find it and activate it without having to change your orientation. Actual flow rates for dumping would be faster to hold up the oral inflator up high and push the button, because through the rapid exhaust valve, there's a smaller pressure differential than through the oral inflator end held up high. Walt Hendrick: The only readily apparent advantage of having the valve lower on the BC would be in the situation of a valve failure, so that you don't lose every pound of buoyancy, by still having some air trapped in the upper portion of the bladder.

Dennis Graver: The alternate air source should be able to be used by the donor as well as the recipient. "Left hand" octopus rigs may not be used this way without difficulty in emergency air sharing situations.

Bill Oliver: You might consider the wording of a recommendation that would state that the dive should be started with no air in the BC, implying that you have to be weighted properly. Walt Hendrick: It needs to be specified when you're talking about neutral buoyancy, because a lot of the literature will state that a person is neutrally buoyant when their nose is 4-5 inches above the surface. First, that's not neutrally buoyant, and second, it has to be stated very specifically, what breath you're holding at that moment. There is also a vast difference, obviously, when establishing neutral buoyancy with or without a wetsuit. Glen: When you talk about being neutral, you mean a condition with an empty tank, without air in the BC and with a normal inhalation.

Glen Egstrom: Dick, there is a recommendation that dry suits be equipped with an auto exhaust valve, rather than a manual valve. My question is how does that help you if the bubble is trapped in the leg. Dick Long: Obviously, it doesn't help you at all. Glen: Would it be fair then to have this panel go on record that we recommend that dry suits, which we did once before at the AAUS Coldwater Diving Workshop in Seattle, but reinforce it from the point of view of ascent control, that we have our people trained in dry suits. Dick Long: Absolutely. Dry suits should only be used with appropriate training that meets specified standards and dry suits should include an automatic dump valve with manual dump override. Bob Stinton: An automatic valve is not the same as a valve with an override. There's another valve on the market called an automatic valve, it's used in the U.K. It just sits there on your wrist and has a fixed flow rate. You can change the rate by moving your arm up and down, whereby you increase the pressure head. These other valves are actually adjustable automatic valves. The reason they have a press-to-dump is if you have that valve turned to the highest pressure, it will allow you to put a 15" bubble in your suit. Mike Lang: We may want to restate, as we did in Seattle, that a BC must be worn with a dry suit. Dick Long: Yes. I believe all the dry suit manufacturers feel it is unsafe to do otherwise. Phil Sharkey: It's not the same issue. We only wear a BC with a dry suit for surface flotation. Dick Long: Or as a back-up if you get a major suit leak. Glen: So a BC with a dry suit should be mandatory for ascent control as well as for emergency situations. Glenn Boden: Should a recommendation be made with regard to ascents with the older neoprene dry suits. Dick Long: I would personally strongly recommend the use of membrane dry suits to avoid problems with ascents. The foam dry suits need a larger volume of air, which will complicate ascent problems. Neal Pollock: At UBC we use both membrane and neoprene dry suits, and when comparing the amount of layering required to achieve similar comfort between the two types of suits, the weight needed for either suit is about the same. Bob Stinton: Here's the trick. I don't disagree with what you've said. Insulation is trapped air. If you have more insulation, it takes more lead to sink, that's absolutely true. The difference is that if we both jumped off the boat with equal insulation, you in a foam suit and I in an membrane suit, with the same amount of trapped air in it, when we get to 60 fsw, I only add air to relieve the squeeze of the membrane suit. You in the foam suit, you have now lost insulation. The compression of that insulation has made you put in a free air volume in it. Dick Long: On ascent, the amount of exchange of air that has occurred, in order to compensate for the change in buoyancy of that suit is at least twice that of the membrane suit.

Glen Egstrom: I want to take advantage this morning of some additional time to ask those individuals who helped us with the modeling on the first day and the understanding of the physics of this operation to help us with a couple of issue that have arisen. At last year's workshop, as a function of the requirements of the various dive computers on the market, we made the recommendation that the ascent rate should not exceed 40 fpm. That is consistent with the idea that we follow the instructions of the manufacturers and the designers of the algorithms. This year, it seems that what we're saying is that ascent rates should not exceed 60 fpm or should be less than 60 fpm, because that's very slow and that's where we have our database. Now these two appear to be somewhat at odds with one another. Can we get some intelligent closure on that problem? Is there a problem with having the same ascent rates for all diving or just dive computers?

Bill Hamilton: Physiologically, there isn't any difference. The numbers are different and somehow we have to come to grips with the fact that we got different numbers from last year. Glen: The statement last year, which if we still concur, says that if you're diving a dive computer, you don't come up faster than 40 fpm because that's the upper limit for dive computers at 60 fsw or less. On the other hand what we're saying this year is that as a concern with ascent rate, from the point of view of decompression sickness cerebral gas air embolism, not to exceed 60 fpm. While they're not incompatible as statements, I think they lead to different ascent rates. The question is are there advantages to coming up slower so that we increase the length of that curve. If you recall, Hugh Van Liew talked about these little windows where we get these explosions and one of the ways to avoid that window was to have a slower ascent rate. Hugh Van Liew: I don't think that the changes you're talking about between 40 fpm and 60 fpm, that I doubt if that matters. Glen: Based on that, the agreement seemed to have been that a safety stop was probably a better way to resolve that same problem. Then the question was if the safety stop was to be used, do we use a number or an envelope? It was suggested I believe that an envelope made as much sense as anything, so that we should now look at the parameters of the envelope. David Yount: As long as you're not deeper than 25 fsw or so, you could stay there forever and not worry about loading up the slow tissues. You could spend a week at 25 fsw and still surface so that would be the deepest, the shallowest would be whatever is convenient. I think we could set the envelope from 15-25 fsw or 10-25 fsw on a single dive. Glen: Last year we came up with 10-30 fsw. David Yount: I would recommend 10-25 fsw. Glen: When we say not on repet, then what do we have to do with the envelope on repetitive dives, or do we have one? David Yount: Your safety stop is short, it's three minutes. The depth is shallow, it probably doesn't matter too much on repetitive dives. You are picking up gas in the very long time constant tissues.

