Proceedings of Reverse Dive Profiles Workshop

Reverse Dive Profiles
Reverse Dive Profiles

October 29 and 30, 1999

Smithsonian Institution
Washington, DC

DAN
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About the Smithsonian Institution
http://www.si.edu/dive

The Smithsonian Institution was established in 1846 with funds bequeathed to the United States by James Smithson. The Institution is an independent trust instrumentality of the United States holding some 140 million artifacts and specimens in its trust for "the increase and diffusion of knowledge". The Institution is also a center for research dedicated to public education, national service, and scholarship in the arts, sciences, and history.

The Smithsonian is composed of sixteen museums and galleries and the National Zoo and numerous research facilities in the United States and abroad. Nine Smithsonian museums are located on the National Mall between the Washington Monument and the Capitol. A three-level underground building houses two museums and the S. Dillon Ripley Center, which includes the International Gallery, offices, and classrooms. Five other museums and the National Zoological Park are elsewhere in Washington, D.C., and the Cooper-Hewitt, National Design Museum and the National Museum of the American Indian are in New York City. The Smithsonian Tropical Research Institute is located in the Republic of Panama, The Smithsonian Environmental Research Center in Edgewater, Maryland, the Smithsonian Marine Station in Fort Pierce, Florida, and the Caribbean Coral Reef Ecosystems Laboratory at Carrie Bow Cay, Belize.

The Smithsonian Scientific Diving Program is in the Office of the Provost and conducts approximately 4,000 scientific dives annually. Headed by the Smithsonian Scientific Diving Officer, a staff of 6 Unit Diving Officers authorizes approximately 200 scientific divers to conduct underwater research under the auspices of the Institution.

About Divers Alert Network
http://www.diversalertnetwork.org

Divers Alert Network (DAN), a nonprofit organization, exists to provide expert information and advice for the benefit of the diving public. DAN's historical and primary function is to provide emergency medical advice and assistance for underwater diving injuries, to work to prevent injuries, and to promote diving safety.

Second, DAN promotes and supports underwater diving research and education, particularly as it relates to the improvement of diving safety, medical treatment and first aid.

Third, DAN strives to provide the most accurate, up-to-date, and unbiased information on issues of common concern to the diving public, primarily, but not exclusively, for diving safety.

For scuba divers worldwide, DAN means safety, health, and peace of mind.

Founded in 1980 to provide an emergency hotline to serve injured divers and the medical personnel who care for them, DAN is a 501(c)(3) non-profit dive safety organization affiliated with Duke University Medical Center in Durham, North Carolina, and supported by the largest membership association of divers in the world.

DAN is best known for its 24-hour diving injury hotline, *ALERT DIVER*, the Dive Safety and Medical Information, and its medical research programs. However, DAN America and its international affiliates also serve the recreational scuba community with diving first aid training programs, dive emergency oxygen equipment, affordable dive accident insurance, and books and videos on scuba safety and health.

Most importantly, DAN is a reference for divers, members of the medical community, and emergency medical services personnel who often refer to DAN for consultation about the management of a relatively unusual kind of emergency.

In addition to supporting diving's lifeline, DAN members receive a number of valuable dive and travel benefits. DAN members are also eligible for the exclusive DAN Tag®, diving's original dive and travel emergency I.D. system.

About the American Academy of Underwater Sciences
http://www.erols.com/aaus

The mission of the American Academy of Underwater Sciences (AAUS) is to promote the safety and welfare of its members who engage in underwater science.

To accomplish this mission, the Academy has established five objectives. These objectives underlie all Academy activities:

- To develop, review and revise standards for safe scientific diving certification and the safe operation of scientific diving programs;

- To collect, review and distribute statistics relating to scientific diving activities and scientific diving incidents;

- To conduct symposia and workshops to educate the membership and others in safe scientific diving programs and practices;

- To represent the scientific diving interests of the membership before other organizations and government agencies; and,

- To fund research, education and development of safe scientific diving programs and practices.

Organized in 1977, the AAUS was incorporated in the State of California in 1983. The Board of Directors, responsible for governing the corporation, consists of an elected President, President-Elect, Secretary, three Directors, an appointed Treasurer and four standing Committee Chairs (Standards, Statistics, Membership and Finance).

An Advisory Board of past board members provides continuity and a core of expertise to the AAUS.

Membership in the Academy is granted to individuals in the member, associate member and student member categories, and to organizations currently engaged in scientific diving activities.

In 1982, OSHA exempted scientific diving from commercial diving regulations (29 CFR Part 1910, Subpart T) under certain conditions. The final guidelines for the exemption became effective in 1985 (Federal Register, Vol. 50, No.6, p.1046). The AAUS is recognized by OSHA as the scientific diving standard-setting organization.

One of the primary contributions of the AAUS to the scientific diving community is the promulgation of *The AAUS Standards for Scientific Diving Certification and Operation of Scientific Diving Programs*. A consensual guideline for scientific diving programs, this document is currently the "standard" of the scientific diving community. Followed by all AAUS Organizational Members, these standards allow for reciprocity between institutions, and are widely used throughout the United States and in many foreign countries. Peer reviewed within the AAUS on a regular basis, they represent the consensus of the scientific diving community and state-of-the-art technologies. To date, over 6,000 copies of this document have been provided to the scientific diving community.

About the Diving Equipment and Marketing Association
http://www.dema.org

DEMA's Mission

The Diving Equipment and Marketing Association is a global group of companies and organizations whose mission is to promote and provide sustainable growth in safe recreational diving while protecting the underwater environment.

Goals and Priorities of DEMA

I. Marketing and Promotional Goal: To increase the awareness of diving to the public. The Marketing and Promotional Plan will include, but not be limited to, a plan that will meet the following parameters:
   A. National in scope
      - Increase participation of new divers
      - Keep existing divers active;
   B. Recognizable as industry campaign;
   C. Has measurable results;
   D. Utilizes appropriate internal and external resources to coordinate promotional efforts; and,
   E. Develops marketing partnerships with major businesses (outside of our industry).

II. Research Goals are to make DEMA the resource for the collection and dissemination of consistent industry data that includes:
   A. Certification data;
   B. Retail sales data;
   C. Manufacturing data; and,
   D. Consumer attitude and interest data
      - Why consumers dive/don't dive
      - Why divers stop diving (drop out).

III. Membership Goals are to:
   A. Create value for the membership through the ongoing development of member benefits;
   B. Implement continued and effective communication; and,
   C. Increase membership by 10% per year.

IV. DEMA Trade Show Goals are to:
   A. Make the DEMA show more beneficial to members, measured by:
      - Better working relationship between show management and exhibitors;
      - Increase perceived value to Attendees; and,
      - Increase perceived value to Exhibitors;
   B. Produce a more successful trade show, measured by:
      - More buyers;
      - More net profit to DEMA; and,
      - Increase number of exhibit spaces in show;
   C. Insure future revenue streams for DEMA
      - Decide on future management of show
      - Assure availability of future venues

V. Budget: Manage the financial resources of the association to assure that a maximum amount of available resources are targeted toward the successful funding of the prioritized goals of the association.

DEMA Represents the Whole Industry

DEMA, as the Diving Equipment and Marketing Association, was formed to encompass the entire diving industry: manufacturers, retailers, publications/media, travel, resorts, education and certification agencies, and government and non-government tourism organizations. In addition to representing all industry stakeholder groups, DEMA is a truly global organization as evidenced by the DEMA multi-national Dive Business Seminars, the Asia Pacific Advisory Committee, the DEMA Europe office in Brussels and our European Advisory Committee.

About *DIVE TRAINING* Magazine
5215 Crooked Road
Parkville, MO 64152
(816) 741-5151

DIVE TRAINING magazine is written and edited for divers in training, their instructors and those who own and operate dive retail operations. Launched in 1991 the publication has become recognized as a leader in presenting how-to, back-to-basics and environmental information for divers of all experience levels. Distributed through over 2,000 local retailers, on the newsstand and through individual subscriptions, the magazine is widely read and quoted.

The Smithsonian Institution World Ocean Report is a regular *DIVE TRAINING* editorial feature that discusses scientific research around the world. In addition, each monthly issue of *DIVE TRAINING* carries of wide variety of information on diving techniques, proper equipment usage, training topics, instructor tips, travel destinations and much, much more.

With the motto of "Good Divers are Always Learning," *DIVE TRAINING* is focused on providing its audience with easy to read articles that have the kind of substance needed to inform, educate, and remind divers of their responsibilities to themselves, their dive companions and the ocean environment. At the same time the editorial is designed to keep divers interested and excited about the world of underwater adventure.

Acknowledgments

I wish to extend sincere appreciation and acknowledgement to the Reverse Dive Profiles Workshop Co-Sponsors: Dr. J. Dennis O'Connor (Smithsonian Institution), Dr. Peter B. Bennett (Divers Alert Network), Mr. Edward J. Maney (American Academy of Underwater Sciences), Ms. Regina Franklin (Diving Equipment and Marketing Association), and Mr. Gary S. Worden (*DIVE TRAINING* Magazine). This diving safety research effort would not have been possible without their combined support.

Many thanks to all the workshop speakers who helped immensely by submitting their manuscripts on time. The short turn-around time for the production of proceedings for a workshop of this size is unprecedented and could not have happened without the full cooperation of the authors. We are very satisfied to have assembled this expert cast of professionals who shared their expertise on this topic with the workshop. The international, interdisciplinary nature of this project is evidenced by the participation of colleagues from the recreational, commercial, military and scientific diving communities and the papers they presented. Participants from Scotland, Norway, Finland, Switzerland, Germany and Canada had the opportunity to interact with colleagues from across the United States.

Smithsonian Institution staff who were very helpful during various phases of this workshop's organization deserve special recognition: Cheryl L. Thacker (NMNH) for her assistance with many of the complicated logistical aspects, Shelly Borden (Office of the Provost) for her assistance with participant travel and purchase orders, Joan R. Zavala (Office of the Provost) for authorizing expenditures and keeping track of the budget, Mary R. Tanner (Office of the Provost) for helping me convince our Provost that this project was worth the effort to increase our diving safety knowledge, and Anson (Tuck) Hines (SERC) for his support and facilitation at SERC.

Finally, I thank my Workshop Co-Chair, Charles E. Lehner, for his pertinent, diving physiological insights and support, and above all, pleasant willingness to ensure that this workshop and proceedings become a model for those that follow. I enjoyed our collaboration and, from all indicators, have the sense that we succeeded in accomplishing our workshop objectives.

Michael A. Lang
Smithsonin Institution
Workshop Co-Chair

PRESENTATION OF THE ISSUES

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Washington, D.C. 20560-0415 U.S.A.

The conduct of reverse dive profiles is being performed with increasing frequency. Some dive industry leaders have taken the position that if a particular brand of dive computer permits a reverse dive profile, then such a dive must therefore be acceptable. Questions have arisen from diving supervisors and colleagues with respect to the appropriateness of conducting reverse dive profiles. Is there a physiological basis for not conducting these or is there a mechanical constraint within the dive tables that penalizes the diver with a reduction in bottom time for making a deep dive after a shallow exposure? Is the common, recommended practice of conducting progressively shallower dives favored by experimental evidence? Within a single profile exposure, for what reasons is it contraindicative to spike to a deeper depth after a long shallow exposure? What is the role and importance of bubble nucleation in assessing the risk associated with reverse dive profiles? Does it really matter in which order dives are conducted as long as one keeps track of nitrogen loads and performs adequate decompression? What role does the rate of ascent play after conducting reverse dive profiles? How do diving supervisors manage divers after reviewing submitted dive logs showing reverse pressure exposures? Is there an acceptable gray zone for reverse dive profiles, *e.g.*, not more than a 10-meter pressure differential?

These questions framed the scope and objectives of this workshop. The interdisciplinary backgrounds of this workshop's participants are important in combating insularity, because, in our particular field, you can do your research and get results and know more and more about less and less. Questions surrounding an activity such as diving demand significant input from various segments of the community: professionals in physiology, physics, decompression modeling and hyperbaric medicine; diving equipment manufacturers; and training organizations from the recreational, scientific, commercial and military communities.

A critical examination of reverse dive profiles was a logical extension of the dive computer, biomechanics of safe ascents, and repetitive diving workshops where we successfully addressed those related issues as an industry. Through formal presentations and discussions by workshop participants, findings and a conclusion will perhaps be delivered as a consensus.

It would not be unreasonable, for the purposes of this workshop, to define a reverse dive profile as either two dives performed within 12 hours in which the second dive is deeper than the first; or, as the performance of a single dive in which the latter portion of the dive is deeper than the earlier portion.

THE EVOLUTION OF REPETITIVE DIVING: FROM HALDANE (1908) TO HARDY (1999)

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The historical evolution of both dive tables and dive computers is presented and, where relevant, theoretically analyzed. Experimental data are included, and where available, test data for reverse profiles are identified. An attempt is made to summarize the present state-of-the-art, and an analysis of multilevel diving is attempted. Finally, an opinion as to the relevance of a rule to restrict reverse profiles is included.

Introduction

If a diver is using the U.S. Navy Repetitive Dive Table, "reverse profiles," *i.e*, deeper second dives, always produce less bottom time or increased decompression times for the same bottom times. Thus, one reason for avoiding deeper repetitive dives is a practical one. If a diver is using the PADI Recreational Dive Planner or a dive computer that is based on the same experimental data base, one reason for avoiding deeper repetitive dives is that they are beyond the tested experimental envelope.

Both are sound reasons. However, the question still remains as to whether there is any theoretically or experimentally demonstrable reason that a subsequent repetitive dive should be shallower than the previous dive. For recreational divers using a dive computer, multilevel diving poses the more complicated issue of what is the proper depth for comparison of dive profiles.

The historical evolution of both dive tables and dive computers is reviewed and, where relevant, theoretically analyzed. Experimental data, in particular test data for reverse profiles, are evaluated. An analysis of multilevel diving is attempted, and an opinion as to the relevance of a rule to restrict reverse profiles is included.

A Little History

Rules for repetitive diving are as old as the foundation of all present decompression theories. "A diver has often to descend twice or (more) at short intervals. To meet the increased risk . . . add together the two periods of exposure and adopt the corresponding rate of decompression shown in the Tables. As the interval between successive dives increases, the added danger of decompression diminishes. With an hours' interval the extra precautions might be halved, and with two or three hours' interval they might be omitted." - (Boycott, Damant, and Haldane, 1908).

The UNIVAC Method

Haldane's rule, at least the simpler form of it, was adopted by the U. S. Navy. "Use the combined times on bottom for all exposures and the depth of the latest dive in determining the decompression schedule to use." - Bureau of Ships Diving Manual (1952).

By the mid-1950's, Dwyer, des Granges, and others at the Navy Experimental Diving Unit (NEDU) recognized that this rule was unsatisfactory for a number of reasons and began evaluating other methods. Dwyer (1956) reported the following method (referred to as the "UNIVAC method" because it required calculations by the UNIVAC computer at the David Taylor Model Basin). "To keep the number of tables within practical limits, it is desirable to assume that for the preceding dive all tissues surfaced fully saturated to their maximum allowable tissue pressures."

Dwyer's approach does not depend in any way on the previous dive, since all tissues are assumed to be saturated to their allowable limits. It does, however, depend on the depth of the repetitive dive. Consider, for example, two no-decompression (NoD) dives to depths of 60 and 100 ft, and contrast Dwyer's theory with the Bureau of Ships Diving Manual (1952) rule of simply adding times. As can be seen in Figure 1, for the conventional procedure of making the 100 ft dive first, there is the possibility that for short surface intervals the BuShip rule is inadequate. For the reverse profile example shown in Figure 2, the BuShip rule is dramatically over-conservative. Regardless, the BuShip rule clearly favors the conventional wisdom of making the deep dive first.

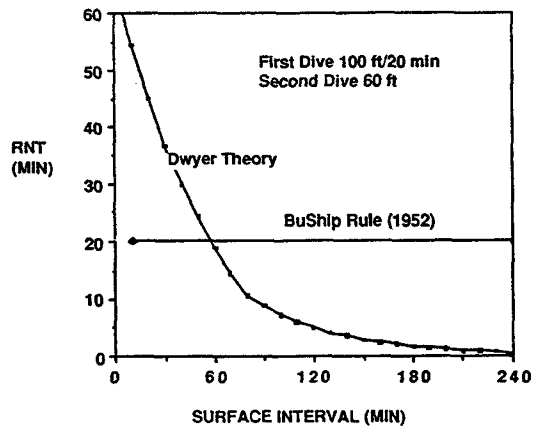

Figure 1. BuShip 1952 rule compared to the theory of Dwyer for conventional shallower repetitive dive. RNT = Residual Nitrogen Time.

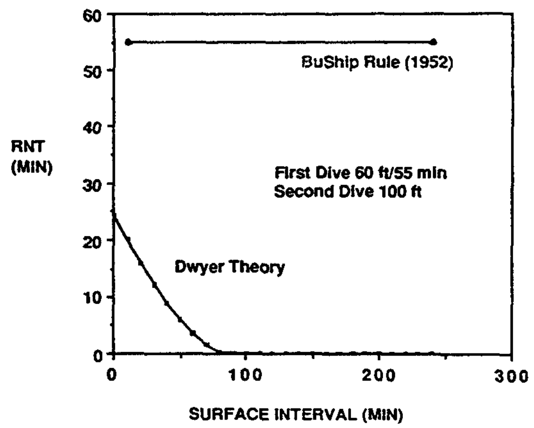

Figure 2. BuShip 1952 rule compared to the theory of Dwyer for deeper repetitive dive.

Dwyer's method appears to be a clear improvement dependent solely on the premise upon which the entire decompression tables are based. However, what does it say about reverse profiles? In Figure 3, the fraction of the NoD times based on Dwyer's theory indicates that Dwyer's theory <u>favors</u> reverse profiles, at least for NoD dives. The reason for this is that NoD diving at shallower depths are controlled by slower tissues, and since all tissues are assumed to be saturated at the beginning of the surface interval, NoD times at deeper depths recover faster.

However, Dwyer's (1956) theory was not recommended for fleet use. The reasons for abandoning the method reported by Dwyer are stated by des Granges (1957) as follows:

1) "One of the greatest drawbacks to the UNIVAC method is the number of pages that would be required. Six surface intervals would require 6 to 12 pages . . . "

2) "The amount (of new calculations) is debatable, but would be considerable."

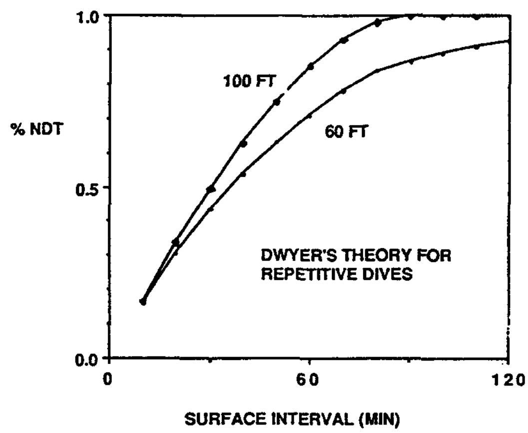

Figure 3. Dwyer's theory for repetitive dives (%NDT = No-Decompression Time)

Thus, the number of pages required for Dwyer's method and the limitations of the 1957 UNIVAC computer would appear to be the primary reasons that the present U.S. Navy Repetitive Dive Table does not favor reverse profiles.

The U.S. Navy Repetitive Dive Table

The approach defined by des Granges, which lead to the present U.S. Navy Repetitive Dive Table, calls for repetitive dives to be controlled by the 120 minute tissue. For dives that are entirely controlled by the 120 minute tissue, the methods of des Granges and Dwyer should be identical. A 200 minute dive at 60 ft, for which over one hour of decompression is required, is one such example, and, as can be seen in Figure 4, Dwyer's theory and the present Navy Table are in close agreement.

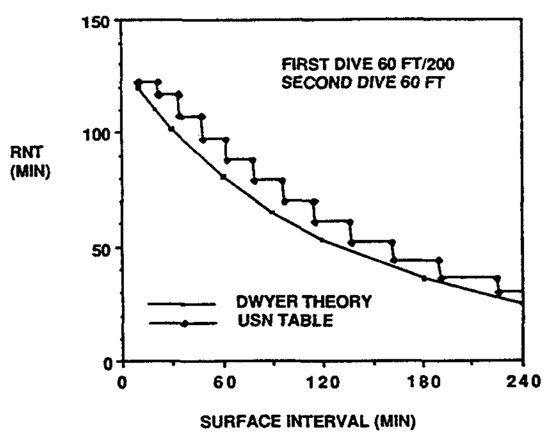

Figure 4. A comparison of Dwyer's theory with U.S. Navy Repetitive Dive Table

In Figure 5, the theories are contrasted for a NoD dive at 100 ft followed by a repetitive dive to 60 ft. For short surface intervals, Dwyer's theory is more conservative because of the assumption of fully saturated tissues. However, for surface intervals greater than about 60 minutes, the Navy Table is more conservative. In Figure 6, the comparable example of a reverse profile shows that the Table is considerably more conservative than even the assumed fully-saturated tissues approach of Dwyer.

The reasons for this seeming *non sequitur* is that the deeper dive is controlled by a much faster tissue. We shall return to this issue later, but for now it is useful to review the experimental validation conducted by des Granges.

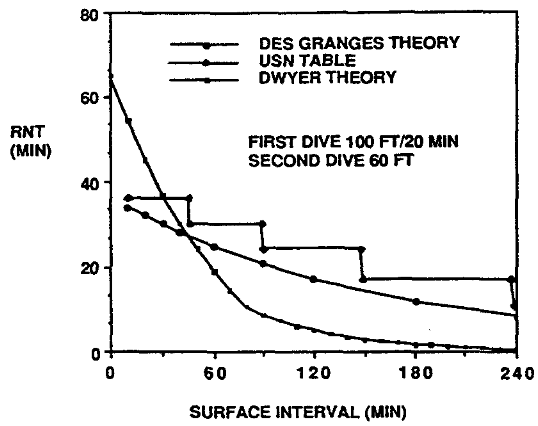

Figure 5. The theories of Dwyer and des Granges compared for a NoD first dive followed by a conventional shallower repetitive dive.

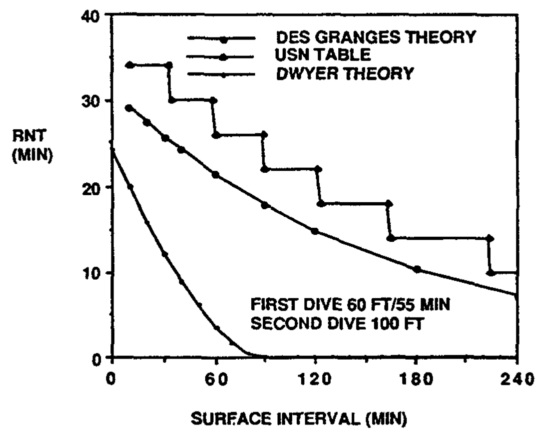

Figure 6. The theories of Dwyer and des Granges compared for a NoD first dive followed by a deeper repetitive dive.