Karl Huggins: It boils down to if you're not using a dive computer and your using tables, how do you handle time spent at that stop and how does it affect your current group designation? If you add your safety stop time to your bottom time and you're still within the limit of your maximum depth, then that's added safety to your calculations. There's also the possibility you can do your step calculation on the tables if you are going to go outside your no-d limit on that. Glen: What you're saying then is that even if we identify a cautionary stop, then on repetitive dives a cautionary stop at 25 fsw would be too deep? Karl Huggins: Not necessarily. If you decide not to surface with more than 100 psi in your cylinder to blow off the rest of the air at that depth, then you need some way to handle the additional offgassing in the slower compartments you're getting if you don't have a dive computer that does that for you. Bill Hamilton: You can make a calculation. If you stay 1 hour at 30 fsw on your way up, you just calculate a 1 hour dive at 30 fsw. I don't think this makes any difference at all. I think we're really kidding ourselves that that time at 30 fsw, deeper than 25 fsw, 30 fsw, is not going to affect tomorrow's dive or repetitive dives that follow. For one thing, it's going to make you in better shape when you finish the dive you just did. You're going to have fewer bubbles and better within the physiological limits. I think that to get too locked into the little bit of gas that is added to the slow compartments is counterproductive. The main reason for stopping is to ensure you're coming up at a reasonable rate and that it is a controlled ascent. Those are the things that will reduce the accidents. John Lewis: I think you can avoid problems with multiple day diving by staying at 30 fsw or less for 30 minutes or until 100 psi. Walt Hendrick: The stop time has to be included in the bottom time or preferably fall into the step record so you can look at that as if you had finished your dive, going to a repetitive dive at that depth for the amount of time I put in. As has been pointed out before, if you're using a dive computer, it's done for you.

Bruce Wienke: I wanted to make a few comments about safety stops. First, as far as minimized bubble growth, calculations show that a safety stop for 3-5 minutes does a lot to minimize bubble growth. Research at the University of Hawaii has shown that bubbles up to 250 microns in size could be dissolved in 30 fsw within 5 minutes or less. This is actually part of the Hawaiian in-water recompression that the fishermen use. For dissolved gas phases a safety stop is helpful and it doesn't hurt when you add safety stop to bottom time in your dive profile if you use tables.

Ray Rogers: A short safety stop time gives you great benefit in the fast and moderate compartments, is not going to have any adverse effect in the slow compartments. I recommend a 3-5 minute stop in a 10-20 fsw range, which would cover a lot of ground and is easy to do. Glen Egstrom: The recommendation of a safety stop for 3-5 minutes in a 10-30 fsw range is on the floor, does any think that is not a good idea? Dennis Graver said that educationally, a number would be better remembered than a range according to Kelly Hill. Bill Hamilton disagreed with limiting the length of the stop to 5 minutes. Lloyd Austin suggested verbage such as "approximately 15 fsw", because it was so hard for divers to maintain an exact depth. Glen expressed that he thought one of things we were trying to do here was get clarity. If, in fact, in doesn't make any difference really from 10-30 fsw, I personally think that is a very valuable piece of knowledge. If, in fact, it doesn't make any difference if it's 3-5 minutes is also very valuable. However we deal with this in training objectives, for us to know what these limits are, will let us do that. Bill Hamilton: We don't think it makes a difference. Mike Emmerman: AAUS is not a recreational diver training agency. Therefore, if we're going to give realistic guidelines to the community we are serving, and these are based on the data we have which indicates some range, we should recommend some range and let the training agencies figure out how to teach this. Walt Hendrick felt that by recommending a different ascent rate from the Navy tables, we were deviating from the stated standard and procedure. This might result in some legal ramifications and liabilities, especially when based on the limited data available. Dennis Divins: The Navy bottom time definition is the time when you leave the surface until you leave the bottom. Most of the training agencies have modified the definition of bottom time to: time when you leave the surface until you reach the surface", which if you add the 3-5 minute stop to the bottom time, you're actually more conservative, in addition to not really deviating from bottom time definition. Bruce Wienke: With regard to tables, when taking safety stops and adding that time to the bottom time, this results in a more conservative bottom time and should therefore be an appropriate procedure. John Lewis finished the discussion with a suggestion that we all buy dive computers.

INSIGHTS GAINED: DIVING ACCIDENTS CONCERNING ASCENTS

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I have summarized over 100 legal cases I have served on and zeroed in on those that involved ascents. Then I read hundreds of accident reports, including a major study I did with NAUI years ago and an unpublished study from insurance companies, as well as observations in the filed. We thus have three levels of input: actual legal cases, actual accidents that have been reported and actual observations.

In diving we have a decrease of pressure during ascent that is unique to diving and we have a special concern because of the possible tragic consequences. Most other activities are not saddled with this particular unique situation. The diver needs to understand what he is doing, be able to maintain control, to go slowly and pause. Pauses have become a correct ascent procedure taken from all these sources.

Obviously, not having adequate training, or the typical diver who is in general inept, contribute to diving accidents. Karl Huggins stated: "Diving should be the center of a person's life while they are diving". However, are they capable of focusing that much attention, do they have that high a level of awareness? Divers do not really understand the need or importance for correct ascents, while using dry suits without training is madness.

Causes that are fundamental during the dive include:

- Not having instruments or not using them;
- Overweighting is a gross abuse and a sincere problem. The general diving public can not function underwater with.radical buoyancy changes;
- Inability to use the BC correctly to control ascents. Use of oral inflators when it is inappropriate, when the power inflator is the more efficient device within their skill level;
- Low or out of air situation where you have no option but to ascend rapidly;
- Improper breathing technique of overbreathing the regulator;
- Rushing through transitions by not allowing the physiology and psychology of the human body to calm down at a transition point;
- Lack of attaining neutral buoyancy before beginning the ascent;
- Actual ascent rate being grossly violated;
- Loss of buoyancy control in the 20-10 fsw range.

With regards to emergency situations the following cases have been observed:

- Some divers are so obsessed with the rule to ascend when reaching 500 psi, that they essentially perform an emergency ascent when they reach that pressure in their cylinder;
- Lack of proper training in the use of shared air breathing with an alternate air source;
- Failure to achieve positive buoyancy when needed, either by ditching the weightbelt or inflating the BC;

- There is a need for positive buoyancy and stabilization at the surface at the end of an ascent which needs to be considered.
- Rather than going to the surface, going for the alternate air source.

Several equipment causes of accidents with regard to ascent have been identified as:
- BC and dry suit inflator mechanisms sticking;
- Lack of rapid exhaust dump valves;
- Lack of systematizing both the BC and instruments in terms of human engineering

Consequences of incorrect ascents. Obviously, we are concerned about decompression sickness (treated and untreated). The really bad cases are, in the vast majority, reported to DAN. I worry more and more about the untreated cases which may have long term consequences. Lung overpressure injuries can result as well from incorrect ascents and can be minor incidents as well as the tragic ones. Several cases concluded that due to complications with the incorrect ascent, the diver drowned on the way up or were rescued and termed a near miss. There are other problems on ascent, such as overhead obstructions and entanglements which also demand attention.

I had the opportunity to review 900 accidents with NAUI in the late 1970's. The analysis showed that the category of ascents comprised 10% of the total accidents. This is a very low number and resulted in sixth place for all the kinds of accidents at that time. Then, we analyzed only training accidents and the number changed to 20% of the total, moving to second place. More people were hurt proportionately in training than in general diving. These are not hard numbers because in our analysis we had broken out decompression sickness and air embolism as a separate categories. Based on the original numbers, I predict that 30-40% of the all the accidents had to do with ascents in one form or another. It's a soft number but I did want to point out the magnitude of the problem.

Some so-called normal, correctly done ascents end up in air embolisms and decompression sickness. They might have been due to one or several medical reasons. Training has historically lagged behind equipment. To this day, the training agencies do not effectively teach their instructors how to use power inflators, their range of capability, how to deal with problems of power inflators, etc.

There are instructors and students who suffer decompression sickness while doing training dives. The instructor does it apparently by taking a class to open water and repeating simulated emergency ascent training with the students over and over again. The students dive to 40 fsw on the first dive of the day. On the second dive of the day, they are further along in their training, so they can now go to 60 fsw on their certification dive. At this point they can go make an optional fun dive since they are now certified and they descend to 80 fsw. They are not quite that good on buoyancy control yet, have not yet mastered a 60 fpm ascent rate, so they either make a rapid ascent which they feel is at the correct speed, or they lose buoyancy control on a direct ascent from 80 fsw on the third dive of the day. The dive profile reads 40, 60, 80 fsw and they end up with DCS.

Several cases also occurred where after a day of diving, a professional now had to deal with an emergency and make another dive or a rapid ascent.

Methods to control ascent and the state of the art practices are:
- Use BC's with swimming and some instrumentation to ascend;
- Another option is divers will follow the slope of the bottom up to control their ascent
- Another is to come up an anchor or descent line to control ascent
- Safety stops are common in the field

- Using the BC with the dry suit has been pointed out,
- Following smallest bubbles
- Make deeper to progressively shallower dives during the day;
- Adding all underwater time together and calling it bottom time;
- Decreased use of classic buddy breathing of sharing one regulator.

The cutting edge skills which could become common practice soon are:

- A complete emergency skill for a power inflator stuck in the on position (dump, disconnect, flare exercise);
- Slower ascent rates;
- Safety stops with a common definition
- Planned split-level diving;
- Reducing allowed decompression time;
- Use of a dive computer, by repeatedly ascending to the warning device and stopping, which results in a series of many stops;
- Buoyancy check: At 500 psi, go to ten fsw, no air in BC, take a normal breath, adjust weight to be exactly neutral. Now they can easily do a safety stop in the 10-20 fsw range and burn up the remaining 500 psi.

I have already heard it mentioned that in a legal case we are creating a required decompression stop by making a safety stop. You can probably see some attorney twisting around what we do by saying we advocate no-decompression diving and we now require a decompression stop by creating a safety stop. I am identifying a concern. Weightbelt ditching is not taught well enough. Faster rates of ascent provide less room for error and less time to adjust. What we can do as professional divers is not what we can expect the diving public to be able to do. Informational overload with the dive computers is a final concern. Divers cannot cope with all the pieces of information being displayed to them at once.

INDIVIDUAL PERSPECTIVES

Chair: Michael A. Lang

Comments by Mike Emmerman

AAUS is a unique organization. It has the rare ability to attract some of the best thinkers in various disciplines and bring them together to attempt to define the state-of-the-art in areas that directly affect the safety of divers. Because of this rare ability, AAUS, when offering guidelines, should not be constrained by what the general diving public would be willing to comply with. We should inform the scientific diving community as well as the general diving population of the true current state-of-the-art as defined by the availability of verifiable data.

To that end, I can support a guideline of a maximum ascent rate of 60 fsw/min with a stop in a zone of 10 to 30 fsw for some variable time frame, as long as AAUS also prefaces this guideline with a statement that qualifies the guideline as consensus opinion based on the availability of limited data.

By qualifying the guideline with this statement, AAUS can maintain its credibility while giving a clear message to the diving community that we have only just begun to gather and quantify the data needed to establish more accurate verifiable guidelines. AAUS should offer these guidelines as a current working solution to a serious problem that needs much more research.

Comments by Don Short

What we are dealing with is trying to put a slight patch on a slight problem on the Navy procedures or Huggins procedures. It is really important to understand what that safety stop is doing according to the capillary model or the compartmental model. In effect you are knocking the top off the fast perfusion tissues. In the compartment model, you're looking at the 5 min and 10 min compartments. John Lewis pointed that out very clearly. When you have problems with those compartments, you have problems on deep dives. That's where those compartments load up, that is where they control. The models aren't perfect. The compartmental model chops the body up into so many pieces and the capillary model has its problems. DAN data also says that Type II DCS problems come from deep dives. Deep dives are exciting those very fast tissues. What you are doing with that 5 min safety stop is reducing gas tension substantially by 30-40% in either of those models. If you run that same stop for 20-30 min, you have already reduced the potential danger from the very fast compartments. Now you run into a counter course where you are spending time at that depth which is a substantial fraction of the slow tissues (120, 80 and 40 min). A 3-5 min stop can hardly be considered serious by models, where 20 min can be considered another dive with step procedures in the dive computer. That's why I would recommend the stop to be taken deeper than 10 fsw in the stop range. I would like to see the stop range narrowed to 15-25 fsw.

Comments by John Lewis

The question arose as to whether the safety stop from one dive is equivalent to what it is for another. Let's assume most divers dive to the no-d limits as a hypothesis. Given that, what is the relative effectiveness of a slower ascent and a safety stop? There is an indication that you can expect that all safety stops are not the same. Time scales are very relevant. A five minute safety stop after a 100 fsw dive for 25 min can be an entirely different situation than a 60 fsw dive for 60 min or a 190 fsw dive for 5 min. The charts I showed during my presentation were the number of minutes to reduce the time to 90% of the Navy limits. The calculations I made found that a slower ascent rate was ineffective.

Comments by Ron Coley

We were trying to describe a zone in which to make safety stop, which I agree with. In his next statement John Lewis said that all dive computers forgot about multi-days or repetitive dives after a while. Having watched the dial face of a particular unit for many, may hours, both in-water and in testing, I see a safety zone described that increasingly gets smaller. We have a diver computer that will describe a decompression ceiling and a decompression floor when you exceed the no-decompression limits. If you take that on repetitive dives or multi-day dives, that decompression range continues to get smaller and smaller and moves closer and closer to the surface. The unit also expresses what most people consider unlimited dive time. Three dashes is our symbol for a number that is greater than 250 min. The depth at which you receive that symbol changes. It gets continually shallower as you go on multi-repetitive dives and as you go on multi-day diving. That's what is happening to the model inside that dive computer. I was very thrilled when AAUS met last year at Catalina and said there is no perfect algorithm and that what happens to the model is really of very little concern to us. What we care about is what happens to the diver. Because of what happens to the diver is at issue, I would like to think about whether the slower ascent rates are entirely aimed at just limiting or restricting the exposure for decompression sickness. Slower ascent rates are very manageable. I have less trouble with my ears since I've slowed my ascent rate, I've never been hit, I've never had an air embolism and I actually do feel a little bit better. The cave divers are more comfortable using the British Sub Aqua Club tables. Bill Hamilton mentioned that he felt that the dive computers with the slower ascent rates were accomplishing many of the same things that were being accomplished by the deeper, longer stops by the BSAC tables. At the same meeting, Andy Pilmanis described the fact that he had very small pipes on the Catalina Chamber that resulted in remarkably slow ascent rates and that in 10,000 hours of training dives they did not suffer a hit. I think that perhaps regardless of how these ascent rates affect those mathematical models, they affect people in a different way altogether. We cannot come up with a database that is factual, well established and well researched in the course of our discussions. We can formulate opinions and recommend suggestions but we shouldn't come up with rubber-stamped approvals of an idea or try to espouse that we've established certain known truths just because the workshop is now concluding.