Some Data at Last

Over 60 dives were conducted to validate the Repetitive Dive Table devised by des Granges. These dives are reported fully in the Appendix, but in order to get a sense of the emphasis of the approach and des Granges's attitude toward reverse profiles, the data are presented in graphical form.

Shown in Figures 7 and 8 are histograms of the depths of the first and second dives, and it is clear that the emphasis of these series of tests was on reverse profiles.

This is shown even more clearly in Figure 9, where the depth of the second dive is plotted versus the depth of the first dive. Over 62% of the second dives were deeper than the first dives. In Figure 10, a histogram of the surface intervals shows that a major emphasis of des Granges was short surface intervals, where the new theory was less conservative than the approach of Dwyer.

Before leaving these data, it should be noted that a majority of these dives were decompression dives (46% of the first dives, 70% of the second dives, and 43% of both dives required decompression).

In summary, des Granges does not appear to have believed that reverse profiles should be avoided. Further, his test data do not show any bias in favor of shallower repetitive dives. The primary conclusion of these tests was that with the avoidance of any repetitive dives deeper than 190 ft, the U.S. Navy Repetitive Dive Table represented a valid approach.

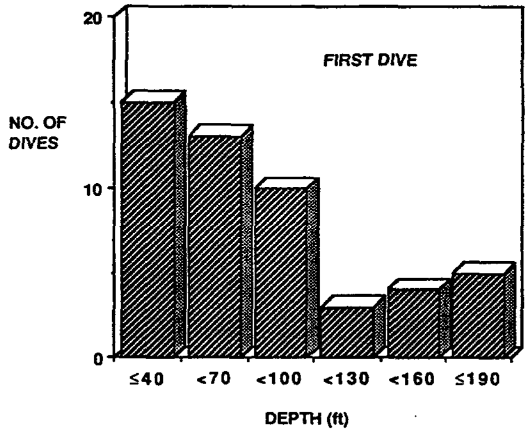

Figure 7. Depth distribution of first dives tested by des Granges

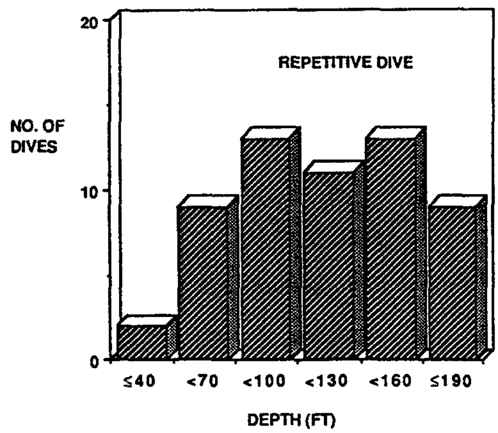

Figure 8. Depth distribution of repetitive dives tested by des Granges

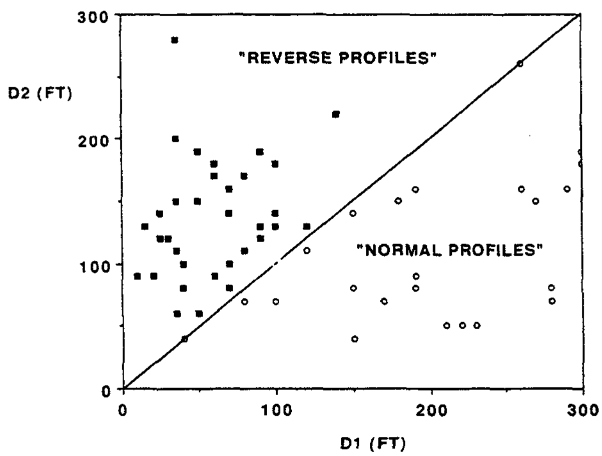

Figure 9. Distribution of depths for des Granges's test data.

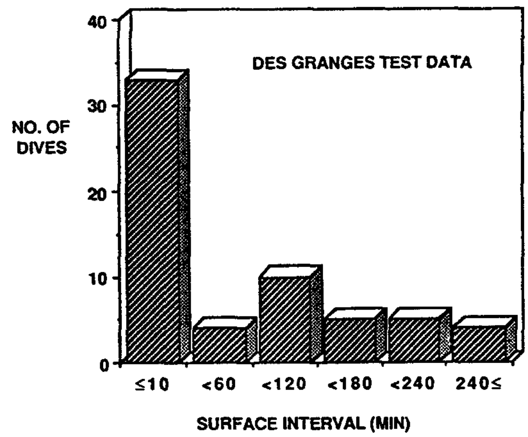

Figure 10. Surface intervals for des Granges's test data

Time for Some Theory

If we return to the same depth after no surface interval and ignoring decompression during ascent, any tissue could be used to quantify the first dive. Further, if we choose the slowest tissue and there is a surface interval, this will always be a conservative choice. However, what if the depth is different? Is the Residual Nitrogen Time (RNT) calculated always greatest for the 120 minute tissue? The answer is no, but almost, and the problem does not lie in deeper repetitive dives.

In addition to the 190 ft restriction on repetitive dives, des Granges cautions divers to observe a minimum 10 minute surface interval. The reason for this is a theoretical consideration rather than a practical one. This problem is illustrated in Figure 11, where nitrogen loading for short surface intervals following a dive to 100 ft for 20 minutes is presented.

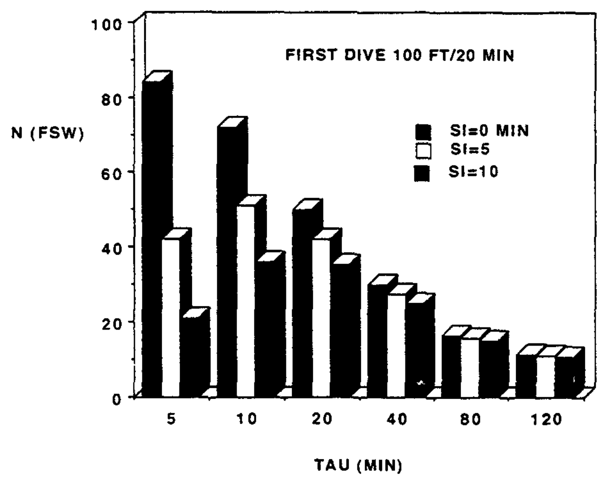

Figure 11. Nitrogen loading for various tissues as a function of surface interval for a dive to 100 ft.

By definition, RNT is the time spent at the repetitive depth required to reach the residual nitrogen loading, N. When the repetitive depth is less than N, RNT has no meaning. For a minimum repetitive depth of 40 ft, this no longer presents a problem for surface intervals greater than 10 minutes.

For the example of a dive to 60 ft for 55 minutes illustrated in Figure 12, it is clear that no such issue exists for any depth greater than 60 ft, let alone a repetitive dive to 100 ft, *i.e*, reverse profiles present no limitation on the surface interval.

Actually, there are examples for which the 10-minute surface interval is not sufficient to insure that the RNT for the 120 minute tissue is greater than all others, but such examples are rare and vanish well before 15 minutes. The concept defined by des Granges appears to be theoretically sound with the minor exception of very short surface intervals, which he recognized, and then only for shallower repetitive dives.

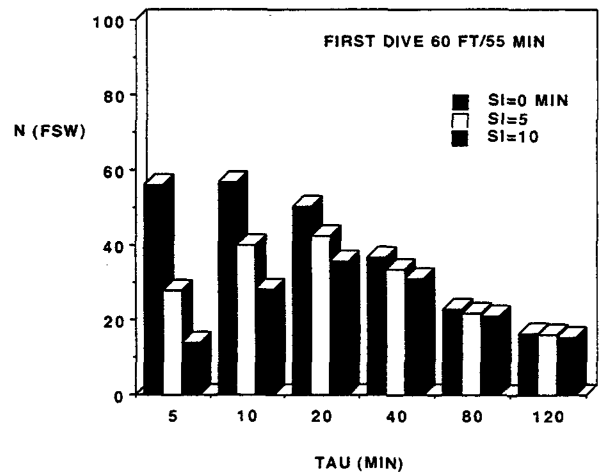

Figure 12. Nitrogen loading for various tissues as a function of surface interval for a dive to 60 ft.

Dive Computers and New Data

By the late 1970's, inexpensive pressure transducers, microprocessors, and LCDs became available and many efforts were underway to develop what would become dive computers. The first commercially successful device was the EDGE (Loyst *et al*, 1991), which was distributed by ORCA industries and lead to the pioneering experiments on multilevel diving by Karl Huggins (1983).

Karl Huggins

These experiments included 3 dives to maximum depths of 130 ft for bottom times in excess of 40 minutes. The U.S. Navy Standard Air Decompression Tables call for over 60 minutes of decompression. Huggins's tests (see below), which were successful, used none. Based on maximum depth, this series of tests also consistently included the reverse profiles illustrated below:

	Day 1	Day 2	Day 3
Dive 1	D_{MAX}=130 ft	D_{MAX}=130 ft	D_{MAX}=130 ft
Dive 2	D_{MAX}=25 ft	D_{MAX}=60 ft	D_{MAX}=40 ft
Dive 3	D_{MAX}=100 ft	D_{MAX}=110 ft	D_{MAX}=70 ft

However, the final depths while "reverse" for the third dive present a somewhat less convincing case

	Day 1	Day 2	Day 3
Dive 1	D_{FINAL}=40 ft	D_{FINAL}=50 ft	D_{FINAL}=30 ft
Dive 2	D_{FINAL}=25 ft	D_{FINAL}=25 ft	D_{FINAL}=25 ft
Dive 3	D_{FINAL}=40 ft	D_{FINAL}=50 ft	D_{FINAL}=40 ft

Regardless of the issue of reverse profiles, these test dives demonstrated beyond any reasonable doubt that multilevel diving, the most important contribution of dive computers, was a demonstrably sound procedure.

Capt. Ed Thalmann

During this same period, the U.S. Navy was embarked on an effort to develop a dive computer for use with the MK-15 rebreather, which produces a breathing mixture with a constant oxygen content of 0.7 ata. This effort, which was directed by Capt. Ed Thalmann (1980, 1983, 1986), was accompanied by extensive testing of various decompression algorithms. In the course of these test programs, Thalmann tested at least 2 reverse profiles successfully.

EAD (FT)	DIVE TIME (MIN)		EAD(FT)	DIVE TIME (MIN)
30	210		43	142
0	80		0	80
106	16		81	8

However, the most significant result of this series of test programs was the conclusion that safe repetitive dive profiles could not be attained when maintaining reasonable NoD limits unless the theoretical relaxation of nitrogen loading was abandoned. Thalmann called this a "E-E model" referring to the exponential uptake and exponential relaxation, and while this model was unsatisfactory, the U.S. Navy Repetitive Dive Table was shown to be considerably more conservative than necessary.

Thalmann (1986) performed a systematic evaluation of various algorithms for NoD repetitive air dives at depths of 80, 100, 120, and 150 ft with a 60-minute surface interval. At the 80 ft depth he tested two additional surface intervals of 95 and 180 minutes, and finally at the depth of 100 ft, he added a third dive.

All of the test dives with the 60-minute surface interval were successful and are shown in Figure 13, contrasted with the theory of des Granges and a E-E theory. As can be seen, the RNT based on the 120-minute tissue is shown to be overly conservative by about a factor of 2. In Figure 14, the test data at 95 and 180-minute surface intervals for the 80 ft dives are again contrasted with the theory of des Granges and the E-E theory. For these additional test dives, the results were not always satisfactory, indicating that these intermediate RNTs are near an acceptable limit.

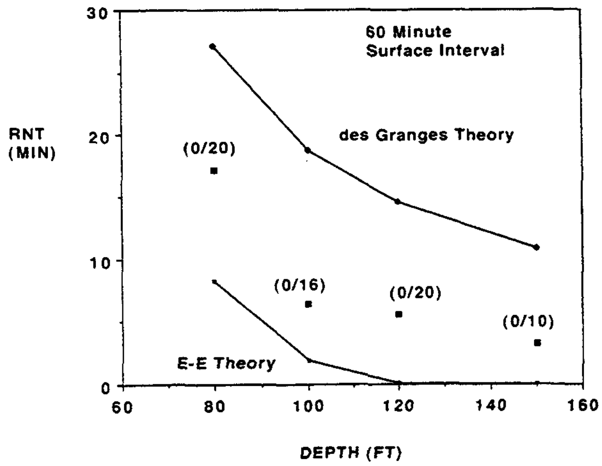

Figure 13. Thalmann's repetitive NoD air dives at various depths with a 60-min surface interval.

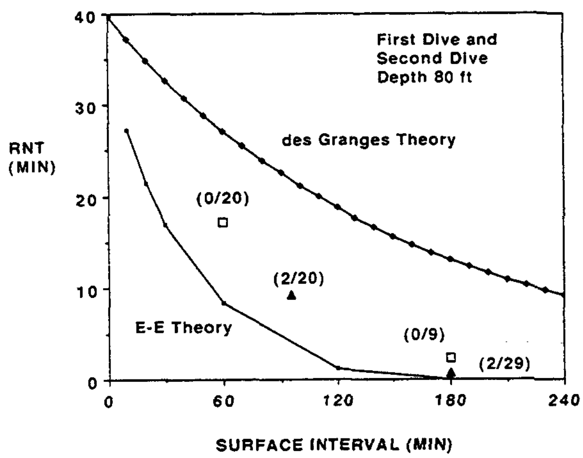

Figure 14. Thalmann test data for 80 ft repetitive NoD air dives.

The triple NoD dives to 100 ft were remarkably unsuccessful. Out of 19 test dives, 2 cases of DCS in the test divers plus one case of a tender that was 7 ft shallower and warm. This result, coupled with the data of Leitch and Barnard that is described below, indicates that repetitive deep dives seem to have inherent risks that are not comprehended by theories that work well for other dive profiles.

Depth/Time	Surface Int	Depth/Time	Surface Int	Depth/Time
100ft/26.5	60 min	100 ft/17.7	60 min	100 ft/15.9

As can be seen in Figure 13, while des Granges' theory is overly conservative, the E-E Model fails for these 80 ft repetitive air dives. Other repetitive dive profiles were tested: some successfully, others not. However, their interpretation is clouded by the simultaneous attempt to increase established NoD limits.

Dr. Carl Edmonds

In 1989, Lang and Hamilton chaired the American Academy of Underwater Sciences (AAUS) workshop on dive computers at Catalina Island. During this meeting, Dr. Carl Edmonds pointed out that "EDGE-like" dive computers allowed multiple deep repetitive dives with virtually no restrictions, whereas the tests of Leitch and Barnard (1982) indicated that even with limited NoD times, this type of model was inadequate.

Leitch and Barnard

The following test dives produced a considerable percentage of cases of DCS.

DEPTH (FT	DIVE TIME (MIN)		DEPTH (FT)	DIVE TIME (MIN)
120-140	10		147	5
0	120		0	60
120-140	10		147	5
0	120		0	60
120-140	10		147	5

Interestingly, repetitive deep decompression dives (See Fife *et al*, 1992) that do not push the limits do not seem to have the same problems.

The Leitch and Barnard tests also involved one successful series of reverse profiles:

DEPTH (FT)	DIVE TIME (MIN)
82	5
0	60
115	5
0	60
147	5

PADI, Rogers, and Powell

Within one year of the AAUS workshop on dive computers, PADI had issued a new set of repetitive dive tables based on an extensive set of multilevel, repetitive NoD dives conceived by Dr. Ray Rogers and conducted by Dr. Michael Powell. Rogers hypothesized and Powell demonstrated that for NoD dives with reduced limits, the 120-minute control tissue could be relaxed to a 60-minute tissue.

This series of 743 test dives (Powell *et al.*, 1986) represented a dramatic extension of the original tests by Huggins as well as the test of a new hypothesis for repetitive recreational diving. The dives were Doppler monitored and were successful.

Pelagic Dive Computers

Beginning in 1990, all Pelagic dive computers have used this database for validation of their algorithms. Examples of the comparison of these data with a Pelagic dive computer are shown below.

Table 1. Pelagic Dive Computer compared to Powell Test Data

Depth (ft)	Test Data(min)	Pelagic DC (min)
100	20	19.7
50	29	29.3
110	17	16.5
0	37	37
65	31	30.1
0	23	23
45	51	46.1
85	27	28.1
0	43	43
45	72	68.5
45	100	101.5
0	75	75
85	20	21.3

As can be seen, Powell's test data include one example of a reverse profile. With the exception of deep repetitive dives, such as those demonstrated by Leitch and Barnard to be unsafe, Pelagic dive computers have no explicit restriction on reverse profiles.

Jon Hardy

Up until recently, the term deep repetitive dives has been used to describe the unsuccessful tests of Thalmann (1986) and Leitch and Barnard (1982). These consisted of multiple dives to the same depth followed by a direct ascent to the surface with the depths varying between 100 and 150 ft. Perhaps after reviewing the recent results of Hardy (1999), these dives should be more carefully referred to as repetitive deep bounce dives.

A total of 14 man-dives were conducted in the fall of 1998 that involved reverse profiles. The first dive was made to a shallow depth of about 55 ft followed by a much deeper repetitive dive to a depth of 125 ft. The surface interval was 60 minutes, and no cases of DCS occurred. However, these dives have two features that are different from the problematic dives previously described. First, the initial dive is to a shallow depth. A second, more important, feature is that they did not involve a direct ascent to the surface.

As can be seen below, the ascent rates were approximately 25 ft/min, which is equivalent to a 3 minute stop at 60 ft for an ascent rate of 60 ft/min, and all dives had a 3 minute stop at 10 ft.

Dive No.	Descent	D1	T1	Ascent	SI	Descent	D2	T2	Ascent	10 FT
1	2	52	36	4	60	3	125	9	5	3
2	3	55	40	3	60	3	125	8	7	4
3	1	58	30	3	60	2	125	9	5	3
4	1	57	29	3	60	2	125	9	5	3
5	1	59	34	2	60	2	125	9	4	3

No incidents of DCS occurred, and the generally accepted "rule" of always making the deepest dive first has been tested once again, but with the important exceptions listed above.

Multilevel Diving

Multilevel diving represents a new issue when evaluating what is a reverse profile. Recall that all of Huggins' final repetitive dives were reverse profiles when the maximum depth was considered. However, if one looks at the theoretical nitrogen loading of various tissues after a single dive where repetitive control is not an issue, the following figures indicate that maximum depths may not be the proper criteria.

In Figure 15, the surfacing value of nitrogen loading for various tissues is shown for two of Powell's test dives: Profile #1 is a bounce dive to 130 ft for 12 minutes, and Profile #14 is a multilevel dive with a maximum depth of 130 ft/12 followed by 20 ft/21, 45 ft/23, and 35 ft/42 minutes. As can be seen, the resulting nitrogen loading is dramatically different.

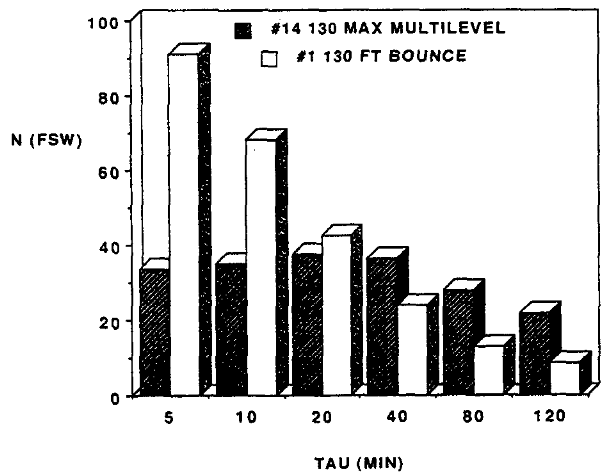

Figure 15. Nitrogen loading following 2 dives to 130 ft max depth.

In Figure 16, Powell's #14 multilevel dive is compared with a single bounce dive to 45 ft for 100 minutes. Clearly, the nitrogen loading is much more similar, with only the fastest tissues exhibiting any significant differences.

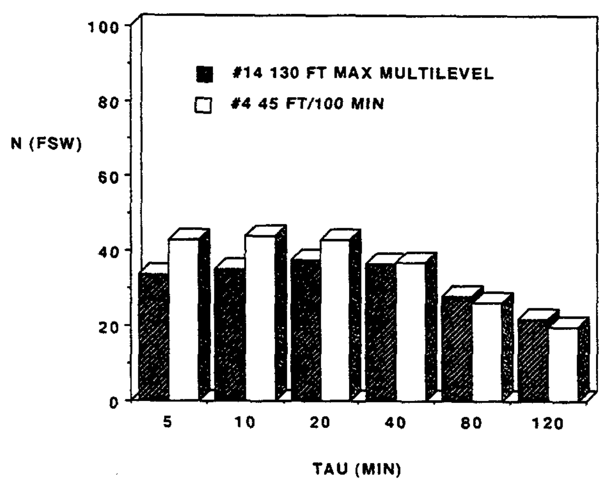

Figure 16. Powell's 130 ft max depth multilevel dive compared to a long shallow dive.

It is concluded that for dive computer controlled NoD diving, the maximum depth is not a proper criterion for categorizing a repetitive dive as a reverse profile. Many recreational dives, including repetitive dives, involve maximum depths in excess of 100 ft. These dives are conducted with dive computers that allow multilevel diving, and, excluding safety stops, the final depths of these dives typically vary between 30 and 60 ft.

Theoretically, the final tissue loading is governed by the final shallow depths of the dive. In point of fact, these dives act like decompression dives insofar as fast tissues that control deep dives are concerned.

Further, unlike deep repetitive bounce dives that have been shown to be unsafe and clearly should be avoided, these dives have not produced any reported increase in the occurrence of DCS.

Summary

Despite a careful review of the literature from Haldane (1908) to Hardy (1999), no theoretical or experimental evidence has been found that indicates a repetitive dive must be shallower than the dive that precedes it. An important exception is deep repetitive dives that are followed by a direct ascent to the surface, which have repeatably been shown to produce a high incidence of DCS. Repetitive deep decompression dives that do not push the limits do not seem to have the same problems.

For those divers who use a dive computer and are taking advantage of its multilevel capability, any rule to avoid reverse profiles would seem to be irrelevant.

For those unfortunate few still using a dive table, the avoidance of reverse profiles is an important practical rule that results in more bottom time.

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Appendix 1. Repetitive Dive Test Data of des Granges

All depths in fsw. Bottom times and surface intervals in minutes.