Comments by Andy Pilmanis

I have been and am in agreement with a safety stop under most conditions. It hasn't been mentioned in this workshop, and it should go on record that there are other options and we shouldn't tie the hands of the divers in the future. Obviously, you can reduce your bottom time, you can increase your surface interval, you can decrease your depths, you have all those parameters to work with. This workshop seems to have gotten blinders on towards the safety stop. I think that those other aspects should always be kept in mind. You don't have to make a safety stop, if you make a 40 fsw dive for 10 min. There are other options in addition to the Navy tables. The origin of the safety stop was linking it to the Navy tables because they were developed in the 1950's and we have additional data. They were good, and close to what they should have been, but because they were old, did not have the technology etc. So we added the safety stop to update. Karl Huggins' has put out tables, indirectly based on bubble detection, the Canadian Forces have published tables based on experimental bubble detection as the end point. Not bends as the end point, but bubble detection as the endpoint. If you're using those tables, I'm not sure you need a safety stop. It's still good operationally to slow down your ascent for other reasons, but decompression-wise, if you're using Huggins' tables, as we did in Catalina, it was to eliminate the safety stop. We used the tables as they were, to make it simple. The safety aspect is inherent in the tables. There are other options.

My second point is regarding omitted decompression. If you read the latest Navy manual, there is a statement that says: However, the preferred action is to put the diver in the chamber and treat him on Table 5. That is the Navy's current position. The reason I don't like that procedure is a very basic principle. Decompression procedures are for the purpose of preventing bubble formation. Treatment tables are for treating bubbles after they form. Omitted decompression procedure assumes that you don't form bubbles once you get to the surface, and go back down immediately. There is some kind of grace period there. But there really is no grace period, since bubbles are already there immediately upon surfacing. Some people argue that the bubbles are there, but by jumping right back down real quickly, you may prevent formation of additional bubbles. That may be true and I would hedge on that if you did that and had no other recourse (no chamber or oxygen), there may be a benefit. Secondly, Frances' work on latency of decompression sickness has shown that at the point of surfacing around 50% of the symptoms have already occurred. This is serious DCS. At 5 min it was approaching 60%. You really don't have a grace period upon surfacing. If you surface, the assumption is that you form bubbles. To go back down and continue with a decompression procedure, is the wrong thing to do because you have already formed bubbles. Decompression is for the prevention of bubbles. A much more useful procedure for us is the use of surface oxygen. I know it isn't practiced universally, but I personally believe every dive site should have 100% oxygen available. If you accept that, then a better procedure is to stay on the surface and go on oxygen. If nothing happens, fine. If you get symptoms, go to the chamber. Obviously there are different grades of omitted decompression. If you miss 30 seconds, that's one situation, if you miss 35 min of decompression, you are in trouble, in which case your action should be different.

The Navy tables to this day are still the worldwide standard, whether you like it or not, that's more or less fact. My impression of this meeting is that the safety stop has been applied to the Navy tables as a means of making them better. If you are nowhere near the limits, the only reason for a safety stop then is operationally: Buoyancy, prevention of air embolism, etc.

Additional comments

Chris Wachholz: There should be a caveat statement: This is not to preclude the concept or idea of reducing bottom times, depths, and all the other rules that also increase your safety.

Don Short: A safety stop is cutting back the loading of very highly perfused tissue with fast compartmental half times. You don't have to be close to those limits to really load up those compartments on deep dives. They will saturate very quickly. The 5 min compartment is halfway to full loading in 5 min. From 100 fsw depth and beyond you get very close to saturation of the fast compartments. Even if you back off the bottom times on deep dives, you still have high nitrogen loading. A safety stop takes care of those.

John Lewis: The profiles of the diver have changed. The recreational diver is also a worldwide traveler. Any serious type of diving, even with dive computers can take advantage of a safety stop. Some of this multi-day repetitive diving is uncharted territory and is pushing the limits. There is a big uncertainty there.

Andy Pilmanis: As a Diving Control Board Member, I know that if you make one rule and pass that out to your divers, it will be taken literally and other options will be forgotten, but they do exist.

GENERAL DISCUSSION AND CONCLUDING REMARKS

Discussion Leaders: Michael A. Lang and Glen H. Egstrom

Mike Lang: We are now at the point where I would like to keep the general discussion very pertinent. Up until this point your individual ideas and comments have been duly recorded in the proceedings. From my organizational viewpoint, it is now time to try to reach some sort of concluding consensus to be able to formulate the end product, based on the information that has been transferred and discussed relative to the biomechanics of safe ascents.

Glen Egstrom: We do want to reach some kind of closure. Sometimes it is as necessary to clarify an issue where we have unknowns as it is to clarify issues we now know are fact. The recommendations can take the form of a positive or essentially negative statement. There are things we don't know or need to know, which we can also put in recommendation form.

We would like to take just a second on this stop terminology. It has been suggested that the language of what that is is important. There is a connotation with the word safety. If we use the term safety stop then what it does by inference is suggest that it is unsafe not to take this stop, therefore this becomes a hazard, therefore this a mandatory thing. I don't think we're at that point. What we suggest is that there may be more advantages under some circumstances than others in taking this pause near the surface. It has been suggested to use caution stop (c-stop), or precautionary pause or prophylactic pause (p.p. stop), or you could have a precaution stop (p stop). Bill Hamilton: To define our conditions, we are talking about ascents from no-stop dives that are near the limits. If you have decompression stops that are required, this exercise has no meaning. We are not talking about emergency ascents, we're talking about no-stop diving that approaches the limits, particularly if deep.

Mike Lang: Most dive computer manufacturers use the term "safety stop" in their owner's manual. A discussion followed with comments from some manufacturers that for liability reasons, they were advised to get away from the word "safety", because diving was could then be considered unsafe. On the other hand it was pointed out that the majority of the university programs were termed diving safety programs.

Mike Lang and Glen Egstrom lead the group discussion to reach consensus on the workshop recommendations. The terminology to be used for the "interruption" or "halt" during the ascent for precautionary purposes, was decided by simple majority vote. "Ascent interruption", "control stop", "precautionary pause", "precautionary stop", "ascent control stop", "stop", "precautionary decompression stop", "ascent stop", "safety stop" were the suggested possible terms. It was decided to use the term "STOP" for uniformity's sake.

SAFE ASCENT RECOMMENDATIONS

It has long been the position of the American Academy of Underwater Sciences that the ultimate responsibility for safety rests with the individual diver.

The time has come to encourage divers to slow their ascents.

1. Buoyancy compensation is a significant problem in the control of ascents.
2. Training in, and understanding of, proper ascent techniques is fundamental to safe diving practice.
3. Before certification, the diver is to demonstrate proper buoyancy, weighting and a controlled ascent, including a "hovering" stop.
4. Diver shall periodically review proper ascent techniques to maintain proficiency.
5. Ascent rates shall not exceed 60 fsw per minute.
6. A stop in the 10-30 fsw zone for 3-5 min is recommended on every dive.
7. When using a dive computer or tables, non-emergency ascents are to be at the rate specified for the system being used.
8. Each diver shall have instrumentation to monitor ascent rates.
9. Divers using dry suits shall have training in their use.
10. Dry suits shall have a hands-free exhaust valve.
11. BC's shall have a reliable rapid exhaust valve which can be operated in a horizontal swimming position.
12. A buoyancy compensator is required with dry suit use for ascent control and emergency flotation.
13. Breathing 100% oxygen above water is preferred to in-water air procedures for omitted decompression.

AMERICAN ACADEMY OF UNDERWATER SCIENCES
Biomechanics of Safe Ascents Workshop
Woods Hole Oceanographic Institution
September 25-27, 1989

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THE AMERICAN ACADEMY OF UNDERWATER SCIENCES

BIOMECHANICS OF SAFE ASCENTS WORKSHOP

Woods Hole Oceanographic Institution
and
The Marine Biological Laboratory

Woods Hole, Massachusetts

September 25 - 27, 1989

PROGRAM

Michael A. Lang, SDSU, Workshop Co-Chair
Glen H. Egstrom, UCLA, Workshop Co-Chair

Sponsored by: American Academy of Underwater Sciences
Diving Equipment Manufacturer's Association
NOAA Office of Undersea Research

MONDAY, SEPTEMBER 25, 1989

07:30-08:30: Breakfast: Swope Center, MBL.

09:00: Workshop participants meet at Whitman Auditorium, MBL.

09:30: *Welcoming Address.*
Michael A. Lang.

10:00: *Presentation Of The Issues.*
Glen H. Egstrom, PhD.

10:30: *A Historical Look At Ascent.*
Rev. Edward H. Lanphier, MD.

10:45: Break.

11:00: *Phase Dynamics And Diving.*
Bruce R. Wienke, PhD.

11:30: *The Physics Of Bubble Formation.*
David E. Yount, PhD.

12:00-13:30: Lunch: Swope Center, MBL.

13:30: *Growth Of Pre-Existing Bubbles In The Body During Ascent From Depth.*
Hugh D. Van Liew, PhD.

14:00: *Ascent Rate Experiments And Diver Safety.*
Charles E. Lehner, PhD.

14:30: *Ascent And Silent Bubbles.*
Andrew A. Pilmanis, PhD.

15:00: Break.

15:30: *Slow Ascent Rates: Beneficial, But A Tradeoff.*
R.W. Hamilton, PhD.

16:00: *Ascent Rates Versus Inert Gas Dynamics Algorithms.*
Donald R. Short, PhD.

16:30: Discussion Leader: Glen Egstrom.

17:30: "Bubble-breaker" Reception: Dome Restaurant.

19:00: Dinner: Swope Center, MBL.

TUESDAY, SEPTEMBER 26, 1989

07:30-08:30: Breakfast: Swope Center, MBL.

IMPACT OF EQUIPMENT ON ASCENT RATE

09:00: *Dry Suit Buoyancy Control.*
Richard Long.

09:30: *Dry Suit Valves And Performance.*
Robert Stinton.

10:00: *Biomechanics Of Buoyancy Compensation And Ascent Rate.*
Glen H. Egstrom, PhD.

10:30: Break.

11:00: *Dive Computer Monitored Ascents.*
Manufacturer's Panel.

12:00: Discussion Leader: Mike Lang.

12:30: Lunch: Swope Center, MBL.

IMPACT OF TRAINING ON ASCENT RATE

14:00: *A Review of Ascent Procedures For Scientific And Recreational Diving.*
John E. Lewis, PhD.

14:30: *Buoyancy Control And Ascent Rates.*
Walter F. Hendrick, Sr.

15:00: *Non-Emergency Ascent Training Procedures For Recreational Divers.*
Dennis K. Graver.

15:30: Break.

16:00: *Recreational Training Agencies' Ascent Training Policy Statements*
Panel.

16:30: Discussion Leader: Jim Stewart.

17:30: AAUS Reception: Meigs Room, Swope Center, MBL.

18:30-19:30: Dinner: Swope Center.

20:00-21:30: *SCUBA Equipment Standardization.*
Discussion Leader: Mike Lang.

WEDNESDAY, SEPTEMBER 27, 1989

07:30-08:30: Breakfast: Swope Center, MBL.

09:00-09:30: *Diving Accidents Involving Incorrect Ascents.*
Jon Hardy.

09:30-10:30: Presentations of individual experiences and personal perspectives.

10:30: Break.

10:45: Summary of Findings.
Glen Egstrom.

11:00: General Discussion And Development Of Consensus Recommendations.
Discussion Leaders: Mike Lang and Glen Egstrom.

11:45: Closing of Workshop.
Mike Lang.

12:00-13:00: Lunch: Swope Center, MBL.

THURSDAY, SEPTEMBER 28, 1989
through
SUNDAY, OCTOBER 1, 1989

The 9th Annual Scientific Diving Symposium sponsored by
The American Academy of Underwater Sciences:

DIVING FOR SCIENCE...1989

Woods Hole Oceanographic Institution
and
The Marine Biological Laboratory

Woods Hole, Massachusetts

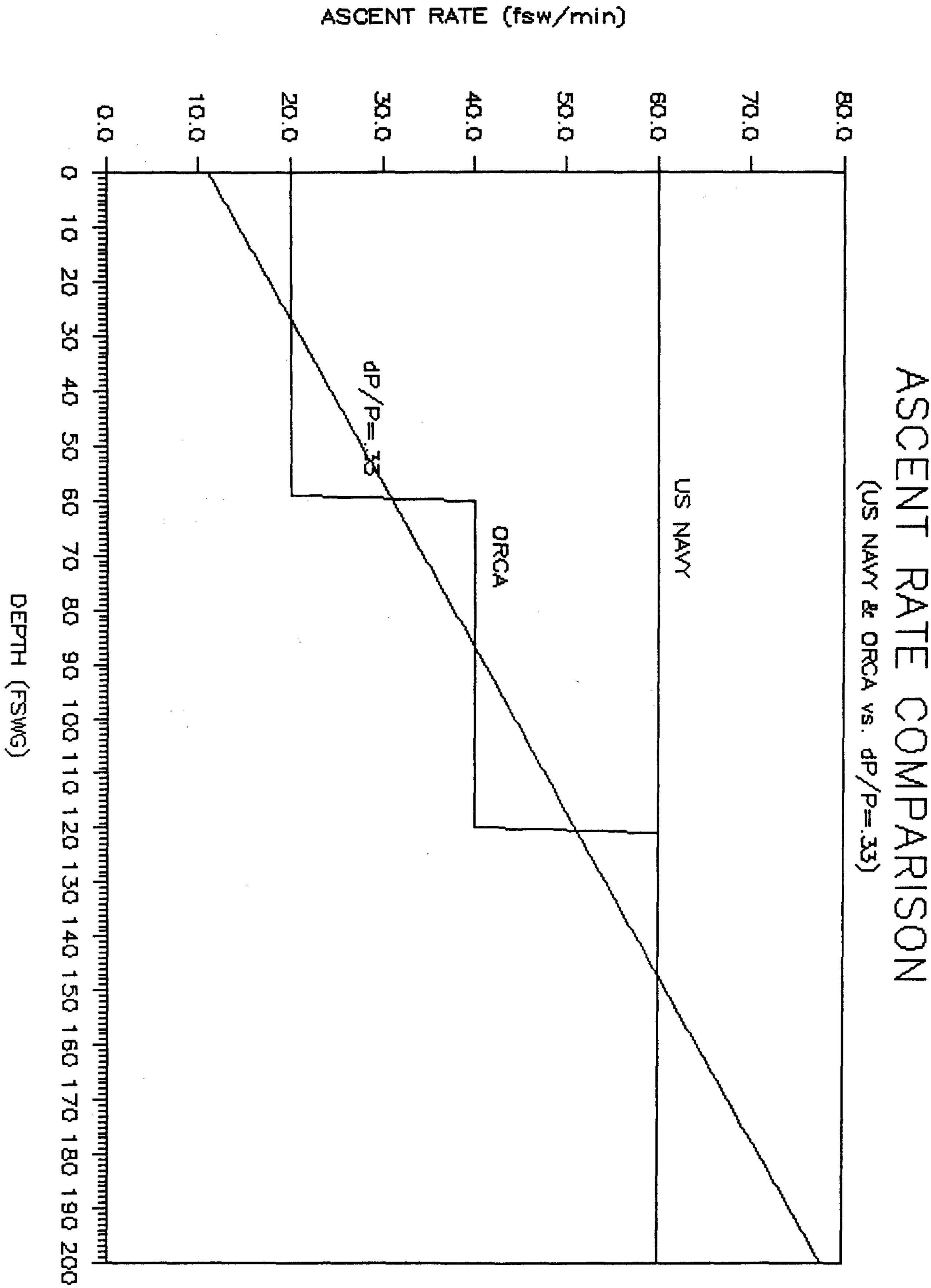
Lang and Egstrom (Eds.): *BIOMECHANICS OF SAFE ASCENTS WORKSHOP*. AAUS, Costa Mesa, CA. 1990.