DIVE NO	D1 (FT)	T1(MIN)	SI (MIN)	D2 (FT)	T2(MIN)
1	100	5	6	180	6
2	20	39	240	90	37
3	150	5	95	40	183
4	25	48	127	140	35
5	180	5	344	150	8
6	70	20	177	140	37
7	80	20	109	170	34
8	50	40	69	190	12
9	70	30	233	160	36
10	90	25	22	120	32
11	50	5	71	150	28
12	120	10	128	110	17
13	50	10	196	60	83
14	100	30	297	130	34
15	190	15	29	80	42
16	60	60	66	180	26
17	100	30	103	140	25
18	60	50	145	170	30
19	190	20	6	160	14
20	90	50	264	190	34
21	150	30	358	140	10
22	190	25	14	90	47
23	60	100	38	170	26
24	80	130	92	70	23
25	80	90	86	110	29
26	70	40	115	80	32
27	70	130	145	100	34
28	90	100	182	130	24
29	150	60	221	80	17
30	40	5	6	100	26
31	70	5	6	100	24
32	35	15	6	110	19
33	120	5	6	110	17
36	25	57	6	120	30
37	210	5	6	50	117
38	220	5	6	50	102
39	70	25	6	140	26
40	270	5	6	150	6
41	35	70	6	150	15
42	300	5	6	180	36
43	35	90	6	200	17
44	230	10	6	50	34
45	40	90	6	100	20

46	35	120	6	60	79
47	280	10	6	70	36
48	40	110	6	80	32
49	300	10	6	190	20
50	35	160	6	280	5
51	260	15	6	260	4
52	60	90	6	90	47
53	40	160	6	40	28
54	290	15	6	160	29
55	100	60	6	70	36
56	280	20	6	80	47
57	120	60	6	130	28
58	260	25	6	160	34*
59	140	60	86	220	23*
60	10	19	6	90	32
61	15	25	6	130	56
34	30	32	6	120	41
35	170	5	6	70	31

* DCS

Appendix 2. Reverse Profile Test Data

All depths in fsw. Bottom times and surface intervals in minutes. - des Granges (1957)

DIVE NO	D1	T1	SI	D2	T2
1	100	5	6	180	6
2	20	39	240	90	37
4	25	48	127	140	35
6	70	20	177	140	37
7	80	20	109	170	34
8	50	40	69	190	12
9	70	30	233	160	36
10	90	25	22	120	32
11	50	5	71	150	28
13	50	10	196	60	83
14	100	30	297	130	34
16	60	60	66	180	26
17	100	30	103	140	25
18	60	50	145	170	30
20	90	50	264	190	34
23	60	100	38	170	26
25	80	90	86	110	29
26	70	40	115	80	32
27	70	130	145	100	34
28	90	100	182	130	24
30	40	5	6	100	26
31	70	5	6	100	24
32	35	15	6	110	19
34	30	32	6	120	41
36	25	57	6	120	30
39	70	25	6	140	26
41	35	70	6	150	15
43	35	90	6	200	17
45	40	90	6	100	20
46	35	120	6	60	79
48	40	110	6	80	32
50	35	160	6	280	5
52	60	90	6	90	47
57	120	60	6	130	28
59	140	60	86	220	23*
60	10	19	6	90	32
61	15	25	6	130	56

* DCS

Appendix 2 (cont.). Reverse Profile Test Data

Leitch and Barnard (1984)

D1	T1	SI	D2	T2	SI	D3	T3
82	5	60	115	5	60	147	5

Thalmann Phase II 0.7 ata (1984)

DIVE NO	EAD1	T1	SI	EAD2	T2
1	30	210	80	106	16
2	43	142	80	81	8

Powell (1988)

DIVE NO	D1	T1	SI	D2	T2
1	45	100	75	85	20

Hardy (1999)

DIVE NO	DESCENT	D1	T1	ASCENT	SI	DESCENT	D2	T2	ASCENT	1O FT
1	2	52	36	4	60	3	125	9	5	3
2	3	55	40	3	60	3	125	8	7	4
3	1	58	30	3	60	2	125	9	5	3
4	1	57	29	3	60	2	125	9	5	3
5	1	59	34	2	60	2	125	9	4	3

REVERSE DIVE PROFILES: RISK VERSUS BENEFIT

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The issue of risk versus benefit has been an integral part of diving technology and research since the beginning of the evolution of scuba. Traditional diving operations have been slow to change in the face of new developments and controversy has followed virtually every new development. Unfortunately, the controversy has generally been based upon traditional points of view and emotion rather than upon credible scientific fact. It appears that we may be in such a quandary with the focus of this workshop. It is well known that repetitive divers are admonished to make the deep dive first followed by progressively shallower dives. In spite of this, there is the well-known fact that many divers will follow a shallow dive with a deeper dive, most commonly with no symptoms of decompression illness. A limited review of literature indicates that there may have been an interpretation made with regard to the issue using tables and gaining bottom time advantages with the deep dive first as opposed to any actual prohibition of the practice. This paper provides information on the evolution of the deep dive first language and reviews the logic as it has been promulgated in the training materials of the various organizations. It also identifies the basis of the expected benefits of the deep dive first view compared to the more recent advice that the dive profile doesn't make any difference as long as the gas loads are within the accepted range.

Introduction

The issue of risk versus benefit has been an integral part of diving technology and research since the beginning of the evolution of scuba. Traditional diving operations have been slow to change in the face of new developments and controversy has followed virtually every new development. A few of the more memorable issues have centered around single versus two-hose regulators, life vests versus buoyancy compensators, front-mounted versus back-mounted buoyancy compensators and "jackets," and dive tables versus dive computers. Unfortunately, the controversies have generally been based upon traditional points of view and emotion rather than upon credible scientific fact. The current reverse profile controversy appears no different than past exercises. I find a quote by Ben Franklin (1887) to provide some perspective on this issue. In the year 1887 he observed "Having lived long I have experienced many instances of being obliged by better information and for consideration to change opinions even on important subjects which I once thought right but found to be otherwise."

It appears that we may be in a similar quandary with the focus of this workshop. There appears to be a traditional and long-standing position that diving shallow before deep carries an unacceptable degree of risk for the diver. The question of the risk versus benefit of performing "reverse profile" dives has not, however, to this date, been provided with a satisfactory answer based upon valid scientific evidence. It is well known that repetitive divers are admonished to make the deep dive first followed by progressively shallower dives. In spite of this, there is the well-known fact that many divers will follow a shallow dive with a deeper dive, most commonly, if the practitioners are to be believed, with no symptoms of decompression illness or other negative effects. The obvious question remains: does the reverse profile increase the risk for DCS? If the risk is minimal, then the question, what are the benefits and are they sufficiently important to warrant the risk, becomes paramount.

All too often we have been placed in the intellectually awkward position identified by Poul Anderson, who stated "I have never encountered a problem, however complicated, which, when viewed in the proper perspective, did not become more complicated." If we are to evaluate the risks of reverse profiles with regard to their acceptability, then it appears that we must delve into the complications that go with the understanding of the problem in order to properly assess any risk involved.

Risk Assessment

It is, perhaps, worthwhile to spend a few moments on the issue of risk assessment in diving. One of the first problems we face is to identify the nature of the risk and to determine whether it is acceptable to our diving population. We know that diving has a number of inherent risks associated with it. By and large they are acceptable to the diving population even though litigators for personal injury are quick to point out that the risks were not clearly defined to their clients, who were, therefore, uninformed about the true nature of the risk prior to their injury.

It appears that risk assessment on this issue must look both forward and backward in order to develop a database for rational assessment. We have elements of the diving population that have amassed a large amount of reverse profile experience. We have elements of the diving population that are adamantly opposed to reverse dive profiles. We have tables that give some dive time advantages to deeper dives first and we have many dive computers that cannot differentiate one way or the other. While we may never gain a complete understanding of the problem, there are some tools available for increasing our understanding.

Friedman (1994) in an Internet paper on "Understanding Risk" identifies four well-accepted analysis steps needed for the assessment of risk. They are: identifying the hazards, establishing the relationship between a dose and the response to that dose, analyzing potential public exposure, and describing the risk. Using his categories and taking the blame for any misinterpretation of his points leads to the following conclusions:

1. The identification of hazards should be based upon existing scientific evidence that can show a cause and effect relationship between making a deep dive following a shallow dive and injury to the diver.
2. The dose/response relationship would require that an objective decision be made as to the degree of differential pressure of nitrogen that causes an observed effect. This would normally involve a study of a population of divers and its known response to reverse dive profiles. We need to know the likelihood of increased injury in the diving population that is produced by the hazard. The length of the exposures, surface intervals and the depth profiles are all part of the "dose" that must be evaluated.
3. The analysis of potential public exposure will depend, in part, on the potential damage or benefits of the practice of using reverse dive profiles. It may also depend upon the effect of a variety of intervening variables such as physiological fitness, age, fluid balance, comfort level, sensitivity to internal change, psychological variables, work rate, temperature and many others that may have an effect on decompression effectiveness. What is the nature of the calculated risk that divers must accept if they choose to conduct reverse dive profiles?
4. The description of the risk is then based upon the objective evaluation of the likelihood of the occurrence of undesirable side effects following a given "dose" of reverse dive profile exposure. We will never be without risk in diving, but we must use reasonable care in determining the degree of risk we are prepared to accept. Usually risks of 1 in 1,000,000 are considered acceptable for virtually any risk. Risks at the level of 1 in 100,000 are minimal, but the severity of the injury becomes an issue. Brylske (1999) identifies 1,000,000 scuba divers with 935 reported injuries in 1996. That appears to be 1 injury for every 1,070 divers, but when compared to swimming, which has one injury for every 634 swimmers, scuba diving is relatively safe. The level of risk associated with diving in general has always been quite well accepted by the diving population. Unfortunately, such assessment needs a review of the actual number of exposures or the accurate size of the population as well as the number and severity of the injuries to make a reasonable assignment of risk. Without the denominator, the attempts at assigning risk are speculative.

A further problem seems to arise when attempting to establish the level of informed consent that would be needed for the individual to adequately evaluate the risk of a given exposure. How much knowledge about the risk is enough to develop a reasonable and prudent basis for acceptance of a given level of the risk? When does the risk become unacceptable? The realistic assessment of risk must rely on an examination of data drawn from the various disciplines that study the various aspects of the problem.

Whoever said that there is no such thing as a simple problem had the right idea. It is critical that we do not develop a "jump on the bandwagon" mentality that obscures the nature of the calculated risk and avoids the serious consideration of the potential consequences of the practice of conducting or avoiding reverse dive profiles. Developing "rules" without sufficient data may well have been an important factor in the development of our current dilemma. It will be important to be able to establish that, based upon the evidence, the risk while conducting the reverse dive profile is either greater, less than, or the same as, the traditional practice of performing deeper dives first.

At any rate, communication of the best information available to the widest membership in the diving community is clearly in the best interest of the safety of divers. This information must be accompanied by the recognition that there can be no guarantee of safety and that all risks are relative to the specific conditions of each dive. Diving does and always has involved a calculated risk that the diver needs to assess for every dive that is made. All concerned must make personal decisions regarding the degree of relative risk that is acceptable to them.

Hardy's Experiment

A recent experiment conducted by Hardy (1999a) reported that six highly experienced scuba divers, with a total of 153 years of diving experience, were able to perform a small series of "reverse" 60 to 130ft dives without obvious symptoms of decompression illness. The provocative banner at the top of the magazine states "Special Report: Deepest dive first? Not anymore!" The Rodale's Scuba Diving October issue reviewed the mail and stated "No Reverse Profiles: An Obsolete Rule?" Hardy (1999b) then adds "Our answer to the question - should you always make your deepest dive first? - is still...maybe not." While the wording in the original article might appear to overstate the significance of the findings, it certainly seems possible that the risks involved with "reverse dive profiles" may also have been overstated and it may be that there is room for serious doubt. While there are a considerable number of questions with regard to the many variables that could impact upon the data that was derived, there is little doubt that valuable information resulted from the study. Issues such as number of subjects and their levels of adaptation, the comfort level of the subjects, the physiological consequences of the reversed profiles, the subjective sensitivity of the subjects to signs and symptoms of DCS, the lack of physiological monitoring tools, and the experimental design were not really addressed. The Hardy study can best be described as an important "pilot study" that may stimulate further research and ultimately lead to additional knowledge with regard to our understanding of DCS. The statement, that "we, along with thousands of other divers in the field, have done tens of thousands of such reverse-profile dives with no harm," if true, would certainly provide credibility for the practice. However, it somehow seems unlikely that the risk of DCS would be less in the reverse profile population than in the total diving population.

U.S. Navy Tables Example

I recall an instructional practice in the 1960's wherein instructors would calculate the reverse dive profiles using the U.S. Navy Tables in order to demonstrate the benefit of gaining additional bottom time when the deeper dives were followed by shallower dives in the repetitive series.

- A 100ft (33m) dive for 25min = repetitive group H, followed by a surface interval of 1 hr. = repetitive group G. This G designation represents 44min of Residual Nitrogen Time (RNT) at 60ft (20m), thus an allowable 16min no-decompression bottom time.

- The reverse dive profile of 60ft (20m) for 60min = repetitive group J, followed by as surface interval of 1hr = repetitive group H. This H designation represents 30min of RNT at 100ft (33m). Thus, the diver cannot perform a no-decompression dive since the no-decompression limit (NDL) for 100ft (33m) is 25 min.

The examples were often followed by an admonition to follow deeper dives with shallower dives. It is not difficult to take the logical leap to "Always do your deep dive first." The standard advice to perform the deep dive first was recommended in order to take advantage of the additional bottom time available. No one said you "could not," they said you "should not" conduct reverse profiles in recreational diving.

Literature Review

A limited review of literature indicates that there may have been an interpretation made with regard to the practice of using tables and gaining bottom time advantages for diving deep first, that led "someone," in the 1970's, to take the position proclaiming the actual prohibition of the practice. The logic of this position could have been very compelling for a safety conscious dive instructor with limited information.

A substantial search of literature and conversations with knowledgeable resource persons has not revealed any objective evidence, scientific or otherwise, that provides for definitive acceptance or prohibition of reverse dive profiles. It appears that a careful analysis of the risk versus benefit issues is long overdue.

The U.S. Navy Manual on Submarine Medicine Practice (1956) recommended only one dive in 12 hours, as a rule. If more than one dive was to be made within 12 hours, the diver was to "take the depth of the latest dive and use the combined time on the bottom (descent time plus actual bottom time) for all of the exposures." However, the next paragraph says, "to cover ALL brief interval repetitive dives, safety demands use of the combined times and the depth of the deepest dive." There was no demonstrated concern for conducting the deep dive first. They did point out that "decompression gauges," such as those being developed by Munk and Groves at Scripps Institution of Oceanography, would be useful for repetitive dives as well as multi-level dives.

The U.S. Navy Diving Manual (1959) gave the following cause of decompression sickness: "Decompression sickness is caused by inadequate decompression following a dive, but does not necessarily mean that the decompression table has not been followed properly. An excessive amount of gas in the tissues can result from any condition (in the man or in the surroundings) that causes an unexpectedly large amount of inert gas to be taken up at depth or that results in an abnormally slow elimination of gas during the decompression procedure. In such situations, following the table to the letter would not always assure adequate decompression. However, the decompression tables are designed to cover all but exceptional cases of this sort, so the actual risk of decompression sickness is small if the right table is properly employed." There is no mention of potential problems if deeper dives follow shallower dives. The reverse dive profile using the tables reduced the bottom time of the second dive; it was not prohibited.

Cole (1993) cites Dennis Walder, a British decompression expert, who, in a 1968 paper put forth the idea that divers can modify their dive depth sequence to improve resistance to bubble formation. Walder suggested that divers should make their first dive a deep, short (crush) dive, which will compress the body's micronuclei down to a smaller and safer size. Walder further suggested that divers make subsequent dives progressively shallower, within the limits of the first crush dive, in order to minimize excitation of smaller micronuclei. This idea is reported as having been adopted into the SAA Bühlmann system. Walder is widely published and well respected, but there does not appear to be data on the subject in his works. This point of view may be the precursor to the interest in differentiating between deep/shallow and shallow/deep profiles.

Tom Mount, then diving officer at the University of Miami, in his Instructor Course Outline (1971), used several reverse dive profile problems for his students and in a personal communication indicated that these were acceptable profiles, for his divers, that proceeded without problems. He further pointed out that the cave diving community regularly follows shallower dives with deeper dives since the very nature of cave diving often makes it a requirement. His early work on the SOS meter included reverse dive profiles in chamber dive comparisons with tables. The results showed that the meter was somewhat more conservative than the tables on an 80ft (26m) dive for 40min followed by a surface interval of 1:39hr, and a 120ft (40m) dive for 20min followed by a surface interval of 1:57hr, and a dive to 110ft (36m) for 35min. The meter required 66min and the tables 54min of decompression time. There was no discussion of the profiles, only the decompression time.

The U.S. Navy Diving Manual (1970) provides a repetitive dive worksheet as an example, and it contains a 105ft (35m) for 24 min dive, followed by a surface interval of 2hrs and a second dive to 145ft (48m) for 12 min. There is no discussion of the sequencing of the dives.

The U.S. Navy Diving Manual (1975) has no mention of deep dive first as an issue. A repetitive dive is defined as any dive conducted in a 12-hour period. Under section 7.4.5., it states: "During the twelve hour period after an air dive, the quantity of residual nitrogen in the diver's body will gradually reduce to its normal level. If within this period, a diver is to make a second dive - called a repetitive dive - he must consider his present residual nitrogen when planning for the dive." Neither the repetitive dive flow chart, nor the worksheet, contains any deep dive first advice.

Ketels and McDowell (1975) state: "Plan repetitive dives so that each successive dive is to a lesser depth. This will aid in the elimination of nitrogen and decrease the need for decompression stops." The repetitive dive worksheet used in this text was borrowed from the U.S. Navy Diving Manual (1970) and duplicated the reverse dive profile example. It is of interest that a number of the dive manuals in the 1970's and 1980's included the reverse dive profile example in the sections on calculating repetitive dives.

Dueker (1978), a former submarine medical officer, told us that "Generally, it saves time to take the deeper of two dives first."

The Jeppeson Sport Diver Manual (1979) offers a section on Avoiding Decompression Stops and suggests that making the first dive the deeper dive will aid in decompression, as each successive shallower dive will actually be helping you decompress. No references or data were included.

A NAUI textbook (1984, rev. ed.) gave the following advice: "When making a series of dives, plan repetitive dives to the same or shallower depth as the previous dive. This allows you to outgas nitrogen on progressively shallower dives instead of carrying a large amount of residual nitrogen on deeper repetitive dives." There is no reference to any supporting data, and this logic seems to assume that residual nitrogen is independent of tissue compartment considerations.

The PADI Open Water Diving Manual (1988) lists some general rules for using their Recreational Dive Planner. Rule #8: Plan repetitive dives so each successive dive is to a shallower depth. Never follow a dive with a deeper dive. Always plan your deepest dive first. Further, an illustration has large letters stating - DEEPEST DIVE FIRST.

Graver (1991) wrote: "When making a series of dives, plan repetitive dives to the same or shallower depth as the previous dive. This allows you to outgas nitrogen on progressively shallower dives instead of carrying a large amount of residual nitrogen on deeper repetitive dives."

The Repetitive Diving Workshop (Lang, M.A. and R.D. Vann, eds., 1991) did not specifically deal with reverse dive profiles. The dives discussed were to the same or lesser depth, with one exception. Gilliam (1991), in a summary of his data from 77,680 dives from a large dive boat, states: "The great majority of diving was conducted with exposures of 100 feet or less. Reverse profiles were conducted by many divers with no adverse effects reported. Computer divers frequently admitted to reverse profiles in their personal diving schedule." All of the seven cases of decompression sickness that he reported were in divers who had limited experience with less than 40 dives, and 5 of the seven were "within the tables" and no "safety stop" was taken. While this does not represent "hard" data, it is nevertheless provocative and would appear to indicate that reverse dive profiles were not uncommon. One might also speculate that there is a possibility that experience and/or adaptation may play a role in DCS under some circumstances.

Brylske (1995) while discussing "beating the bends" admonishes his readers to avoid high-risk profiles. He writes: "While science still argues the reasons why such practices are dangerous, practical experience shows that certain profiles are more likely than others to get you a trip to the recompression chamber. In particular, take care not to dive reverse profiles or saw-tooth profiles. On a multilevel dive, spend the first part of your excursion in the deeper range then move to the shallow. Never return to deeper water once you've come up to the shallower range."

The NAUI Dive Table (1995) rules state: "When making a series of dives, always make your deepest dive first. Plan repetitive dives to shallower depths than your previous dives. This allows you to outgas nitrogen on progressively shallower dives instead of carrying a large amount of residual nitrogen on deeper repetitive dives." The message appears to well-established but still contains no data background.

The PADI Divemaster Manual (1999) has a series of Recreational Dive Planner "rules." Rule #2 states: "Plan repetitive dives so each successive dive is to the same or a shallower depth. Don't follow a dive with a deeper dive. Plan your deepest dive first." It continues: "Although from a model point of view there's no mathematical reason for this recommendation, reverse profiles seem to be associated disproportionately with DCS incidents. This recommendation applies to diving with any table or computer, even though computers will happily crunch out the numbers for such a dive profile. When multilevel diving, this includes starting at the deepest part of the dive and progressing shallower. Small shallow-to-deep changes within the profile wouldn't be expected to cause a problem, but you want to avoid significant up-and-down "sawtooth" profiles."

Conclusion

The development of the current position, toward avoiding reverse dive profiles, appears to be evolutionary in the sense that the logic of the position has grown from well-accepted roots in the diving industry. It is of interest that the major diving medicine texts and the scientific literature do not appear to contain data that are consistent with the current position. Indeed, there does not appear to have been any systematic assessment of the risk of the consequences of injuries resulting from the use of an appropriately planned and executed reverse dive profile. A good deal of the provocative logic for avoiding the reverse dive profiles seems to have developed from anecdotal records. Anecdotal records, when properly documented, can rise to the level of acceptable data and can be used in a justifiable fashion to effect change in procedures. If data are developed from these records that reinforces the changes, the changes are probably a good thing. If, on the other hand, changes are accepted because they "make good sense" and become the "party line" without any reasonable data, then we may find ourselves unnecessarily restricting our diving behavior.

Workshops such as this are by their nature information pools. As these pools of information are brought together, it is like lighting candles in a dark room. The more candles, the brighter the light, and the more definition there is to the details of the room. At the same time, the candles may well provide an ever-enlarging room filled with new details. We should enjoy the light and pay attention to the new details.

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I. Introductory Session Discussion.
Michael A. Lang, Moderator

B. Wienke: I want to add a note to John Lewis' comment about the formulation of the tables back in 1935 and actually in 1950, too. When they were formulated, John pointed out that they couldn't really do a good job of looking at all multi-level staging and things like that. So back about 10 or 15 years ago, we did a study at the laboratory at Los Alamos looking at the U.S. Navy tables - the particular ascent and descent rates - that were requested at the time. We did a computer analysis of all possible multi-level dives in one-minute intervals of elapsed time. I forget, it was either 2 or 3 feet. There were something like 32 million possible dive combinations there. And what we did was subtract all possible dives that didn't violate the critical tensions or M-values in that envelope, and we did this at the time on a Cray-IS super computer, which today is like a desktop computer. The calculations took eight minutes. So, that is 32 million multi-level dives. If such power had been available in those days, I am sure the Navy would have formulated the tables a little bit differently.

B. Hamilton: A comment on terminology. To a commercial diver, a bounce dive is one that doesn't go into saturation. It may require 12 hours of decompression. I think we better be careful how we use that word. Because, you said Hardy's dives were not bounce dives. And yet, a dive that, even if it does a decompression, is still a "bounce" dive. So I guess we have to not use that word at all.

J. Lewis: I shouldn't have used the word bounce dive. What I was really referring to are dives that involve a direct, moderately-rapid ascent to the surface. And, it seems to me that that is the commonality of the problems.

B. Hamilton: No stop?

J. Lewis: Yes, no stop. NoD dives, but no stop. Maybe that is the right terminology. That seems to me to be the one element of the repetitively deep dives that are problematic. At least I think that is an important element of the problem. I think that you will find, like the Turkey dives of the Fife's, where they are taking significant stops, despite the fact that they are repetitive and that they are very deep, it didn't matter. But divers do less onerous things with direct ascents, no stops. Like Thalmann did on his third 100-foot dive and the Leitch and Barnard profiles, which have very small bottom times. They are all doing direct ascents to the surface, with no stop.

M. Lang: Actually, the first question I got about terminology was from Valerie Flook, who e-mailed me with "what is a reverse dive profile?" Obviously, most have a different connotation of what that actually is. This is one item we would like to think about and John's paper contained a proposed definition. For the definition of reverse dive profiles, Charlie and I had envisioned two things. A reverse dive profile, as we understand it, can mean two things. First, it can be in a repetitive series of pressure exposures where a shallow dive is conducted, followed by a surface interval, and then a second dive is performed, where the maximum depth is deeper than the first dive. Second, within a single pressure exposure, where most of the bottom time is spent at a shallow depth, followed by a deeper spike to depth prior to an ascent to the surface. The nucleus of this project actually started about a year and a half ago as my Diving Officer staff kept producing memoranda to the attention of our diving scientists who actually logged dives where the second one was a little bit deeper than the first dive. Examples would be a 46ft maximum depth on the first dive and 53ft on the second dive, and presto, you have diving e-mail in your in-box. So, in compliance with the Paperwork Reduction Act, intelligent minds asked not to be sent unnecessary memoranda, and, by the way, why exactly was it that they could not perform reverse dive profiles? I asked them to let me get back to them. Here we are now searching for a satisfactory answer.

A. Brubakk: I just want to make a comment on the question of risk. I mean, you are talking about the risk of a certain adverse effect happening, in this case decompression sickness, and you are citing a lot of studies. Actually, if you assume that decompression sickness is a random process and assume a binomial distribution, if you have one DCS symptom in 100 dives (assuming the diver tells you about that symptom) you have a 95 percent confidence interval between 0.03 and 5.5 percent. So, having one DCS hit in 100 dives, in my opinion, doesn't tell you anything about risk.

P. Weathersby. I won't argue with the limited information in 100 dives, but it is better than if the 100 observations were not made at all.

IMPLICATIONS OF THE VARYING PERMEABILITY MODEL FOR REVERSE DIVE PROFILES

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There is currently considerable interest in using physics-based bubble models to compute decompression schedules. At the center of this activity is the Varying Permeability Model (VPM), in which as few as three nucleation parameters and one decompression parameter replace traditional M-values as the ascent limiting criteria. For deep and intermediate portions of decompression profiles, supersaturation limits calculated by the VPM are less than those of conventional dissolved-gas algorithms. Progress in the application of this model has been aided by the voluntary Internet information-exchange group known as the "Decompression List."

Introduction

The Varying Permeability Model (VPM) (Yount, 1979a) fundamentally incorporates diving depth into the formulation of ascent criteria. For square-profile dives, where the crushing pressure p_{crush} is equal to the diving depth, the minimum VPM supersaturation gradients have been experimentally determined to be proportional to p_{crush}. With the definitions that a *reverse dive* is a *deeper-than-previous dive*, and a *forward dive* is a *shallower-than-previous dive*, a clear distinction can be made that forward diving places the largest p_{crush} first in series of exposures. This applies to the time-scales of both repetitive and single dives. In the case of non-square profiles, such as very slow descents followed by direct ascents, the determination of p_{crush} is subtle, and relates to the maximum difference attained between dissolved gas tension and the ambient pressure of the dives. Moreover, the VPM predicts that the maximum benefit from crushing gas nuclei is achieved by doing the deepest part of a prolonged or repetitive exposure first.

Here, a dive is considered repetitive when the surface interval between it and its predecessor is sufficiently short that the first dive *influences* the second. Examples of such an influence, as compared to a single isolated dive, are an increased incidence rate for decompression sickness (DCS), enhanced Doppler bubble counts, and the exacerbation of various precursors of decompression sickness, such as fatigue, malaise, or discomfort. Possible mechanisms by which one dive might influence another include excess dissolved gas (gas loading), unresolved free gas (gas bubbles), and changes in the underlying size distribution of bubble formation nuclei (gas nuclei). The first of these effects is accounted for in conventional dissolved-gas algorithms, which keep track of inert-gas loads. The second and third can be addressed in the context of the VPM, which is the focus of this work.

This paper is organized into three sections, beginning with consideration of how the field experience of divers is being used to modify commonly available neo-Haldane tables by incorporating deep decompression stops into ascents. We then review the Varying Permeability Model's foundation in bubble formation experiments, and experimental implications for reverse diving profiles. The final section discusses use of the VPM to formulate diving tables, and applies the model to the analysis of forward and reverse diving profiles.

I. The Influence of Technical Diving on Decompression Practice

Over the past decade, decompression diving has entered the mainstream of upper-end sport diving. The intrinsic risks associated with decompression are widely known, and more than a century has been spent in trying to overcome them. Given these facts, it is surprising that so many highly-intelligent and highly-educated people have recently put aside conventional tables designed and tested by competent professionals, and elected to design and test their own. Recalling Abraham Lincoln's famous aphorism about lawyers, one is tempted to ask, "Doesn't the diver who designs his own tables have a fool for a client?"

The first reason why some technical divers prefer to design and test their own tables is that they can. Many have computational abilities that far exceed those of decompression pioneers, who produced operational tables in an era when the physics of bubble formation in aqueous media was poorly understood, and commercial decompression programs, dive computers, personal computers, and powerful software did not exist. The second reason technical divers might choose to design their own tables is that they have easy access to unconventional algorithms, such as the Thermodynamic Model (Hills, 1966), the Varying Permeability Model (Yount and Hoffman, 1986), and the Reduced Gradient Bubble Model (Wienke, 1991). By "easy access," we mean that they have both the mathematical skills needed to understand these published algorithms and the computational skills needed to implement them, if need be, from scratch. The third reason is that many technical divers are dissatisfied with the results of conventional algorithms. There is also widespread suspicion that something is missing, that there is a need for "deep stops" as called for by LeMessurier and Hills (1965), by Yount and Strauss (1976), by Hennessy and Hempleman (1977), and by others. The VPM tables calculated by Yount and Hoffman (1986) also call for deep stops, but because those tables were calibrated using U.S. Navy (1977) and Royal Navy Physiological Laboratory (1968) tables, which are now considered aggressive and obsolete, the original VPM tables are also considered too aggressive.

One of the pioneers in this endeavor was marine biologist Richard Pyle, who serendipitously discovered the benefit of deep stops while collecting ichthyological specimens (Pyle 1996).

"...so it's abundantly clear... my empirically-derived deep-stop method has more to do with the physiology of fish than ... Humans. ...I first noticed the apparent benefit on dives when I had to stop deep to vent gas from fish's swim bladders. Because of that observation, I repeated those stops on dives when I didn't collect fish...."

Pyle simply felt better after completion of dives that incorporated deep stops. So what we have here is a new paradigm in which a technical diver modifies an existing table, tries it out on himself, and decides to keep or reject the modification to his diving practice on the basis of how he "feels." While more subjective than the usual method of "titrating" Navy divers five at a time, this empirical, try-it-out-on-yourself method is actually far more sensitive because it replaces the bimodal endpoint of bends/no-bends with a continuous scale that associates greater comfort with greater safety. It is important to note that these divers often have personal experience with a full range of decompression sickness (DCS) symptoms, and are therefore discerning observers. There is another reason why Pyle's method is safer: He is moving away from the bimodal endpoint where some divers get bent, rather than toward it. In seeking greater safety, Pyle definitely has an astute client!

Although it is difficult to quantify testimonials of this sort, they are very compelling. Given enough of them, one feels intuitively that they must have some validity. Why is this so? Imagine that a scientist is studying a group of athletes who are required to complete some arduous task, such as a decathlon. The usual method of titrating divers would be equivalent to recording only the number of athletes who competed and the number who got hurt. World record times and distances would be of no interest, nor would the scientist doing such a "titration" care how hard the athletes trained, how tired they got, how sore their muscles were, how much they ate, or how long they slept. A good sports writer, on the other hand, would probably gloss over the casualty report and focus on interviews and anecdotes. In this way, he would reveal what it felt like to compete in the decathlon and help readers like us to experience, along with the athletes, the thrill of victory and the agony of defeat. Indeed, the things that would interest sports fans the most are the very things that the narrowly focused scientist would miss. With this analogy in mind, we have solicited testimonials relevant to reverse dive profiles, deep stops, the VPM, and gradient factors from the Decompression List. A link to the Deco List web page for the Reverse Dive Profiles Workshop can be found on-line at: http://www.phys.hawaii.edu/~dey.

II. The Varying Permeability Model

Numerous experiments demonstrate that cavitation thresholds can be significantly raised by degassing or by briefly exposing the sample to high pressure (Harvey *et al.*, 1944; Yount and Strauss, 1976; Gerth and Hemmingsen, 1976). These are specific tests for stable gas nuclei, yet the very existence of such entities is surprising. Gas phases larger than 1 μm in radius should float to the surface of a standing liquid, while smaller ones should dissolve rapidly due to the surface tension γ. Earlier proposals for coping with this dilemma were critically reviewed by Yount *et al.* (1977), and the Varying Permeability Model was introduced as an alternative to address the inconsistencies between experimental results and existing models (Yount *et al.*, 1977; Yount, 1979a).

Over the years, the evidence that stable microbubbles actually exist in aqueous media has become very compelling. Medwin (1974) has inferred the presence of large and persistent populations in seawater from acoustic measurements, and Johnson and Cooke (1974) have photographed their formation and stabilization in this liquid. Candidates have also been observed in gelatin and distilled water using both light and electron microscopes (Yount, Gillary, and Hoffman, 1984), and several of their physical properties, such as their size distribution and skin thickness, were measured and found to be consistent with VPM expectations.

1. VPM Nuclei

The Varying Permeability Model postulates that cavitation nuclei consist of spherical microbubbles that are small enough to remain in solution and strong enough to resist collapse. The mechanical compression strength is provided by an elastic skin or membrane composed of surface-active molecules. Ordinarily, VPM skins are permeable to gas, but they can become effectively impermeable when subjected to large compressions, typically exceeding 8 atm (0.8 MPa).

By tracking changes in nuclear radius caused by increases or decreases in ambient pressure, the VPM has provided precise quantitative descriptions of several bubble-counting experiments carried out in supersaturated gelatin (Yount and Strauss, 1976; Yount and Yeung, 1981; Yount, Yeung, and Ingle, 1979). The model has also been used to trace levels of incidence for decompression sickness in a variety of animal species, including salmon, rats, and humans (Yount, 1979b; Yount, 1981), and to calculate diving tables for humans (Yount and Hoffman, 1983; 1986; 1989). The rate at which individual VPM nuclei evolve from one equilibrium state to another has been investigated theoretically, and a statistical process by which the equilibrium size distribution of an entire population of VPM nuclei may be generated or regenerated has been proposed (Yount, 1982). In the most recent paper in this series (Yount, 1997), the third independent derivation of VPM was obtained by applying thermodynamic methods formulated by Kozlov and Markin (1990) to describe the strongly-curved amphiphilic interfaces found in micelles, emulsions, giant bilayer vesicles, and biological membranes. The VPM nucleus is thus another example of such a system.

Some additional features of the Varying Permeability Model are depicted in Fig. 1 (Yount, 1982). In Fig. 1(a), the internal gas pressure is p_{in}, and the ambient hydraulic pressure is p_{amb}. If there were no skin, the situation would be described by the well-known Laplace equation,

$$p_{in} = p_{amb} + \frac{2\gamma}{r} \quad (gas\ bubbles), \tag{1}$$

which suggests that p_{in} is always larger than p_{amb} in the case of ordinary gas bubbles.

VPM nuclei differ from ordinary gas bubbles, because the surface-active molecules in the skin generate a skin compression Γ and a skin pressure $2\Gamma/r$ that oppose the surface tension γ and surface pressure $2\gamma/r$ of the surrounding water. Together, they yield a new expression for mechanical equilibrium,

$$p_{in} + \frac{2\Gamma}{r} = p_{amb} + \frac{2\gamma}{r} \quad (gas\ nuclei). \tag{2}$$

Because Γ can be larger than γ in a spherical environment, the net surface tension $\gamma' = \gamma - \Gamma$, and the net surface pressure, $p_{in} - p_{amb} = 2(\gamma - \Gamma)/r$, can assume negative as well as positive values. In this case, mechanical equilibrium can be achieved regardless of whether p_{in} is larger or smaller than p_{amb}.

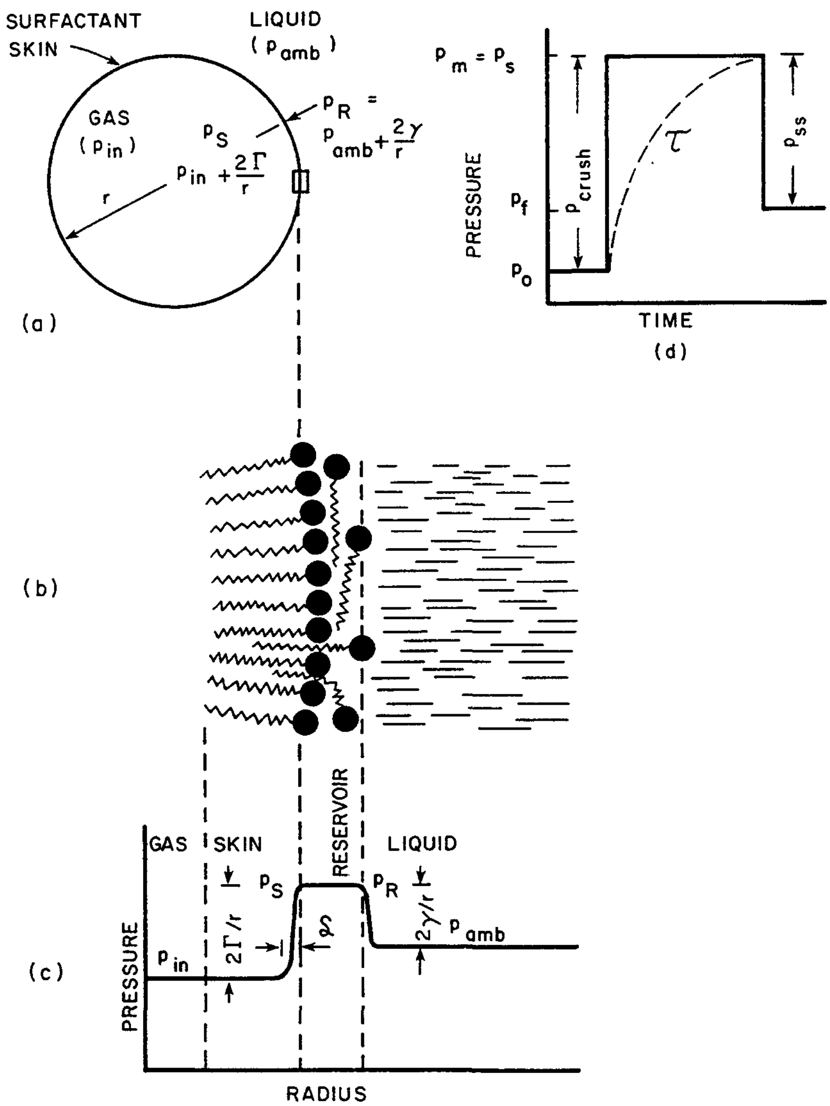

Figure 1. Outline of the varying-permeability model (Yount, 1982). The spherical geometry and the condition for mechanical equilibrium are illustrated in (a). A magnified view of the skin and the reservoir is shown in (b), and (c) is a plot of pressure versus radius indicating at what points the various pressures apply. The rudimentary pressure schedule in (d) consists of a rapid compression from p_o to p_m, saturation of the sample at $p_s = p_m$, and a rapid decompression from p_s to p_f.

2. Bubble Formation Experiments

Excess surfactant molecules are stored in a reservoir, which is represented in Figs. 1(b) and Fig. 1(c) as a concentric shell of negligible thickness that lies just outside the skin and thus has the same radius *r*. Surfactant molecules move from the skin to the reservoir when the radius decreases, and they move from the reservoir to the skin when the radius increases. In this way, the "crumbling compression" γ_c, which is the maximum possible value of the skin compression Γ, is preserved.

Fig. 1(d) shows a rudimentary pressure schedule used to study bubble formation in supersaturated gelatin. The schedule consists of a rapid compression from p_0 to the maximum pressure p_m, saturation of the sample at $p_s = p_m$, and a rapid decompression from p_s to the final pressure p_f. The term "rapid" means operationally that the process involves no change in the dissolved gas tension τ. Saturation at $p_s = p_m$ means that τ assumes the value p_s prior to decompression. The maximum over-pressure or crushing pressure is then

$$p_{crush} \equiv (p_{amb} - \tau)_{\max} \quad (3a)$$

$$= (p_m - p_0), \quad (3b)$$

and the maximum supersaturation is

$$p_{ss} \equiv (\tau - p_{amb})_{\max} \quad (4a)$$

$$= (p_s - p_f). \quad (4b)$$

A salient feature of bubble formation in supersaturated gelatin (Yount and Strauss, 1976) is that the bubble counts depend only on p_{crush} and p_{ss}, and not on the Haldane ratio, p_s/p_f. Two schedules having the same values of p_{crush} (300 psig) and p_{ss} (150 psig) are shown, respectively, in Figs. 2(a) and 2(b). The first has a Haldane ratio of 11.2, and the second has a Haldane ratio of 1.91, yet the average yields, around 16 bubbles per gelatin sample, were nearly the same. The schedule shown in Fig. 2(c) has the same p_{ss} (150 psig) and Haldane ratio (11.2) as that shown in Fig. 2(a), but the average yield was 30 times higher, around 500 bubbles per sample, because p_{crush} (150 psig) was only half as large.

Yount and Strauss (1976) also learned how to decompress gelatin safely. Their prescription, illustrated in Fig. 2(d), calls for "deep stops" and a constant off-gassing gradient, $\tau - p_{amb} = p_{ss}$, throughout the ascent. The theoretically optimum decompression required 12 min and yielded an average of 0.42 bubbles per sample. The corresponding U.S. Navy schedule required 17 min and yielded an average of 12.9 bubbles per sample.

Because p_f is ordinarily greater than or equal to p_o, p_{ss} is ordinarily less than or equal to p_{crush}:

$$p_{ss} \leq p_{crush}. \quad (5a)$$

To explore the region defined by

$$p_{ss} > p_{crush}, \quad (5b)$$

Yount and Yeung (1981) used slow compressions or stepped compressions, which permitted a significant rise in the dissolved gas tension τ while the ambient pressure p_{amb} was increasing. For the pressure schedule shown in Fig. 3, the maximum over-pressure, $p_{crush} = (p_{amb} - \tau)_{max}$, occurred on the very first step, and was simply the magnitude of the initial compression, 4.1 atm. Any other increments, whether they preceded or followed the largest, had no effect. The maximum supersaturation was p_{ss} = 20.4 atm, which was about five times larger than p_{crush} = 4.1 atm.

Figure 4 is a graph of p_{ss} versus p_{crush} for constant bubble number *N*. The "old region" is defined by Eq. 5(a) and the "new region" by Eq. 5(b). As expected, all of the data points in the old region and many of those in the new lie on a family of straight lines generated by the Varying Permeability Model. The smallest initial nuclear radius r_o probed in this experiment was approximately 0.01 µm. At these small radii, the classical VPM begins to break down because the thickness of the surfactant skin was not taken into account. When this deficiency was corrected, reasonable fits to all of the data in the old region were obtained (Yount and Yeung, 1981).

Figure 3 can be regarded as a reverse dive profile in the generic sense that the latter part of the exposure is deeper than the former. The yield in the original or "reverse" direction was greater than 200 bubbles per sample. The yield in the opposite or "forward" direction, corresponding to p_{crush} = 20.4 atm and p_{ss} = 6 atm, would average less than 0.1 bubble per sample, as can be inferred from Fig. 4. The lesson to be learned from these data is that it's best to crush gas nuclei by doing the deepest part of a prolonged exposure first.