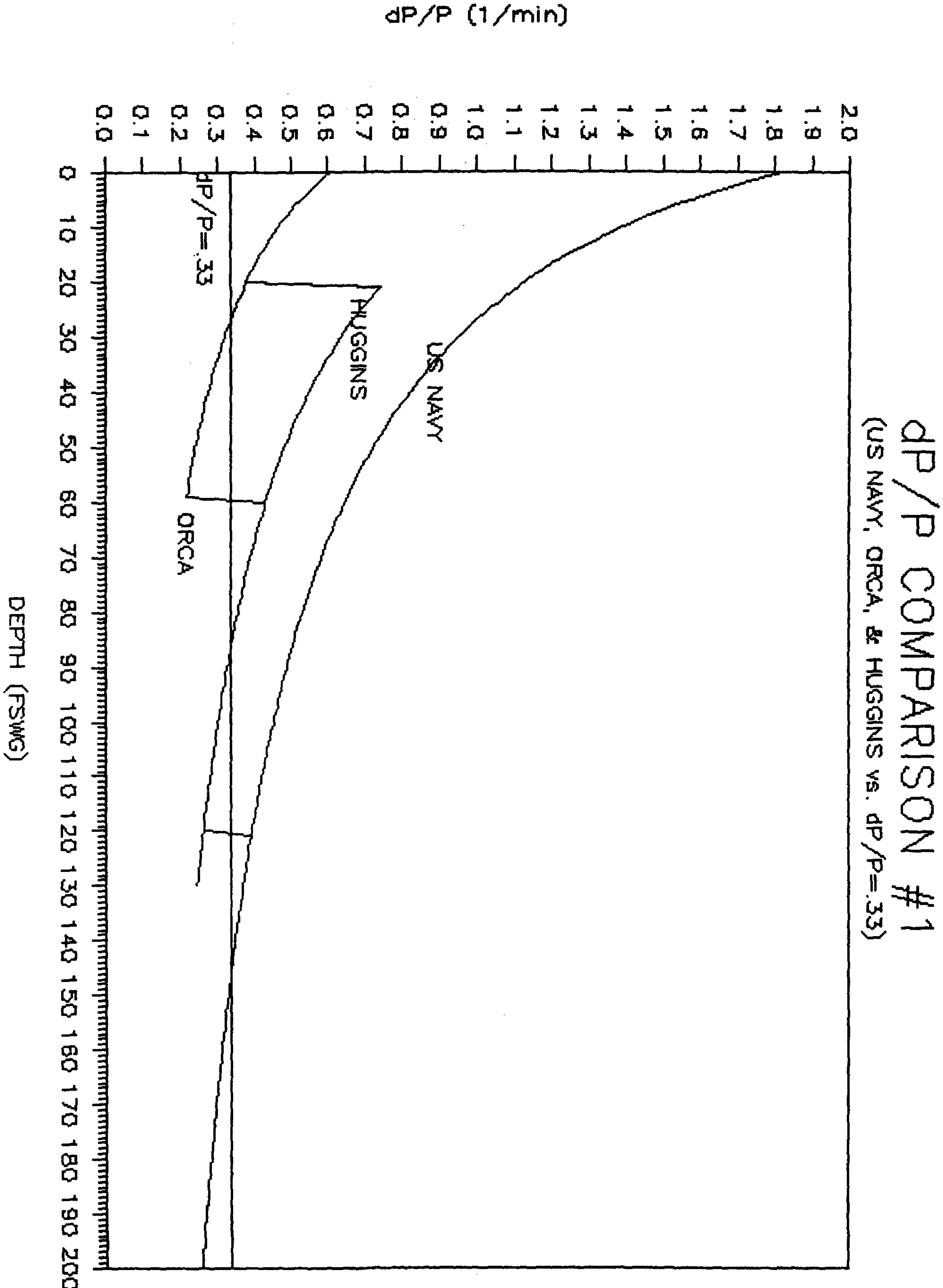
ASCENT RATE COMPARISONS

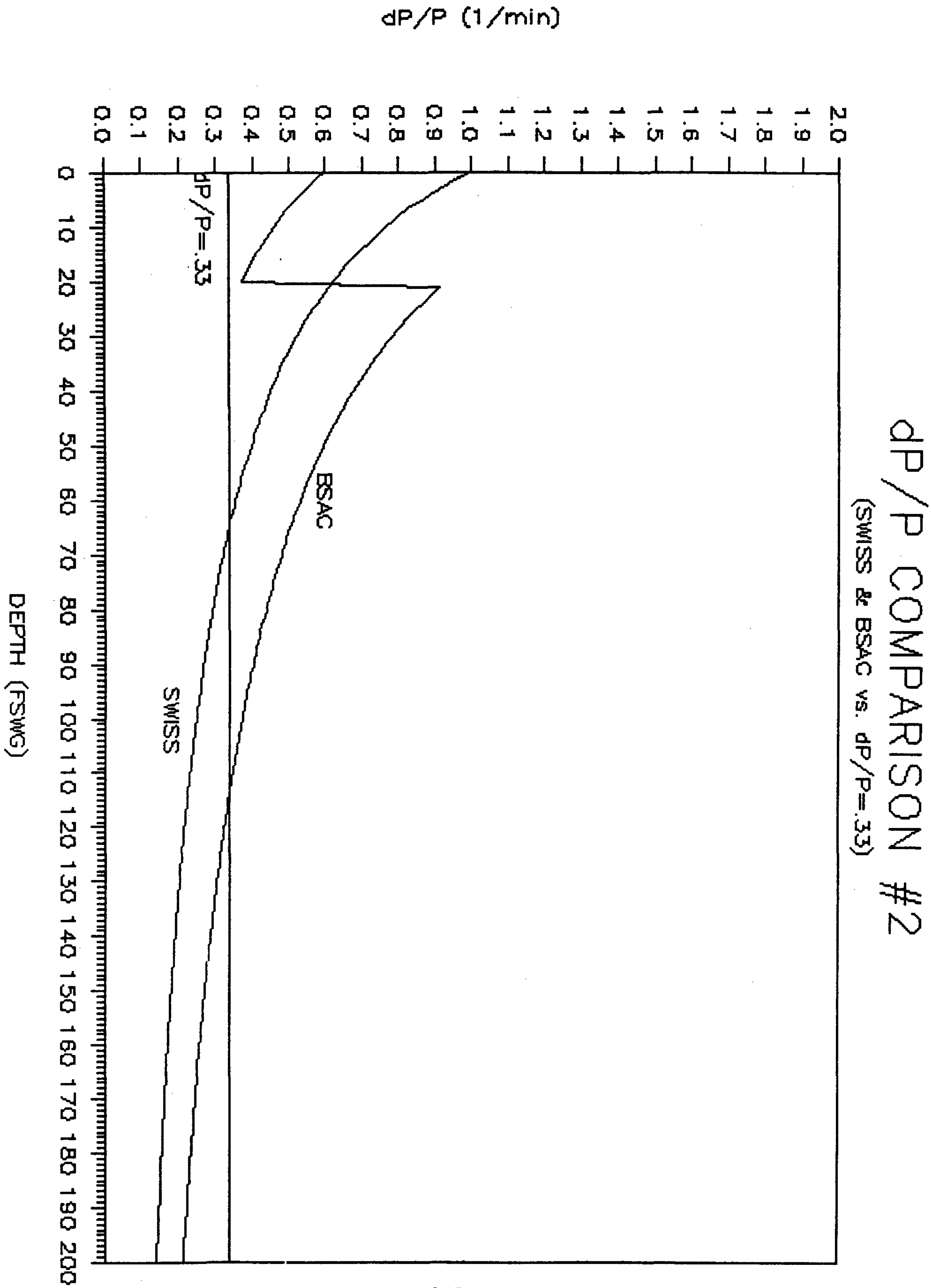
The following graphs represent a comparison of various ascent rates, their resulting times-to-surface, and the reduction of pressure to total pressure ratio (dP/P) produced over a range of depths.

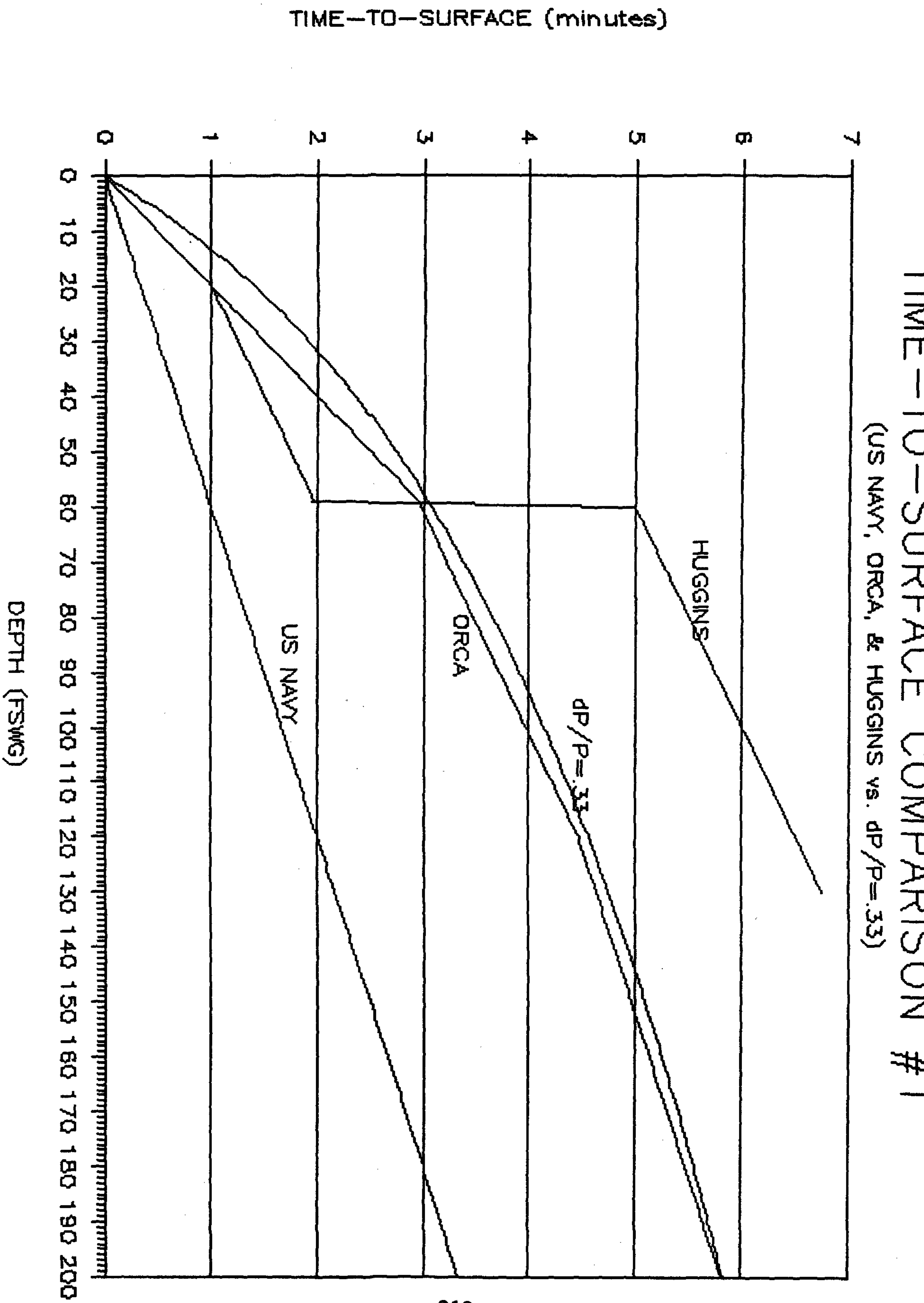
The following ascent criteria are included in the comparison:

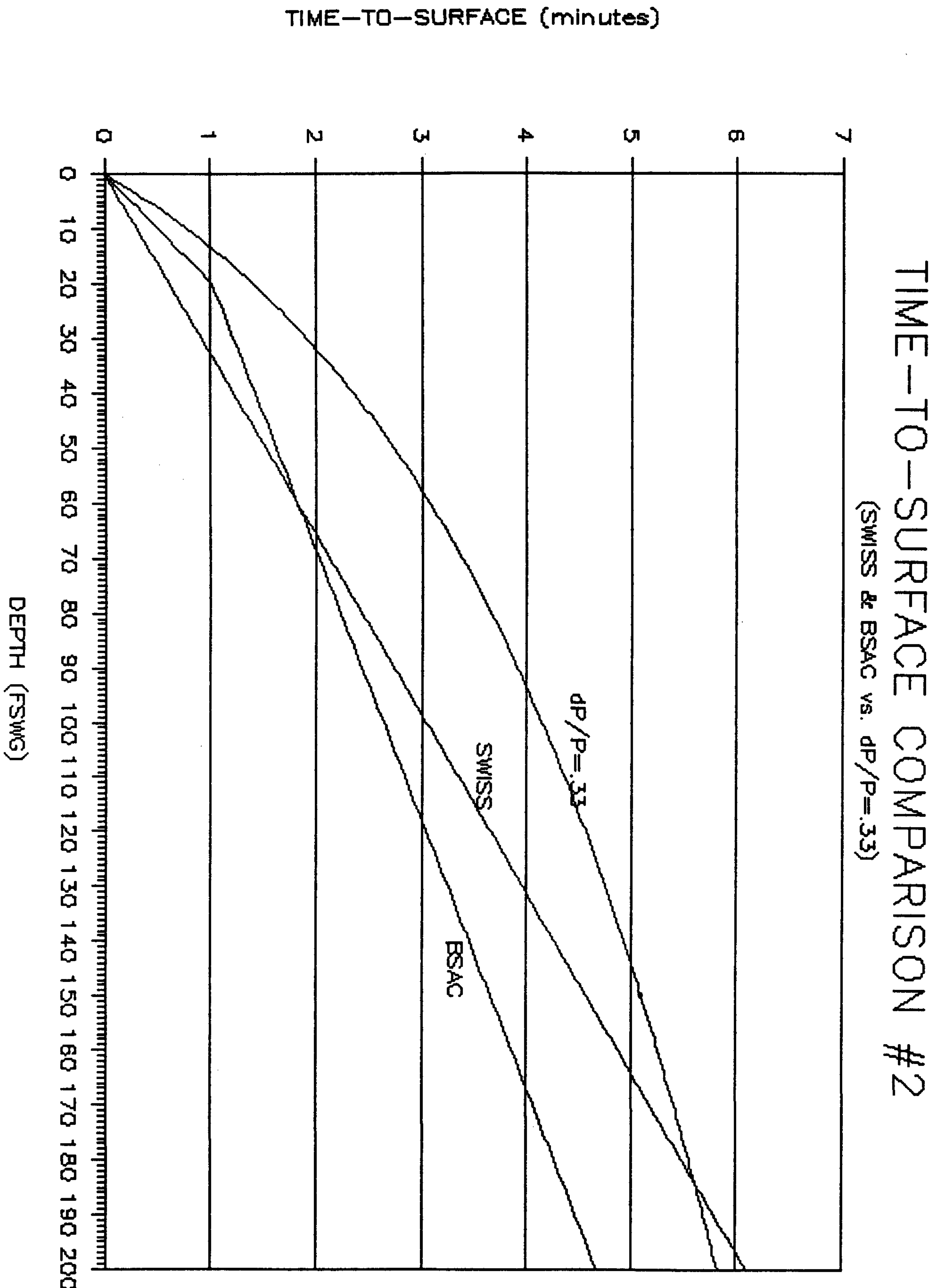
U.S. Navy	60 fsw/min throughout the depth range
Swiss	10 msw/min throughout the depth range
BSAC	15 msw/min to 6 msw 6 msw/min from 6 msw to the surface
Huggins	40 fsw/min to 20 fsw 20 fsw/min from 20 fsw to the surface A 3 minute stop at 20 fsw is required for any dive deeper than 60 fsw.
ORCA	60 fsw/min to 120 fsw 40 fsw/min from 120 fsw to 60 fsw 20 fsw/min from 60 fsw to surface
dP/P=.33	An ascent criteria that maintains a constant dP/P ratio of .33/min. (the average dP/P value obtained from the ORCA ascent criteria from 200 fsw to the surface)


ASCENT RATE COMPARISON
(US NAVY & ORCA vs. dP/P=.33)
ASCENT RATE (fsw/min)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
US NAVY
ORCA
dP/P=.33
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
DEPTH (FSWG)


dP/P COMPARISON #1
(US NAVY, ORCA, & HUGGINS vs. dP/P=.33)
dP/P (1/min)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
US NAVY
HUGGINS
ORCA
dP/P=.33
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
DEPTH (FSWG)


dP/P COMPARISON #2
(SWISS & BSAC vs. dP/P=.33)
dP/P (1/min)
DEPTH (FSWG)
BSAC
SWISS
dP/P=.33


TIME—TO—SURFACE COMPARISON #1
(US NAVY, ORCA, & HUGGINS vs. dP/P=.33)
TIME—TO—SURFACE (minutes)
DEPTH (FSWG)
0
1
2
3
4
5
6
7
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
HUGGINS
dP/P=.33
ORCA
US NAVY


TIME—TO—SURFACE (minutes)
TIME—TO—SURFACE COMPARISON #2
(SWISS & BSAC vs. dP/P=.33)
0 1 2 3 4 5 6 7
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
DEPTH (FSWG)
dP/P=.33
SWISS
BSAC