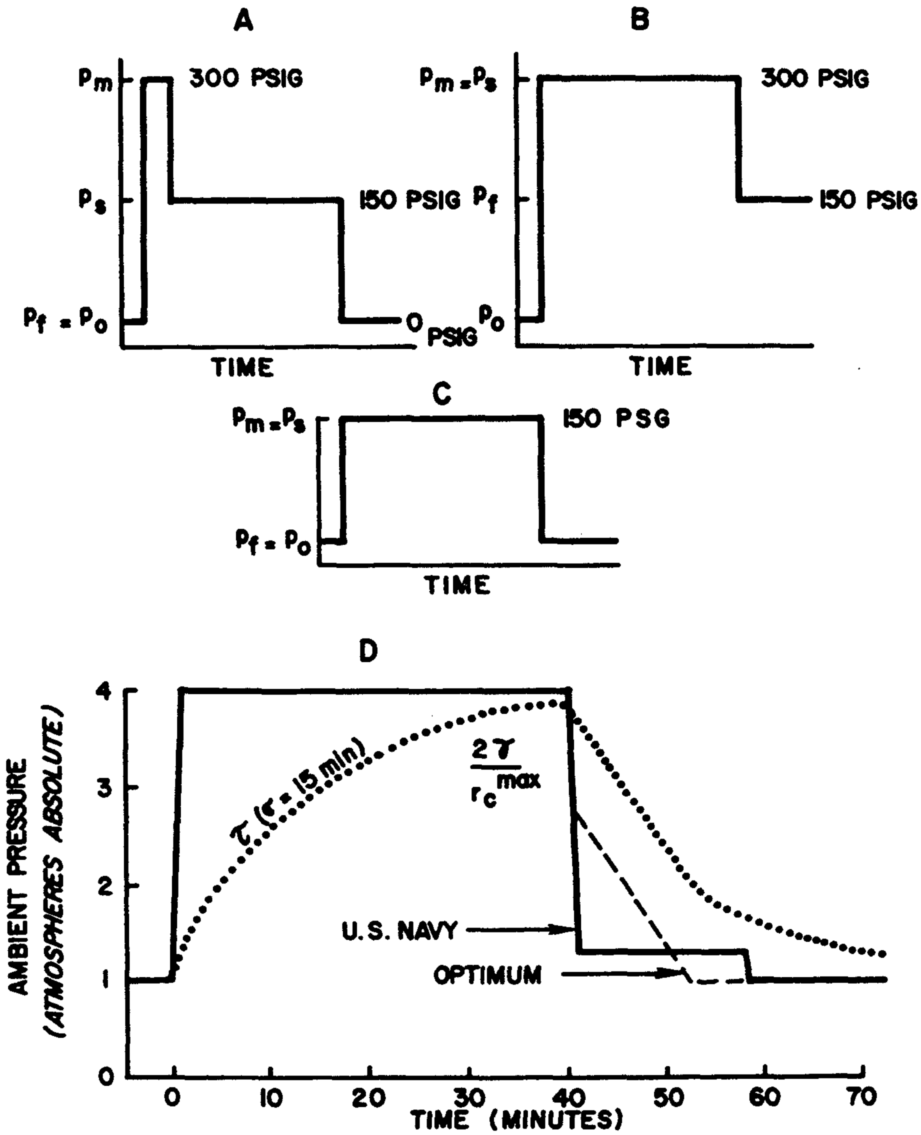

Figure 2. The Haldane-ratio principle has been tested by exposing gelatin samples to the first three schedules shown in this figure (Yount and Strauss, 1976). Schedules A and B have different ratios and produce the same number of bubbles, while Schedules A and C have the same ratios and produce different numbers of bubbles. As discussed in the text, the bubble counts in gelatin depend only on the pressure differences p_{crush} and p_{ss}, and not on the Haldane ratio, p_s/p_f. The optimum decompression procedure for gelatin is compared with the U.S. Navy procedure in Schedule D.

3. The VPM and Reverse Profile Diving

Yount and Hoffman applied the VPM to formulate diving tables for non-repetitive dives (Yount and Hoffman, 1986). Wienke's *Reduced Gradient Bubble Model* (RGBM) (Wienke, 1991) extended the VPM to repetitive-diving situations, such as reverse-profile diving. What does the VPM have to say about reverse-profile diving? We shall draw some conclusions directly from the VPM and certain key experiments that, together with the following assumptions, summarize our current application of the VPM to the etiology of decompression sickness.

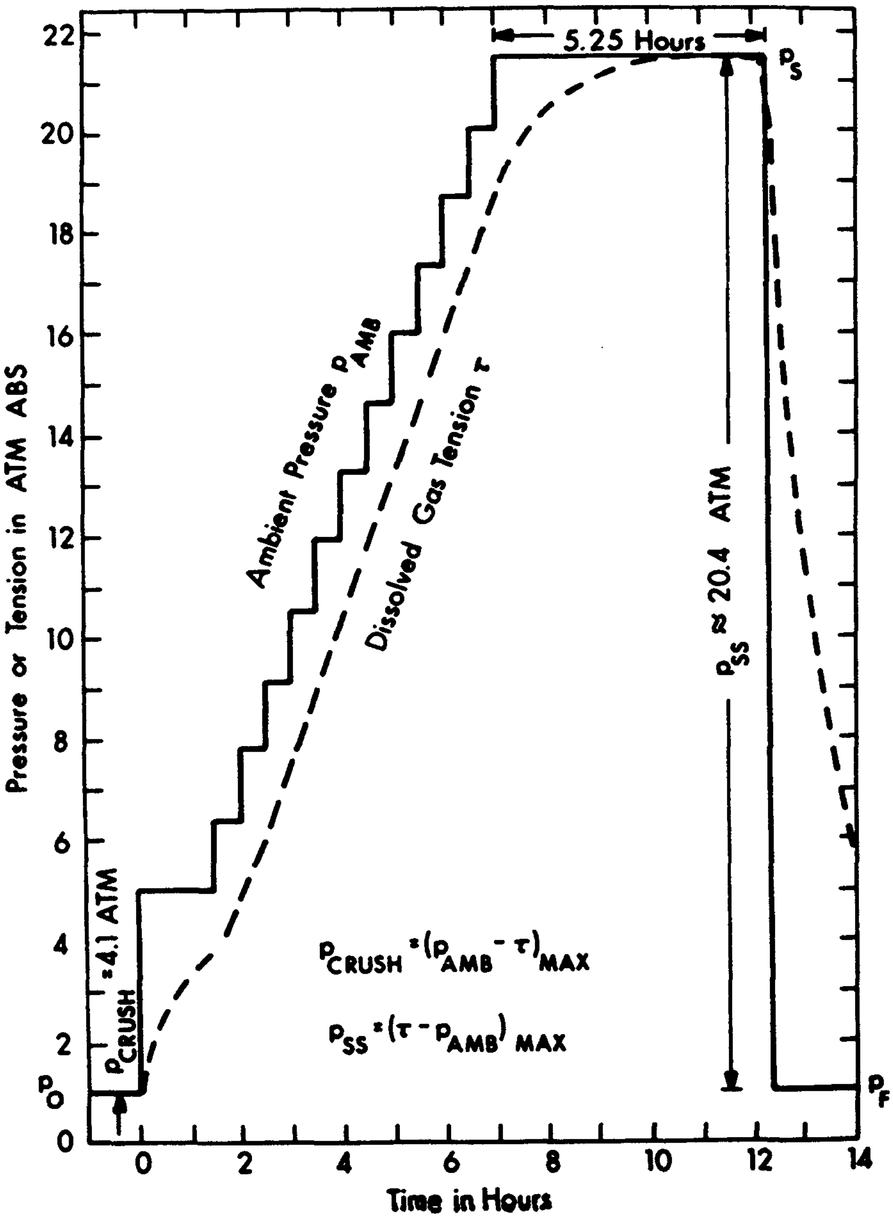

Figure 3. Stepped compression schedule used to limit the over pressure p_{crush} without affecting the supersaturation p_{ss} (Yount and Yeung, 1981).

a. A Set of Assumptions

i) **The VPM is applicable to decompression sickness in humans.**

ii) **Gelatin bubble-counting experiments are applicable to in-vivo DCS.**
Assumptions i and ii are consistent because the VPM was formulated to describe the gelatin experiments. However, both are needed because the VPM might be applicable even if the gelatin experiments are not, and vice versa.

iii) **Abnormalities that exist at the start of a dive have greatest impact for stressful dives.**
Because the second dive in a reverse-dive profile is the more stressful, any abnormalities or irregularities produced by the first dive would have greater impact in the reverse-dive situation

than in the forward situation. Saying this another way, if two successive dives are planned, it's best to do the more stressful dive first while the condition of the diver is still pristine.

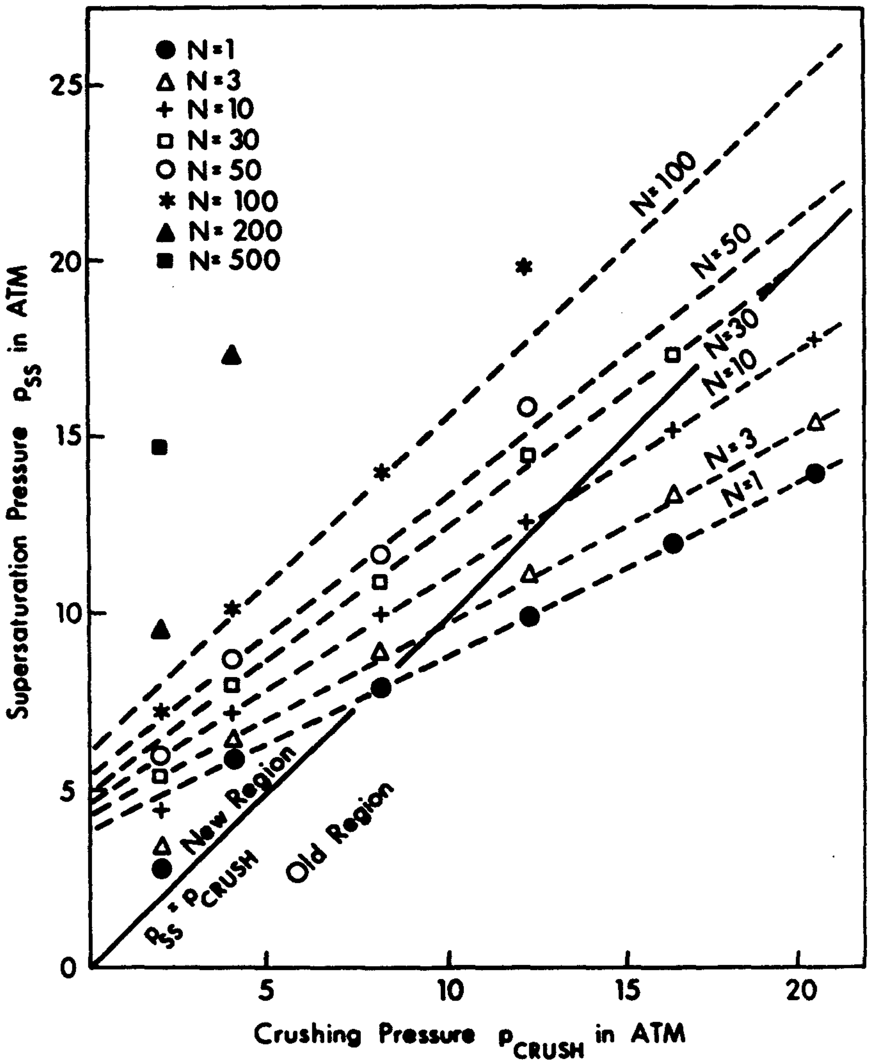

Figure 4. Plot of p_{ss} versus p_{crush} for various numbers of bubbles N (Yount and Yeung, 1981). All of the points in the "old region" and many of those in the "new region" lie on a family of straight lines generated by the Varying Permeability Model.

iv) The number of bubbles present after a typical first dive is large.

Indeed, the number is probably much larger than the number of super-critical nuclei because the growth of a primary bubble in tissue is limited by the local tissue deformation pressure, that pumps most of the gas liberated at the primary site into neighboring secondary sites. Instead of producing one large bubble, therefore, a super-critical nucleus usually produces many small ones, a primary, and many secondaries. Gaspare Albano (1970) published a series of photomicrographs demonstrating that one primary bubble can produce a "rosary" of secondary bubbles. Cowley, Allegra, and Lambertsen (1979) observed the time course of secondary-bubble production by subjecting the ears of New Zealand White rabbits to isobaric counterdiffusion at 1 atm and recording the pressure drops that occurred inside a primary bubble whenever the tissue cleaved. A more detailed discussion of the rosary phenomenon and secondary-bubble production can be found in the paper given by Yount (1979c) at the Workshop on Isobaric Inert Gas Counterdiffusion.

b. Persistent Bubbles and Reverse Dive Profiles

From the point of view of the VPM, any gross bubbles left over from the first dive would be expected to stabilize because the surrounding blood or tissue is loaded with surfactants. Like old soldiers, old bubbles *in vivo* never die, they just become large stable gas nuclei. According to the "ordering hypothesis" (Yount *et al.*, 1977; Yount, 1979a), if there are more large nuclei present at the beginning of the second dive, there will be more large nuclei present at the end. If there are more large nuclei present at the end of the second dive, more primary bubbles will form, and the volume of released gas will be larger than expected had the second dive been performed as a single isolated dive. While it has been demonstrated mathematically that VPM nuclei of any initial size will eventually replicate the primordial or pristine size distribution (Yount, 1982), the surface interval between two dives that are spaced closely enough to be deemed repetitive, whether forward or reverse, would be too short for full restoration to occur. It should also be noted that full restoration in the mathematical sense implies full restoration of the radial dependence with no loss of nuclei and hence no change in the total number N_o.

This mechanism has important implications for reverse dive profiles. It does not arise in conventional algorithms that only keep track of inert-gas loads. Though important and unique, the mechanism is difficult to quantify because the number and size-distribution of any microbubbles that may be present at the beginning of the second dive are unknown. Nor is it certain that the VPM is immediately applicable to stable microbubbles with radii as large as, say, 10 to 100 µm: Although such populations are known to exist in nature and have actually been observed in sea water (Medwin, 1974), the surface pressure $2\gamma/r$ is less than the tissue-deformation pressure in this size range (Cowley, Allegra and Lambertsen, 1979), and both would have to be taken into account. Even if the VPM is applicable in some modified way, the parameter values for stable microbubbles recently formed from gross bubbles could differ from those needed to describe primordial nuclei that have "aged" for days or weeks.

A second mechanism through which the existence of microbubble nuclei can influence an ensuing exposure in a reverse-dive sequence is by changing the underlying size distribution $N(r)$. This effect can go either way. If a deep first dive "crushes" gas nuclei, rendering them smaller, the second dive will be safer than usual, assuming that appropriate allowance has been made for any excess dissolved gas that remains in the various tissues or compartments. If, on the other hand, the quantity of residual dissolved gas is large, it can reduce the effective crushing pressure for the second dive. Less crushing implies that there will be more large nuclei, more primary bubbles, more secondary bubbles, and more free gas than would have been present had the second dive been performed as a single, isolated excursion.

III. The VPM in Practice

The confluence of a number of technologies, including the advent of the Internet, and widespread sport decompression and mixed-gas diving, have lead to world-wide interest in decompression schedules that emphasize small supersaturations. This section discusses the use of the VPM to calculate diving tables and applies the methods to the analysis of an example set of reverse diving profiles.

1. VPM-based Decompression

A derivation of the VPM equations, based on consideration of compression of an elastic shell, leads to the relationship between differential changes in nuclear radius ∂r, external pressure ∂p_{amb}, and internal pressure ∂p_{in}

$$2(\gamma_c - \gamma)\frac{\partial r}{r^2} = \partial p_{in} - \partial p_{amb}, \qquad (6)$$

where Γ of Eq. (2) has been replaced with the crumbling compression γ_C (Yount 1979a). Extending previous applications of Eq. (6), which set $\partial p_{in} = 0$ in the permeable regime, we explicitly consider the effects of compression and decompression rate by setting the internal pressure p_{in} equal to the dissolved gas tension τ.

Section 4.a. applies a numerical method to compute solutions to Eq. (6) for dives with non-instantaneous descent and ascent rates. An analytical solution of Eq. (6) results from integration over compression and decompression cycles, and use of the Laplace equation as an ascent-limiting criterion. The resulting minimum allowed supersaturation gradients for a set of j parallel compartments are expressed as

$$P_{ss\ j}^{\min} = \frac{2\gamma(\gamma_C - \gamma)}{\gamma_C\, r_{0j}} + \frac{\gamma}{\gamma_C}\Delta_j . \tag{7}$$

Here, our notation generalizes the notation used by Yount (1979a) by calculating the minimum gradients for a set of compartments with time-dependent tensions τ_j, and a set of initial nuclear radii distributed across compartments as r_{0j}. For an instantaneous descent and ascent, $\Delta_j \rightarrow (p_m - p_0)$, $r_{0j} \rightarrow r_0$, and Eq. (7) reduces to the Yount (1979a) form, with a single $P_{ss}^{\min}$ for all compartments. In the case of a gradual descent, Δ_j is a set of effective crushing pressures $p_{crush\ j}$ that follow from application of Eq. (3a) to a set of compartments with time-dependent dissolved gas tensions τ_j. As discussed earlier, these pressures are less than the full crush attained for an instantaneous descent, with the fastest half-time compartments affected the most. Use of the method of Schreiner and Kelley (1971) to compute compartment tensions τ_j during a descent at a crushing rate ρ_C, over a crushing time t_C yields

$$\Delta_j = (p_m - p_0)(1 - f_{N2}) + \frac{f_{N2}\rho_C}{k_j}(1 - \exp(-k_j t_C)), \tag{8}$$

with $\ln(2)/k_j$ corresponding to the j'th compartment's half-time. In the limit of a fast descent, $t_C \rightarrow 0$, the crushing pressure is $\rho_C t_C = (p_m - p_0)$, and Eq. (8) reduces to the Yount (1979a) form.

The Yount and Hoffman (1986) method for calculating VPM-based diving tables follows from the dynamic critical volume hypothesis, which restricts the volume of free gas evolved in each compartment j by the condition

$$\int_0^t (N_{actual} - N_{safe})\, P_{ss\ j}^{new}(t')\, dt' \ \leq \alpha V_{critical} . \tag{9}$$

The excess bubble population is $(N_{actual} - N_{safe})$, α is a proportionality constant, and $V_{critical}$ is the critical volume, as discussed by Yount and Hoffman (1986). For diving profiles with direct ascents and descents in the permeable regime, Eq. (9) can be solved analytically. With an assumed linear ascent rate, the allowed supersaturations for the j compartments are

$$P_{ss\ j}^{new} = \tfrac{1}{2}[b_j + \sqrt{b_j^{\,2} - 4c_j}] \tag{10a}$$

with

$$b_j = P_{ss\ j}^{\min} + \frac{\gamma}{\gamma_C}\frac{\lambda}{t_D + k_j^{-1}} - \frac{(\tau_j^{dive} - p_m)t_D}{2(t_D + k_j^{-1})} \tag{10b}$$

$$c_j = \frac{\gamma^2}{\gamma_C^2}\frac{\lambda(p_m - p_0)}{t_D + k_j^{-1}} - \frac{P_{ss\ j}^{\min}(\tau_j^{dive} - p_m)t_D}{2(t_D + k_j^{-1})}. \tag{10c}$$

The total ascent time t_D is always greater than zero for the linear ascent rate. λ is proportional to the critical volume, and τ_j^{dive} denotes the set of compartment tensions at the end of the dive.

The last terms in the expressions for b_j and c_j add to the original expressions for b and c derived by Yount and Hoffman (1986), and reduce to the original forms for saturated, non-metabolizing systems with $\tau_j^{dive} \sim \tau \approx p_m$. These new terms can have magnitudes that are comparable to the others, and increase the gradients allowed during ascents from the Yount and Hoffman values for equivalent ascent times and pressurization-depressurization schedules. The Yount and Hoffman (1986) VPM decompression algorithm uses an iterative method to solve the set of Eqs. (7) and (10), starting with calculation of the minimum allowed supersaturation gradients $P_{ss\,j}^{min}$, and then successively updating the calculation until t_D converges. This results in the relaxation of the stringent $P_{ss\,j}^{min}$ gradients into the set of new, more liberal gradients $P_{ss\,j}^{new}$.

2. Open Source-Code VPM-Based Decompression Program

The Yount and Hoffman (1986) VPM algorithm was implemented in a series of open source-code *BASIC* language computer programs, which have been freely available to programmers since the *tek95* diving technology conference (Maiken, 1995). These programs expand on the original algorithm by modeling generalized nitrox decompression dives with multiple stages, gas switches, and constant ppO_2 rebreather diving. As of October, 1999, the programs have been distributed to approximately 150 diving programmers worldwide, and the VPM methods have been integrated into a number of publicly available programs.

3. Hydrostatic Pressure, Dissolved Gas, and the VPM Gradients

A diver's exposure to hydrostatic pressure affects ascent criteria through the dependence of Eqs. (7) and (10) on the crushing pressure, and inert gas tensions τ_j^{dive}. As an example of the roles of hydrostatic pressure in setting VPM supersaturation gradients, consider nitrox diving. Conventional nitrox use emphasizes the reduced inert-gas loading of nitrox compared to air for identical profiles. Nitrox decompression calculations are often based on the equivalent air depth (EAD), where the EAD is less than the dive depth. The VPM considers the compartment tensions resulting from a nitrox profile and an air dive to the EAD to be virtually identical. However, for a given nuclear distribution, the VPM gradients are determined by p_{crush}. Except for the fastest compartments, this results in a set of larger, more liberal gradients compared to a set calculated for the EAD. Although the dissolved gas EAD concept yields conservative ascent gradients, it does not completely determine ascent criteria in the VPM.

For repetitive nitrox diving, the actual dive depths should be used as criteria to determine whether a set of profiles is forward or reverse. For example, if two dives are made to a depth of 100 feet, separated by a surface interval on air, with one on 36% nitrox and the other on air, the nitrox dive would conventionally be treated as an air dive to the equivalent air depth (EAD) of 75 feet for application of diving tables. Nonetheless, these would not be considered reverse profiles in the VPM.

Yount and Yeung (1981) demonstrated that a slow descent inhibits the crushing of nuclei, and thus leads to enhanced bubble growth compared to rapid compressions. For a linear descent, this effect is quantified by Eqs. (7) and (8), which predict that the allowable minimum supersaturations $P_{ss\,j}^{min}$ of fast half-time compartments are reduced compared to the slower half-times. Although this effect inverts the conventional ordering of M-values by compartments, it is physically reasonable. This is because exposure of nuclei in fast compartments to large dissolved gas tensions during descent results in diffusive growth, and larger equilibrium radii compared to nuclei in slow compartments. Nonetheless, for typical sport diving profiles, Eqs. (10) invert the minimum gradients calculated by Eq. (7), and the $P_{ss\,j}^{min}$ are ordered with the supersaturations of the slow compartments less than those of the fast compartments. For non-standard, though perhaps operationally common profiles, the $P_{ss\,j}^{min}$ may control the ascent. One example is a saw-tooth exposure with a very gradual descent to a final, maximum depth, followed by a direct ascent. In this case, the VPM distinctly recommends reduction in the allowed supersaturation gradients compared to a dive made with a punctual descent to the same maximum depth.

4. Reverse Diving Profile Workshop Series of Exposures

The organizers of the *Reverse Dive Profiles Workshop* asked participants to specifically consider the series of forward and reverse diving profiles summarized in Table I. Recognizing that these profiles fall within the context of sport diving, and for purposes of our graphical analysis, we use the contemporary set of Bühlmann ZH-86 air diving tables as a baseline reference in Table II. The profiles generated by Bühlmann's tables are similar to those produced by the range of dive computers in current use by sport divers.

Table 1. Reverse and Forward Dives

Reverse Dive Series (A)			
Series	First Dive Profile	Surface Interval	Repetitive Dive Profile
1A	40 fsw to NDL	30 min	100 fsw
2A	40 fsw to NDL	60 min	100 fsw
3A	40 fsw to NDL	120 min	100 fsw
Forward Dive Series (B)			
Series	First Dive Profile	Surface Interval	Repetitive Dive Profile
1B	100 fsw to NDL	30 min	40 fsw
2B	100 fsw to NDL	60 min	40 fsw
3B	100 fsw to NDL	120 min	40 fsw
			(NDL: no-decompression limit)

Table II. Profiles Based on Bühlmann ZH-86 Air Decompression Tables

Reverse Dive Series (A)							
Series	First Dive	NDL	RG	SI	RG	RNT	Repetitive Dive
1A	40 fsw	125 min	G	30 min	F	30 min	100 fsw.[1]
2A	40 fsw	125 min	G	60 min	D	19 min	100 fsw.[2]
3A	40 fsw	125 min	G	120 min	B	11 min	100 fsw.[3]

[1]Because NDL = 17 min and RNT = 30 min, it is already a decompression dive. Modeled as a "spike" dive to 100 fsw, followed by immediate ascent. Deco stops at 20 fsw for 2 min and 10 fsw for 7 min.

[2]Because NDL = 17 min and RNT = 19 min, it is already a decompression dive. Modeled as a "spike" dive to 100 fsw, followed by immediate ascent. Deco stop at 10 fsw for 5 min.

[3]Because NDL = 17 min and RNT = 11 min, the NDL is reduced to 6 min.

Forward Dive Series (B)							
Series	First Dive	NDL	RG	SI	RG	RNT	Repetitive Dive
1B	100 fsw	17 min	D	30 min	A	19 min	40 fsw.[4]
2B	100 fsw	17 min	D	60 min	A	19 min	40 fsw.[5]
3B	100 fsw	17 min	D	120 min	A	19 min	40 fsw.[6]

[4,5,6]Because NDL = 125 min and RNT = 19 min, the NDL is reduced to 106 min.

Abbreviations and Notes:
NDL = No-decompression limit (minutes), RG = Repetitive Group,
SI = Surface Interval (minutes), RNT = Residual Nitrogen Time (minutes),
fsw = feet of seawater (a unit of pressure).
Ascent rate is 30 fsw per minute.
A one-minute safety stop is required by the table for all no-decompression dives.

a. Numerical Calculation of a Dynamic Minimum Supersaturation

We have implemented a numerical solution to Eq. (6), which tracks the radii and minimum allowable gradients $P_{ss\,j}^{\min}$ for each compartment during decompression from dives in the permeable regime. The nitrogen partial pressures τ_j were computed by the method of Schreiner and Kelley (1971), using their alveolar ventilation equation. The alveolar partial pressure of inert gas was based on the nitrogen fraction f_{N2} of the breathing mixture, standard values for $P_A\,CO_2$ and $P_A\,H_2O$, and a respiratory quotient of 0.9. The set of 16 nitrogen compartments of the Bühlmann ZH-L16 Calculation Model (Bühlmann, 1995) were used to parameterize the spectrum of tissue half-times in the human body, with half-times ranging from 5 to 635 min.

Under this framework, the internal pressure p_{in} of gas nuclei is equal to the dissolved inert gas tension τ_j of the surrounding compartment. The analysis program tracks an array of radii across the 16 compartments. At the beginning of the first dive, the radius in each compartment is assigned a specific value, r_0. As the dive progresses, the program updates the radius for each compartment based on the instantaneous crushing or supersaturation pressures.

b. Graphical Analysis of Reverse Diving Profiles

We utilize pressure graphs to plot gas loadings, M-values, and VPM gradient lines against ambient pressure. The pressure graph is a useful tool for visualizing the salient characteristics of ascent or decompression profiles. An explanation and further examples of this method are given by Baker (1998a; 1998b). The Bühlmann ZH-L16B set of linear M-values for nitrogen are included to delineate the ascent limiting criteria of conventional dissolved-gas decompression algorithms.

In Figs. 5, 7, 9, 11, 13, 15, 17, and 19, the inert-gas loadings by compartment are compared with the respective Bühlmann ZH-L16B M-values. In Figs. 6, 8, 10, 12, 14, 16, 18, and 20, the inert-gas loadings by compartment are compared with the VPM isopleths of constant bubble number. These lines of fixed gradient are shown upon surfacing and are labeled with the initial radius r_0 assigned at the start of the dive series. A range of initial radii from 0.2 μm to 1.3 μm was selected on the basis of experimental values (Yount, Yeung, and Ingle, 1979) and (Yount, Gillary, and Hoffman, 1984).

The pressure graphs with the VPM criterion for bubble formation display two distinct lines for each of the twelve initial radii considered as can be seen in Fig. 20. These lines correspond to the envelope of Eq. (8) for the range of half-times modeled. The solid line labeled "Cpt 16" shows the gradient for bubble formation upon surfacing for Compartment 16, which has the slowest half-time for gas loading. Because of the very slow uptake of inert gas in this compartment, the effective crushing pressure during compressions will be very near the maximum possible (p_m - p_0), and the $P_{ss\,j}^{\min}$ are identical to the Yount (1979a) values. The dashed line labeled "Cpt 1b" shows the surfacing gradient for Compartment 1b, which has the fastest half-time for gas loading. Because of the fast uptake of inert gas in this compartment, the effective crushing pressure during compressions is reduced. As a result, the decrease in radius of gas nuclei will be less and the corresponding gradient for bubble formation will be smaller. The fixed gradient lines for bubble formation in Compartments 2 through 15 (not shown) fall between the lines indicated for Compartments 1b and 16 on the pressure graphs.

In Fig. 5 the inert-gas loadings for a single 40 fsw dive do not exceed the respective M-values. Accordingly, this dive would be considered safe with regard to the conventional dissolved-gas algorithm. In Fig. 6 the same gas loadings are compared with the VPM criterion for bubble formation, where it can be seen that the fastest compartments probe an initial radius r_0 of 0.6 μm. Based on the 0.8 μm value of Yount and Hoffman (1986), we would expect a substantial number of bubbles to form upon surfacing from this dive. This distinction is not revealed by the conventional dissolved-gas algorithm.

In Fig. 13 the inert-gas loadings for a single 100 fsw dive do not exceed the respective M-values. Accordingly, this dive would also be considered safe with regard to the conventional dissolved-gas algorithm. In Fig. 14 the same gas loadings are compared with the VPM criterion for bubble formation, where it can be seen that the fastest compartments probe an initial radius r_0 of 0.3 μm. Based on the 0.8 μm value of Yount and Hoffman (1986), we would expect that the 100 fsw dive would produce far more bubbles upon surfacing than the 40 fsw dive. Again, this is a distinction not revealed by the conventional dissolved-gas algorithm.

The conventional algorithm fails to identify bubble formation and also fails to distinguish between the 40 fsw dive and the 100 fsw dive on the basis of their severity. The VPM, on the other hand, predicts that both dives will produce bubbles and that the 100 fsw dive would be more stressful than the 40 fsw dive. Given our assumption that any abnormalities existing at the start of a dive will have greatest impact for stressful dives, there is a clear indication that it would be best in this case to perform the 100 fsw dive first.

IV. Discussion

The Varying Permeability Model makes distinct recommendations for diving profiles. First, the crushing pressure p_{crush} should be maximized to the degree possible for any sequence of dives. This applies to single dives as well as to repetitive exposures. For punctual descents, p_{crush} is essentially equal to the change in hydrostatic pressure between the surface and the diving depth. For slow descents, Eq. (8) predicts a reduction in the allowable supersaturation gradients. Second, supersaturation gradients during dives should not exceed limiting values for bubble formation and/or volume of released gas. Following a conventional dissolved-gas algorithm, it is possible that a reverse dive profile, such as a 40 fsw dive followed by a 100 fsw dive, can result in reduced values for effective p_{crush} as well as bubble-forming supersaturation gradients. Under this scenario, the total number of bubbles and the total volume of released gas can be substantial.

There is nothing inherently dangerous about a reverse dive profile providing that the decompression algorithm adequately takes into account excess dissolved gas (gas loading), unresolved free gas (gas bubbles), and changes in the underlying size distribution of bubble formation nuclei (gas nuclei). Only the first of these effects is accounted for in conventional dissolved gas algorithms. All three can be addressed within the context of the Varying Permeability Model.

Acknowledgments

The authors wish to thank the group of enterprising divers, programmers, and scientists that constitute the *decompression mailing list*. These individuals continue to constructively shape our views of decompression modeling and practice. We acknowledge Daniel Reinders, and Richard Pyle's helpful and spirited discussions. In particular, we are grateful for Rob Murray's initiative in creating and administering the Decompression Mailing List, which was instrumental in the writing of this paper.

Glossary of Terms

Decompression list. The latest step in "open-sourcing" decompression software is an electronic mailing list set up by Rob Murray in December 1998. In less than one year, the "Decompression List" has attracted more than 100 subscribers from all over the world, including prominent attendees at this workshop and all three authors of this paper. In a very real sense, the entire list is participating in the workshop because we have been discussing reverse dive profiles and related topics electronically for more than two months, and we expect to continue the dialogue after the workshop ends.

Deep stops. Technical divers commonly add deep stops to conventional ascent schedules. We shall define a deep stop as any decompression stop that is deeper than the first stop computed using a conventional dissolved-gas algorithm.

Open source-code. A non-compiled text listing of the commands used to write a computer program. The open source-code VPM program allows programmers to see the inner workings of the BASIC language computer program that implements the VPM-based decompression model. This program was the first open source-code decompression program available on the Internet.

Sport diving (a.k.a. recreational diving – Ed. note) by definition, involves the use of only one nitrogen-oxygen breathing gas throughout the entire dive (air or nitrox up to a maximum of 40% oxygen fraction), and is performed within the no-decompression limits of the table or dive computer being used. It is generally understood by the sport diver that a direct ascent to the surface can be made at any time during the dive, notwithstanding the recommended practice of safety stops. Such ascents typically create large and rapid gradients between the dissolved gas tension in the diver's body and the ambient pressure in the surrounding medium. Because high-oxygen mixtures are not available to accelerate off-gassing and reduce gradients, problems associated with gas loading become more severe as the depth and/or duration of the dive increase.

Technical diving. A major instigator of this on-going revolution in sport-diving practice was the now defunct magazine AquaCorps, which, from 1991 through 1995, published articles that addressed such technical topics as decompression theory, deep diving, and mixed-gas breathing--topics that far exceeded the interests and comprehension of most sport divers. Hamilton used the term *technical diver* in the very first issue of AquaCorps: More recently, noting that the term was originally used by the British Royal Navy for rebreather diving, he has redefined technical diving as diving with more than one breathing gas or with a rebreather (Hamilton 1999). Pyle defines a technical diver (Pyle 1999b) as anyone who routinely conducts dives with staged stops during an ascent as suggested by a given decompression algorithm. (Ed. Note: The term technical diving was initially used in the United States in 1977 by CACSTD, the California Advisory Committee on Scientific and Technical Diving, to distinguish technical diving from scientific diving for regulatory purposes by OSHA).

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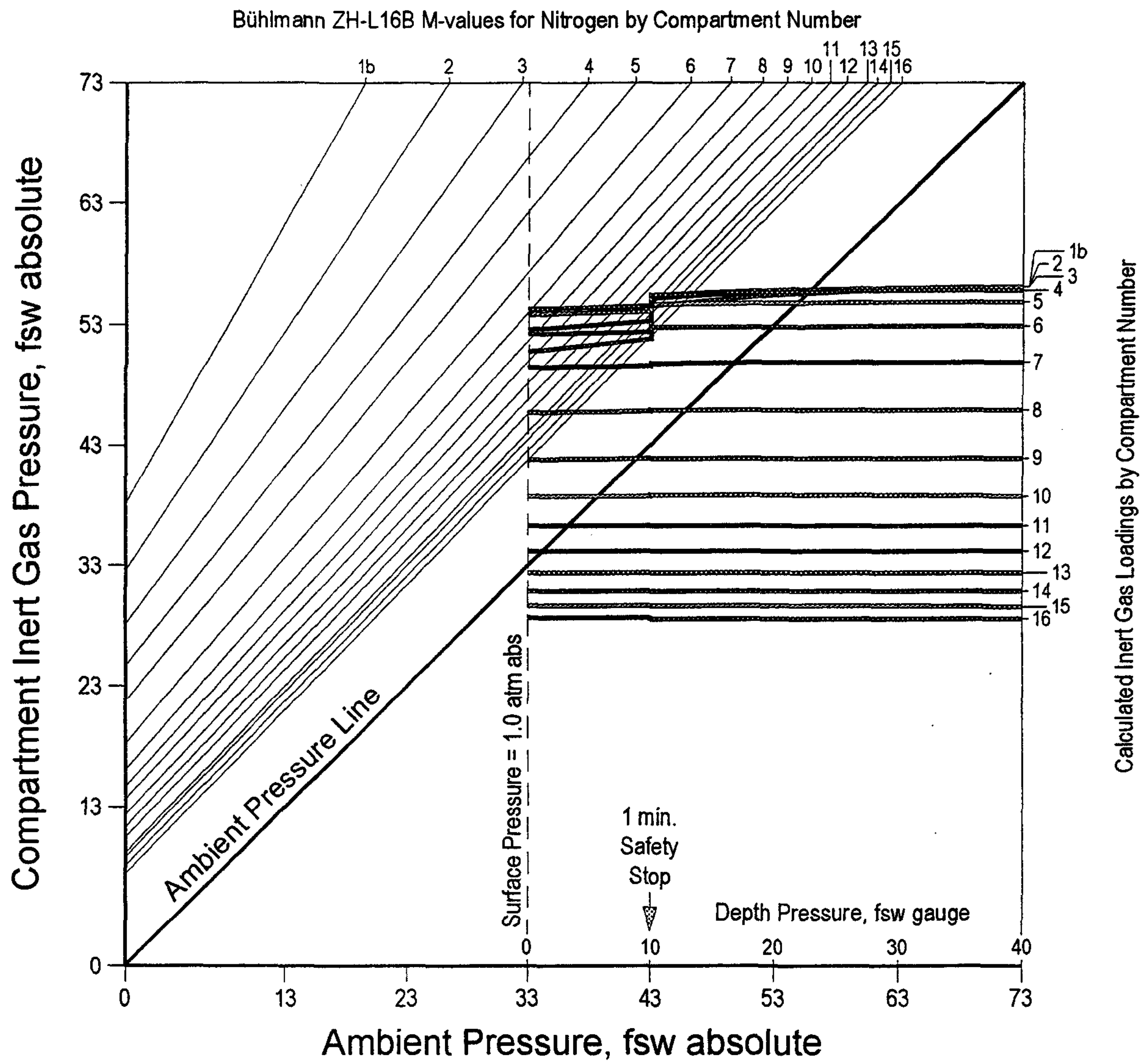
Pressure Graph:

Ascent Profile For First Dive Of Reverse Dive Series 1A, 2A, and 3A
Inert Gas Loadings Versus Conventional M-values



Notes:

1. Air dive to 40 fsw for 125 minutes bottom time according to no-decompression limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. A one minute safety stop is required for all no-deco dives *according to the Bühlmann ZH-86 Air Diving Tables.*

Observations:

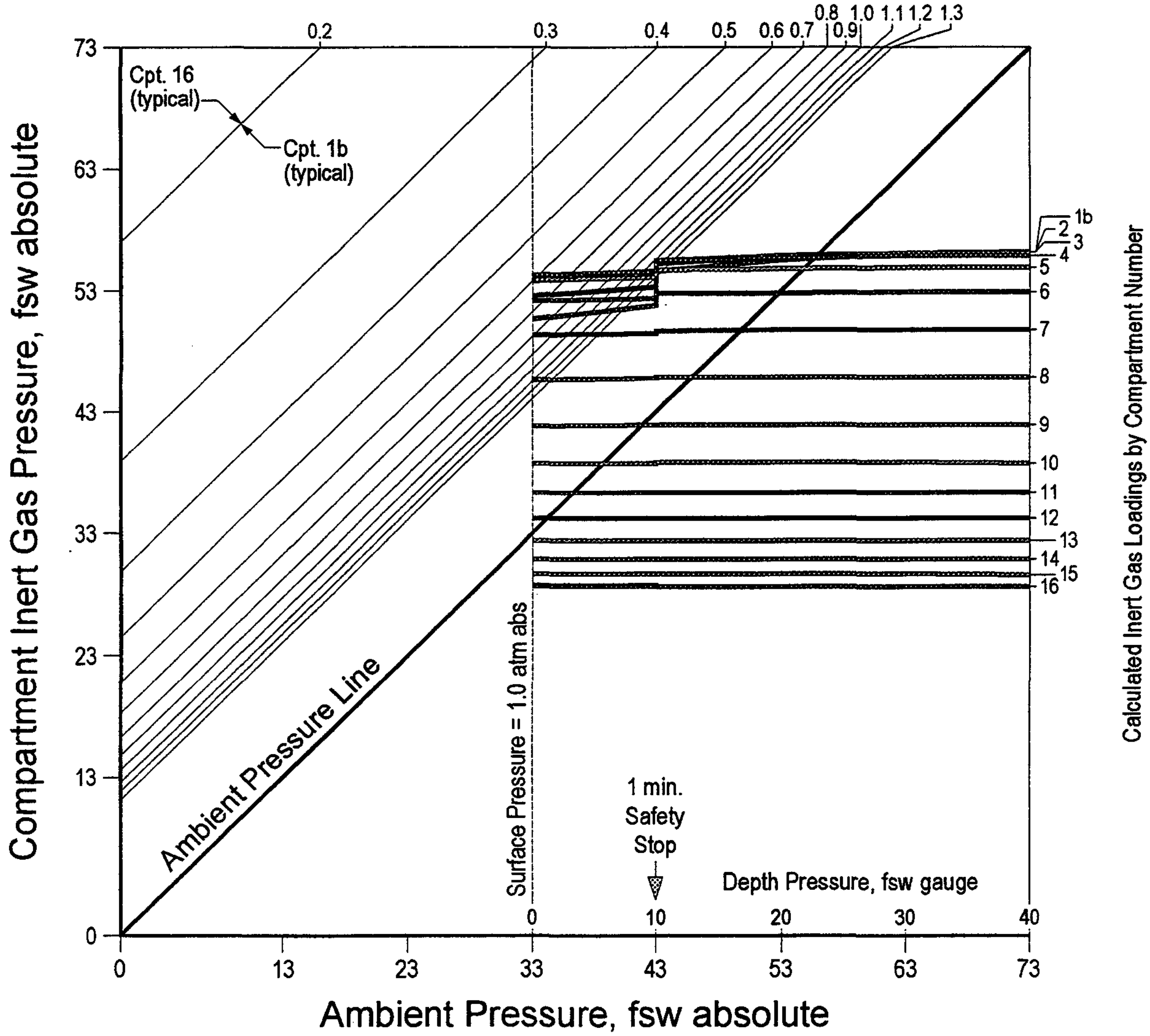
1. M-values for fast compartments permit large overpressure gradients and thus allow profuse bubble formation.
2. Upon surfacing from this dive, Compartments 6 and 7 are leading (gas loadings closest to M-values).
3. The one minute safety stop at 10 fsw has only a mild effect in terms of dropping gas loadings.

Figure 5.

Pressure Graph:

Ascent Profile For First Dive Of Reverse Dive Series 1A, 2A, and 3A
Inert Gas Loadings Versus VPM Criterion for Bubble Formation

Shown Upon Surfacing: Lines of Fixed Gradient = Isopleths of Constant Bubble Number
Calculated Based on Minimum Initial Radius (microns) of Gas Nuclei at Start of Dive Series



Notes:

1. Air dive to 40 fsw for 125 minutes bottom time according to no-decompression limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

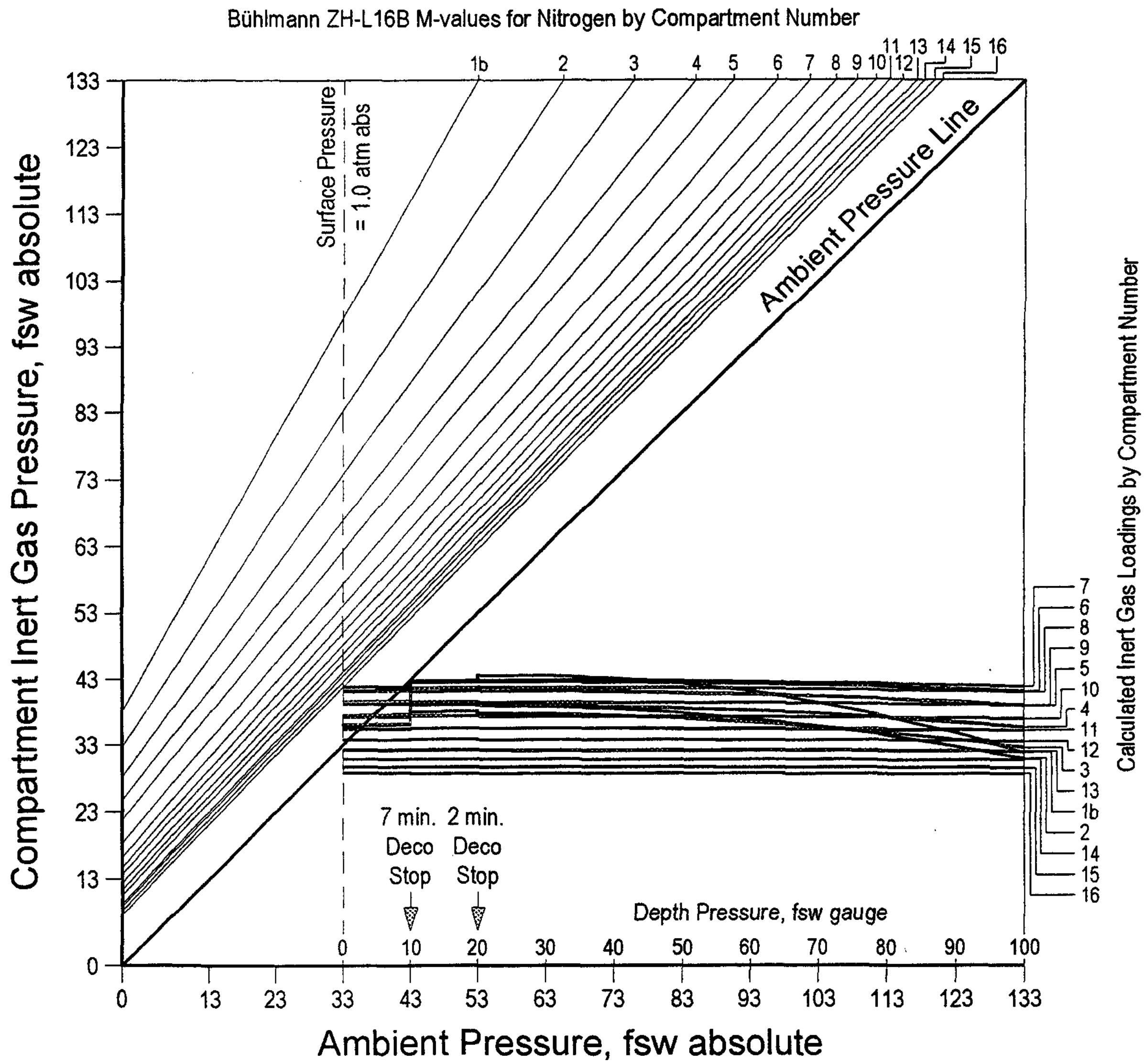
Observations:

1. Bubbles are formed in Compartments 1b thru 7 upon surfacing from this dive.
2. Overpressure (supersaturation) gradients will exist for up to 60 minutes after this dive to drive bubble growth.
3. A surface interval of less than 60 minutes after this first dive could carry free-phase gas over into a repetitive dive as bubbles or gas nuclei with larger initial radius.

Figure 6.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Reverse Dive Series 1A
Inert Gas Loadings Versus Conventional M-values



Notes:

1. After surface interval of 30 minutes, repetitive air dive to 100 fsw followed by immediate ascent (spike dive).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and the bottom time is only momentary.
4. Due to residual nitrogen loading, deco stops are required at 20 and 10 fsw per Bühlmann ZH-86 Air Diving Tables.

Observations:

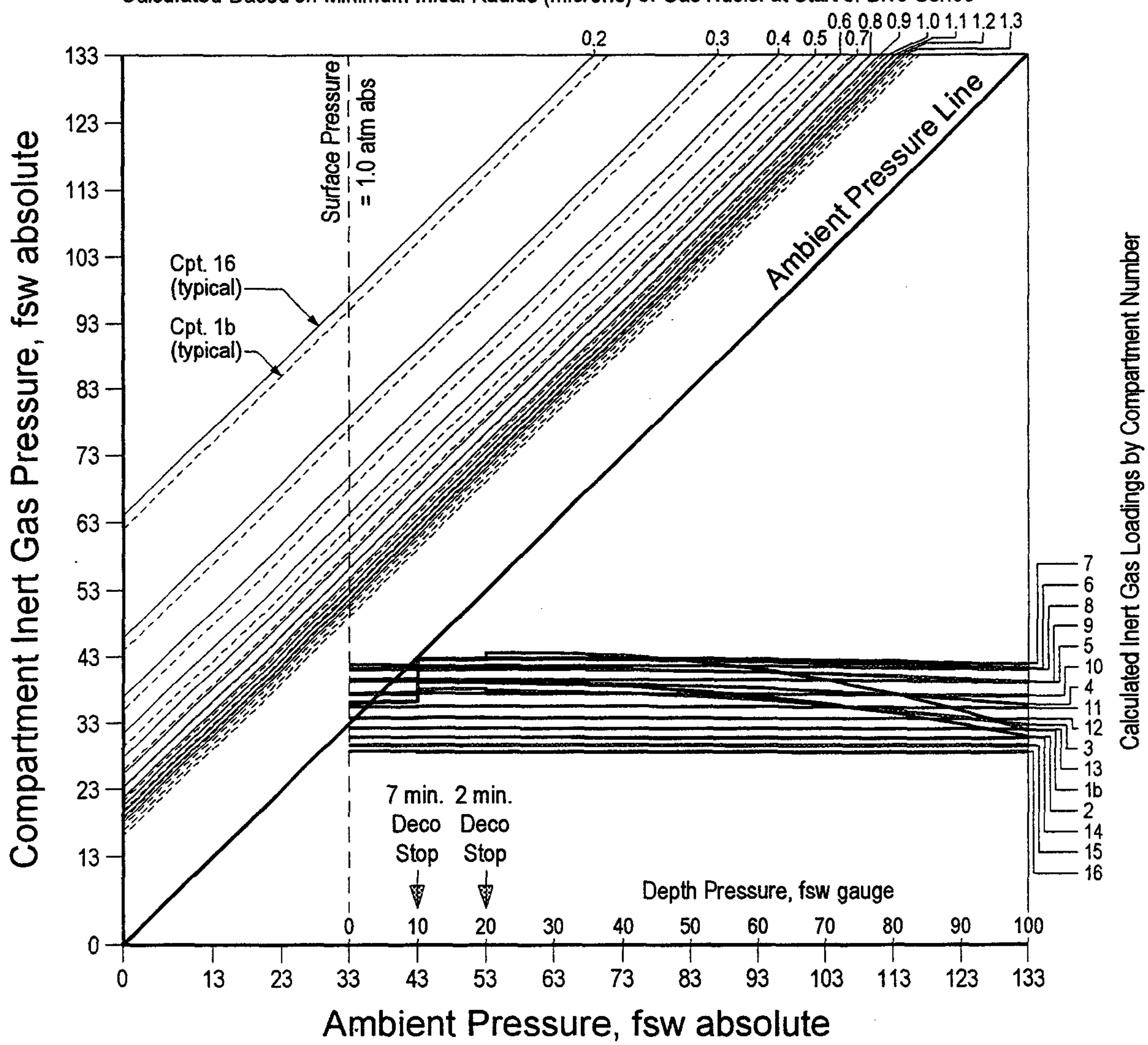
1. Gas loadings are well clear of M-values throughout ascent. No significant on-gassing during this dive.
2. Upon surfacing from this dive, Compartments 8 and 9 are leading (gas loadings closest to M-values).
3. It does not appear that there should be any problems following this dive unless free-phase gas (bubbles or large nuclei) carried over to this dive from the first dive.

Figure 7.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Reverse Dive Series 1A
Inert Gas Loadings Versus VPM Criterion for Bubble Formation

Shown Upon Surfacing: Lines of Fixed Gradient = Isopleths of Constant Bubble Number
Calculated Based on Minimum Initial Radius (microns) of Gas Nuclei at Start of Dive Series



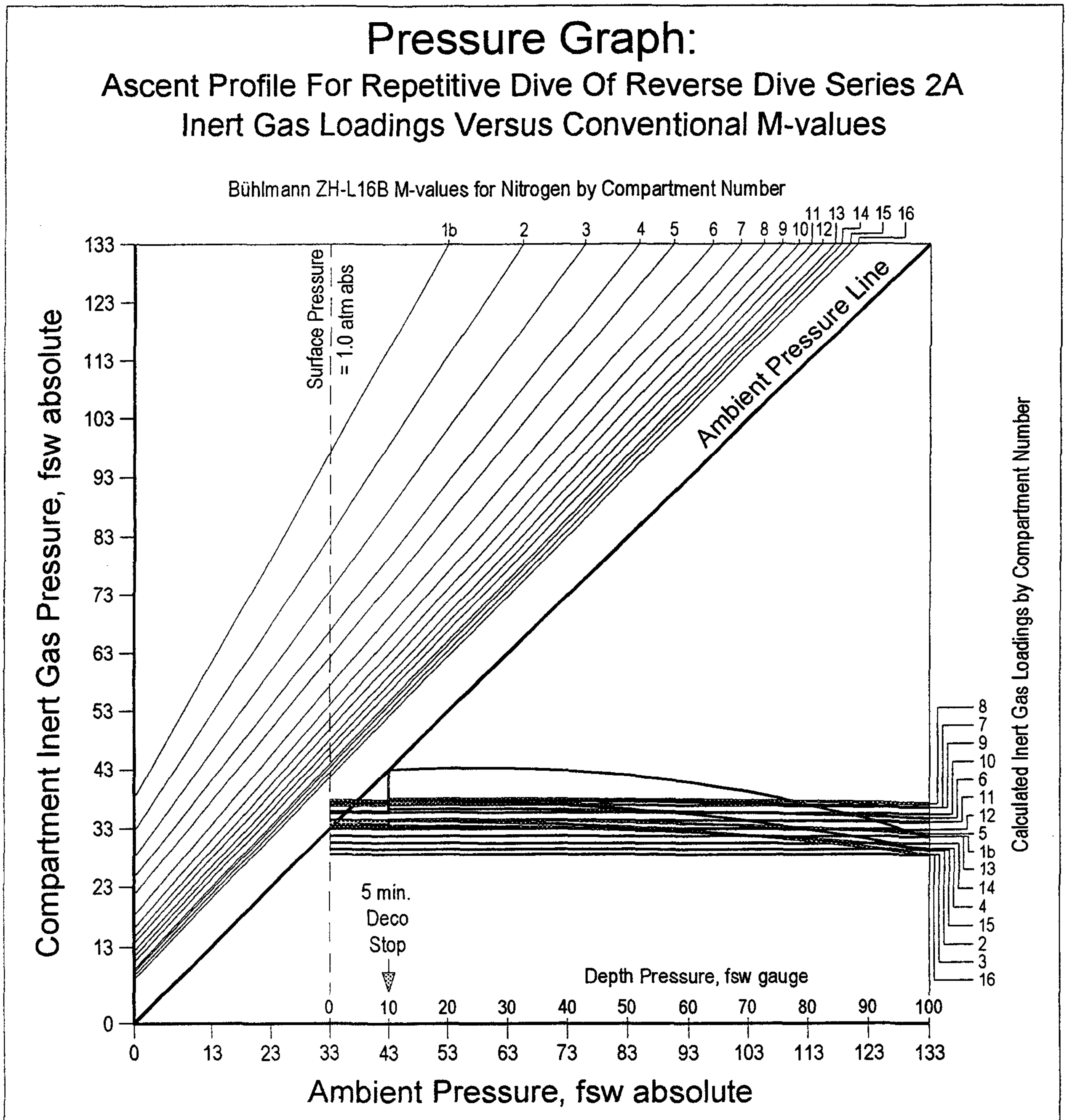
Notes:

1. After surface interval of 30 minutes, repetitive air dive to 100 fsw followed by immediate ascent (spike dive).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and the bottom time is only momentary.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

Observations:

1. No bubbles are formed as a result of the repetitive dive.
2. It does not appear that there should be any problems following this dive unless free-phase gas (bubbles or large nuclei) carried over to this dive from the first dive.

Figure 8.



Notes:

1. After surface interval of 60 minutes, repetitive air dive to 100 fsw followed by immediate ascent (spike dive).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and the bottom time is only momentary.
4. Due to residual nitrogen loading, a deco stop is required at 10 fsw per Bühlmann ZH-86 Air Diving Tables.

Observations:

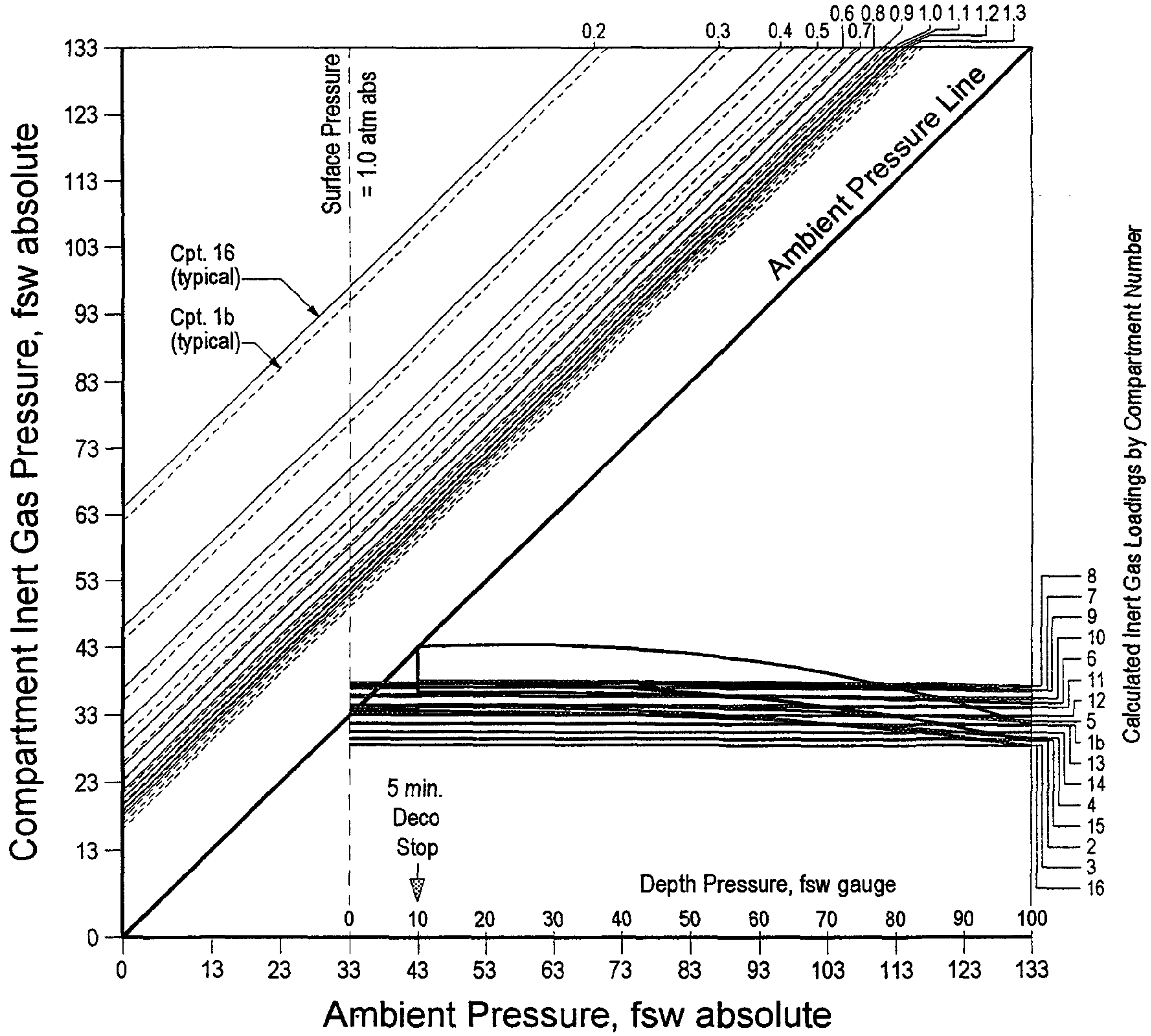
1. Gas loadings are well clear of M-values throughout ascent. Noticeable on-gassing in Compartment 1b during this dive.
2. Upon surfacing from this dive, Compartments 9 and 10 are leading (gas loadings closest to M-values).
3. It does not appear that there should be any problems following this dive unless free-phase gas (bubbles or large nuclei) carried over to this dive from the first dive.

Figure 9.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Reverse Dive Series 2A
Inert Gas Loadings Versus VPM Criterion for Bubble Formation

Shown Upon Surfacing: Lines of Fixed Gradient = Isopleths of Constant Bubble Number
Calculated Based on Minimum Initial Radius (microns) of Gas Nuclei at Start of Dive Series



Notes:

1. After surface interval of 60 minutes, repetitive air dive to 100 fsw followed by immediate ascent (spike dive).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and the bottom time is only momentary.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

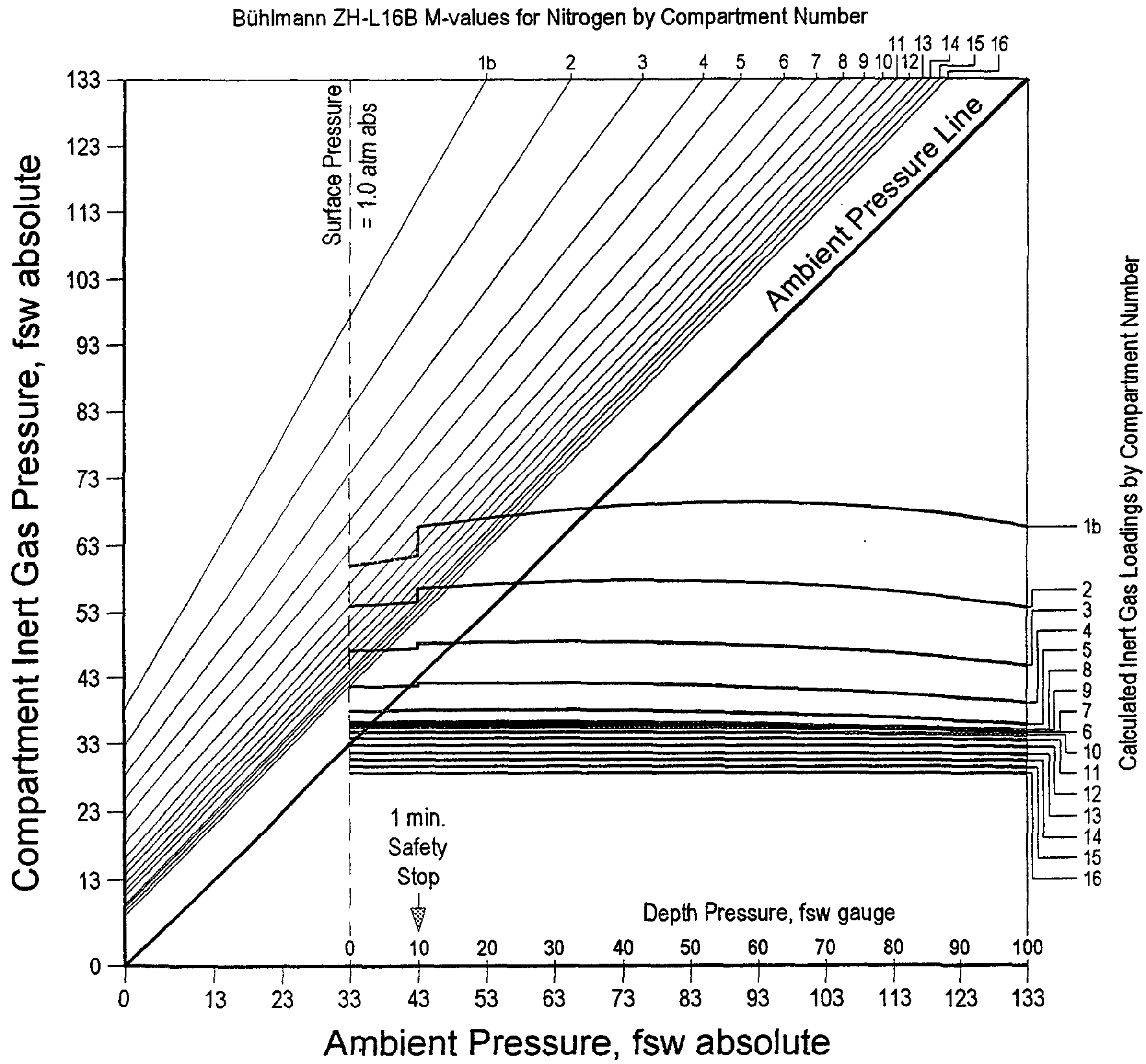
Observations:

1. No bubbles are formed as a result of the repetitive dive.
2. It does not appear that there should be any problems following this dive unless free-phase gas (bubbles or large nuclei) carried over to this dive from the first dive.

Figure 10.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Reverse Dive Series 3A
Inert Gas Loadings Versus Conventional M-values



Notes:

1. After surface interval of 120 minutes, repetitive air dive to 100 fsw for 6 minutes bottom time according to no-deco limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. A one minute safety stop is required by the table.

Observations:

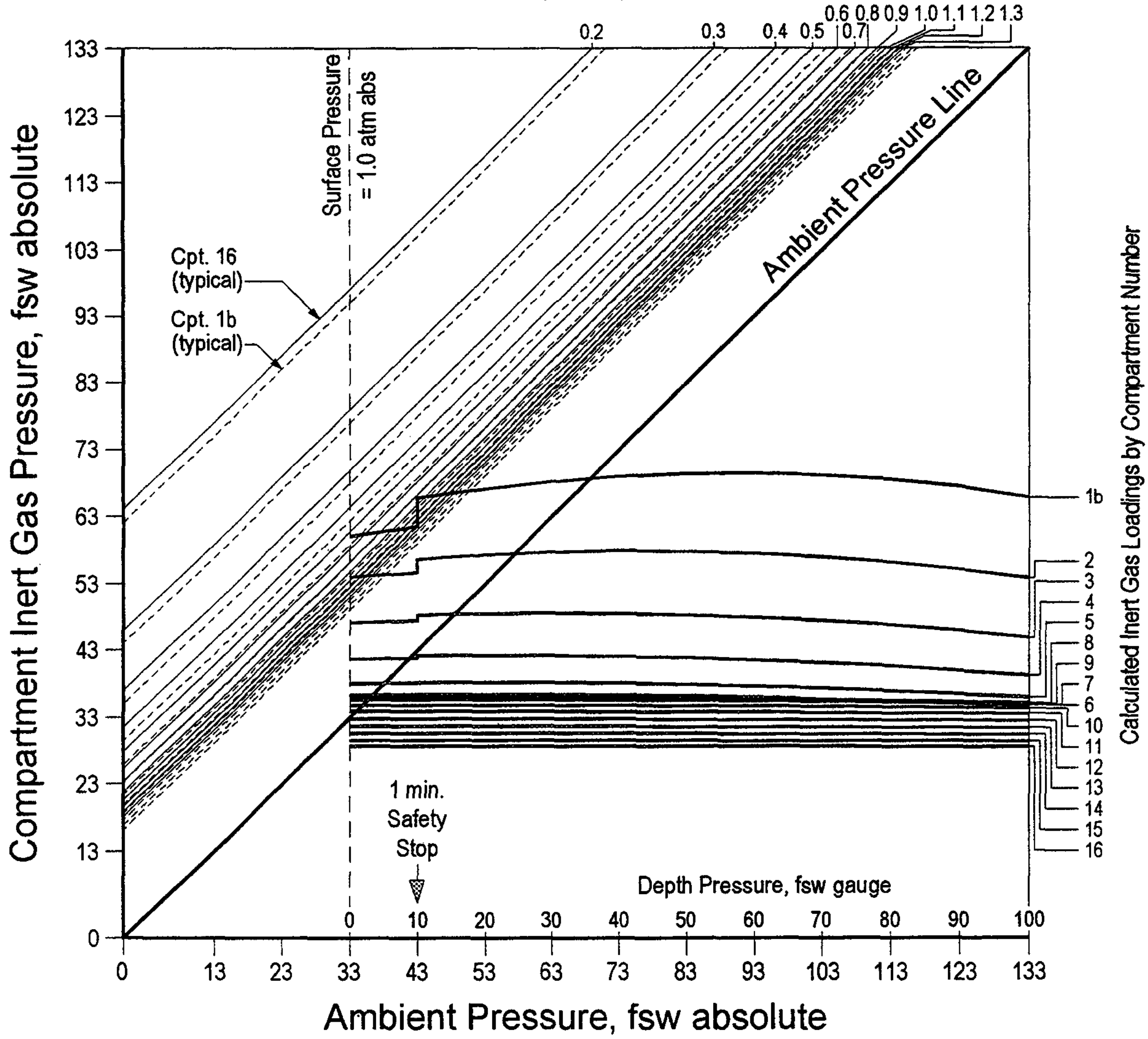
1. M-values for fast compartments permit large overpressure gradients and thus allow profuse bubble formation.
2. Upon surfacing from this dive, Compartments 10 and 11 are leading (gas loadings closest to M-values).
3. The one minute safety stop at 10 fsw has only a mild effect in terms of dropping gas loadings.

Figure 11.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Reverse Dive Series 3A
Inert Gas Loadings Versus VPM Criterion for Bubble Formation

Shown Upon Surfacing: Lines of Fixed Gradient = Isopleths of Constant Bubble Number
Calculated Based on Minimum Initial Radius (microns) of Gas Nuclei at Start of Dive Series



Notes:

1. *After surface interval of 120 minutes, repetitive air dive to* 100 fsw for 6 minutes bottom time (no-deco limit).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

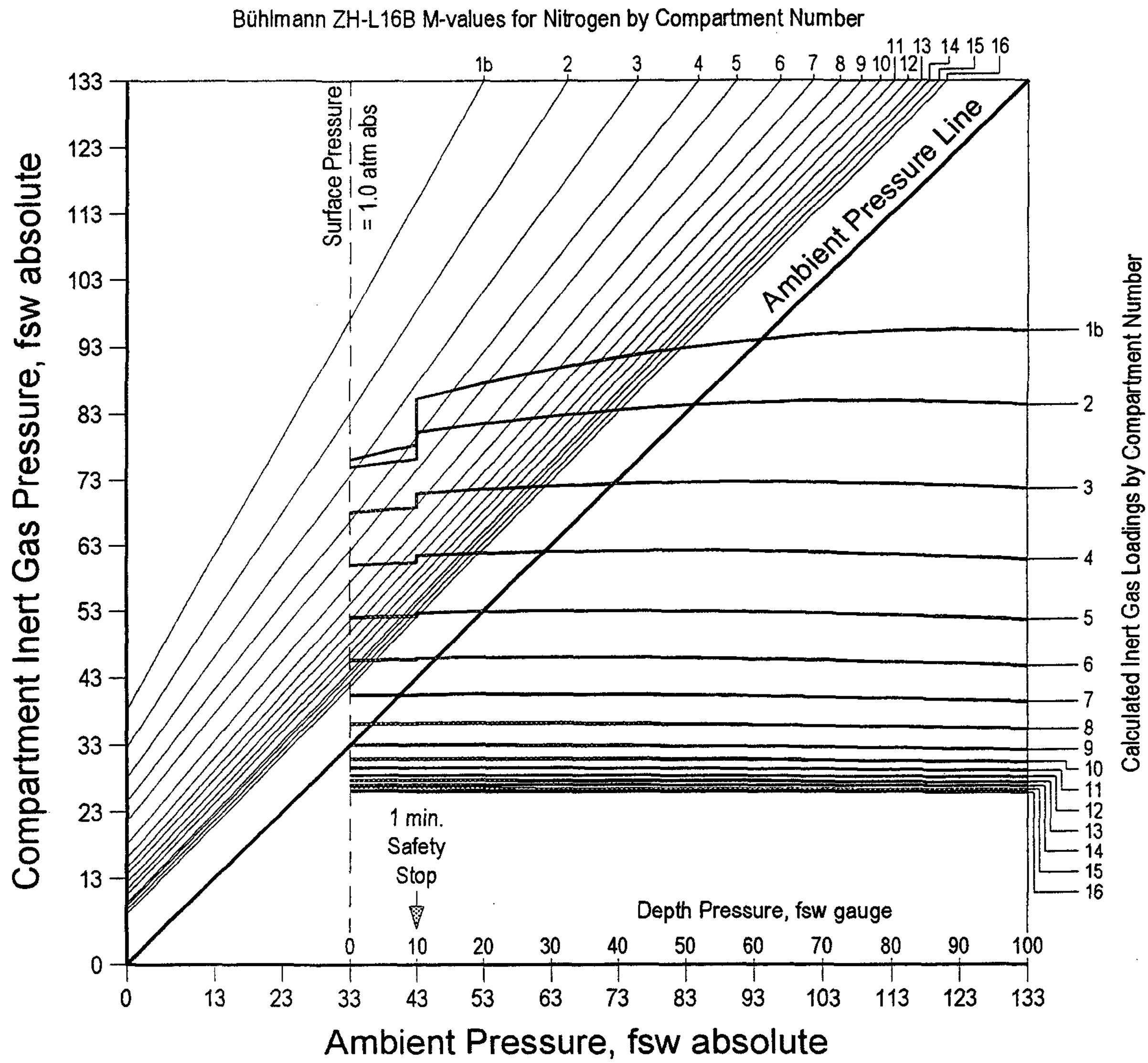
Observations:

1. *Bubbles are formed in Compartments 1 and 2 upon* surfacing from this dive.
2. Overpressure (supersaturation) gradients will exist for more than 10 minutes after this dive to drive bubble growth.

Figure 12.

Pressure Graph:

Ascent Profile For First Dive Of Forward Dive Series 1B, 2B, and 3B
Inert Gas Loadings Versus Conventional M-values



Notes:

1. Air dive to 100 fsw for 17 minutes bottom time according to no-decompression limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. A one minute safety stop is required for all no-deco dives according to the Bühlmann ZH-86 Air Diving Tables.

Observations:

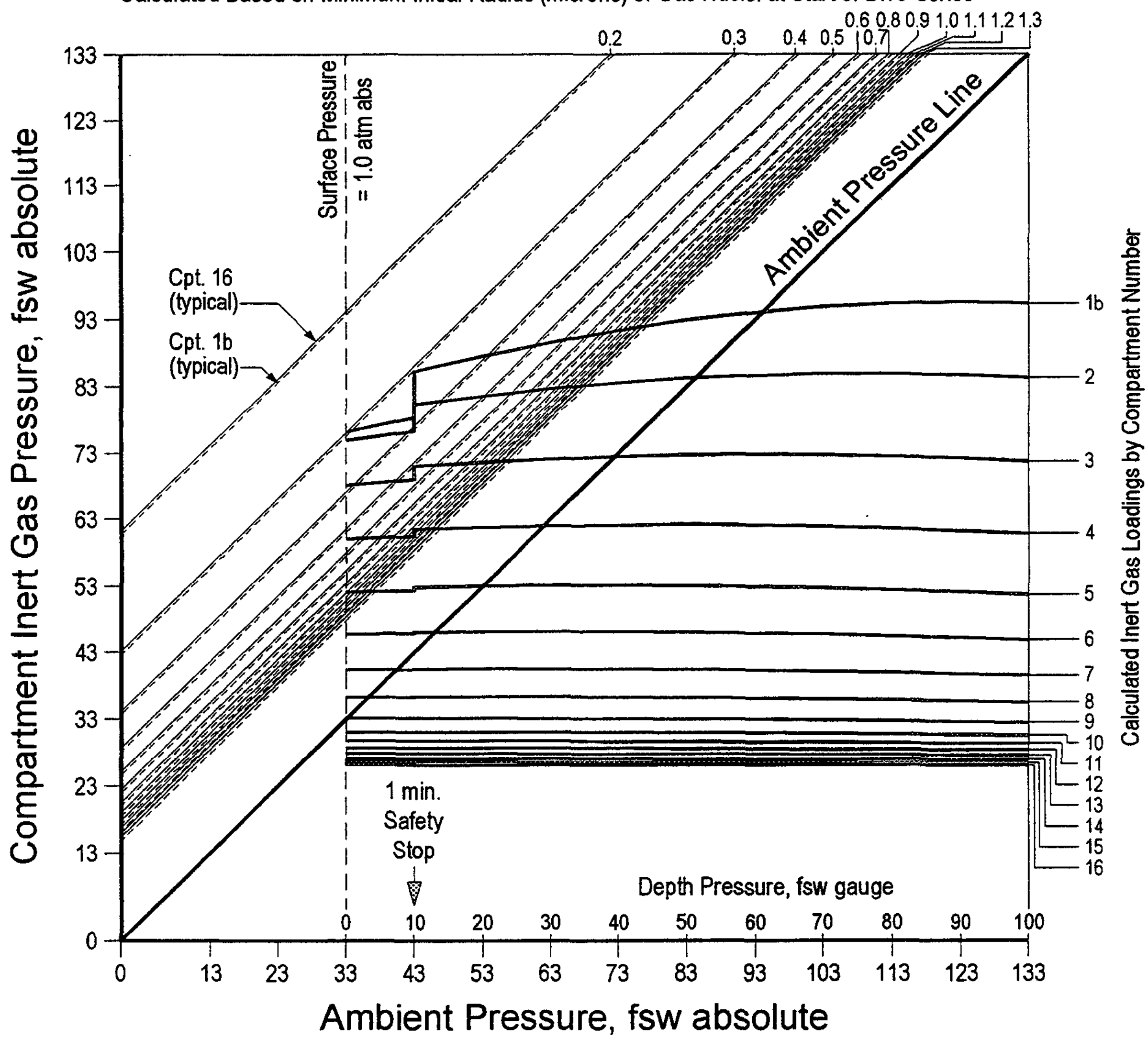
1. M-values for fast compartments permit large overpressure gradients and thus allow profuse bubble formation.
2. Upon surfacing from this dive, Compartments 2 and 3 are leading (gas loadings closest to M-values).
3. The one minute safety stop at 10 fsw has a moderate effect in terms of dropping gas loadings.

Figure 13.

Pressure Graph:

Ascent Profile For First Dive Of Forward Dive Series 1B, 2B, and 3B Inert Gas Loadings Versus VPM Criterion for Bubble Formation

Shown Upon Surfacing: Lines of Fixed Gradient = Isopleths of Constant Bubble Number
Calculated Based on Minimum Initial Radius (microns) of Gas Nuclei at Start of Dive Series



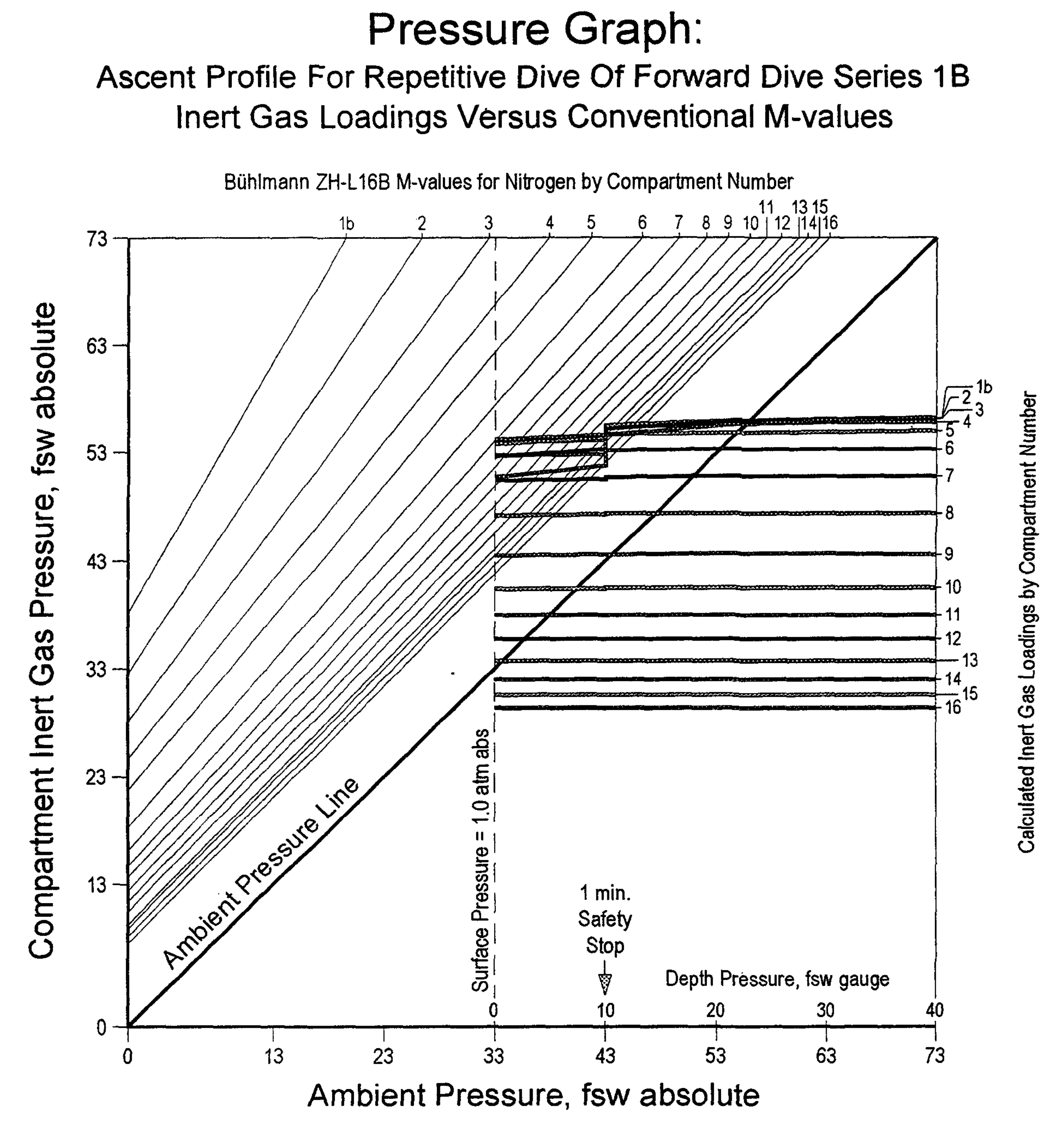
Notes:

1. Air dive to 100 fsw for 17 minutes bottom time according to no-decompression limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

Observations:

1. Bubbles are formed in Compartments 1b thru 5 upon surfacing from this dive.
2. Overpressure (supersaturation) gradients will exist for more than 30 minutes after this dive to drive bubble growth.
3. A surface interval of less than 30 minutes after this first dive could carry free-phase gas over into a repetitive dive as bubbles or gas nuclei with larger initial radius.

Figure 14.



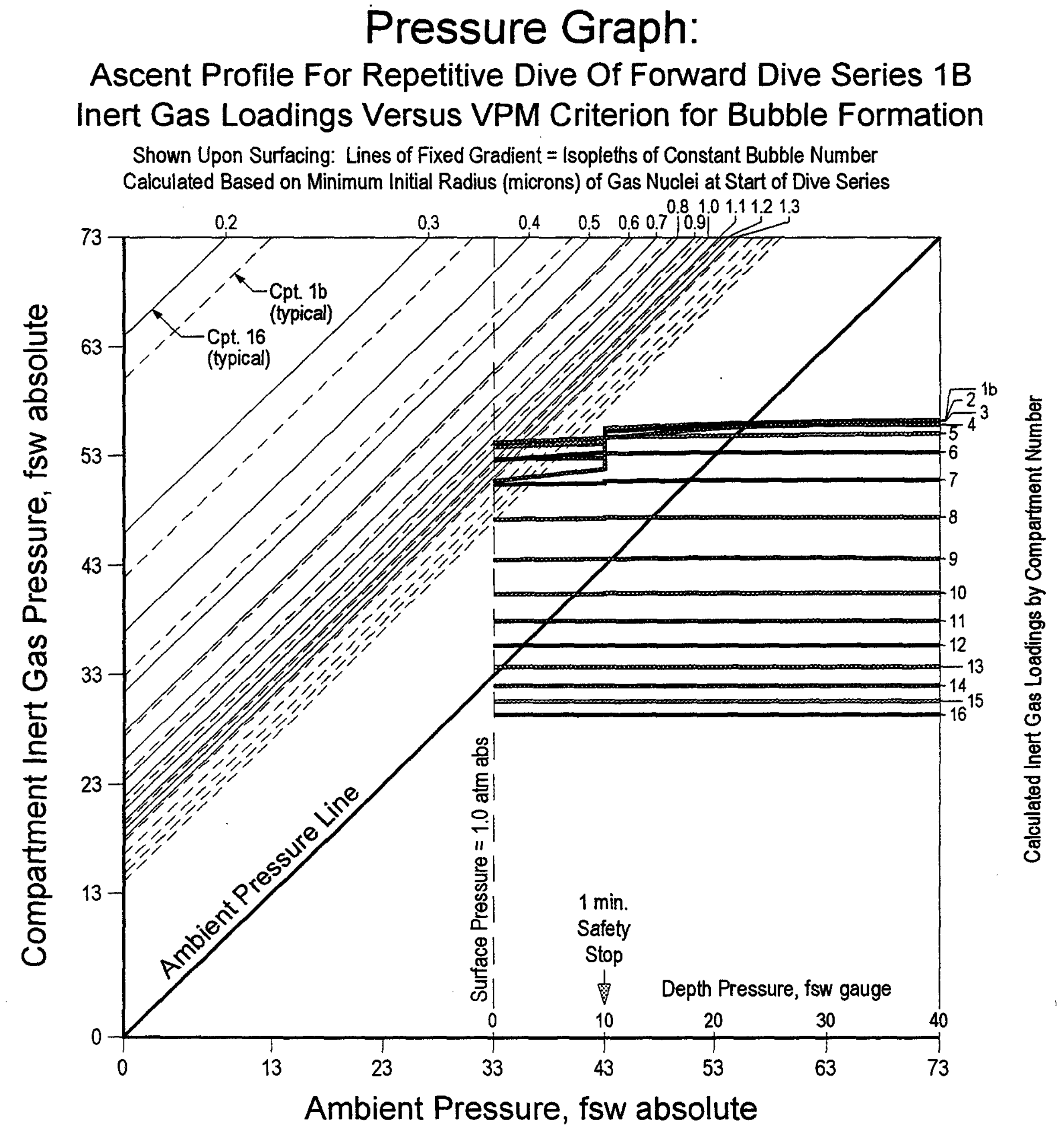
Notes:

1. After surface interval of 30 minutes, repetitive air dive to 40 fsw for 106 minutes bottom time according to no-deco limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. A one minute safety stop is required by the table.

Observations:

1. M-values for fast compartments permit large overpressure gradients and thus allow profuse bubble formation.
2. Upon surfacing from this dive, Compartments 6 and 7 are leading (gas loadings closest to M-values).
3. The one minute safety stop at 10 fsw has only a mild effect in terms of dropping gas loadings.

Figure 15.



Notes:

1. After surface interval of 30 minutes, repetitive air dive to 40 fsw for 106 minutes bottom time (no-deco limit).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

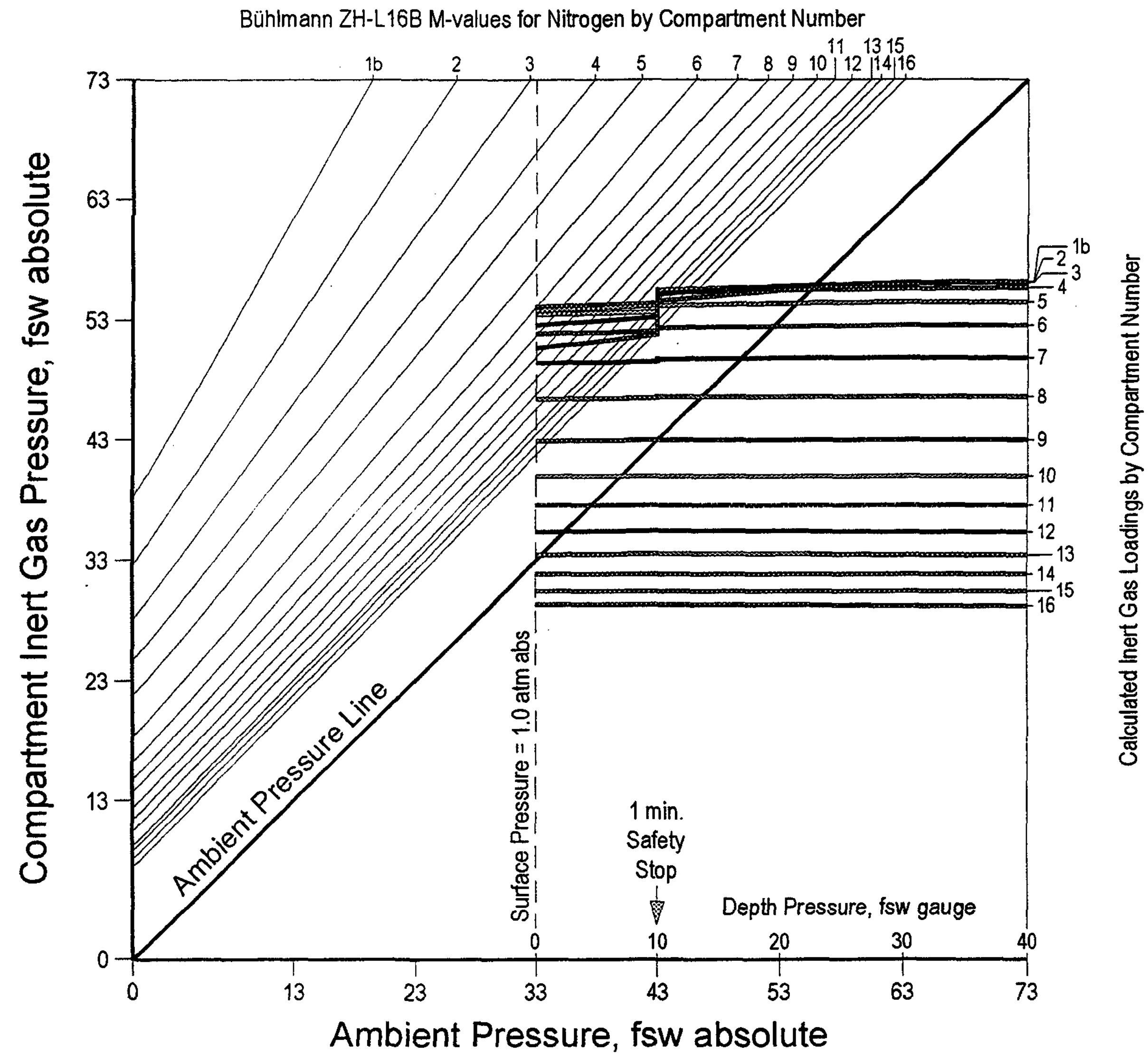
Observations:

1. Bubbles are formed in Compartments 1b thru 6 upon surfacing from this dive.
2. Overpressure (supersaturation) gradients will exist for over 30 minutes after this dive to drive bubble growth.
3. There is a difference of 4.0 fsw in allowable gradients between Compartments 1b and 16.

Figure 16.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Forward Dive Series 2B
Inert Gas Loadings Versus Conventional M-values



Notes:

1. After surface interval of 60 minutes, repetitive air dive to 40 fsw for 106 minutes bottom time according to no-deco limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. A one minute safety stop is required by the table.

Observations:

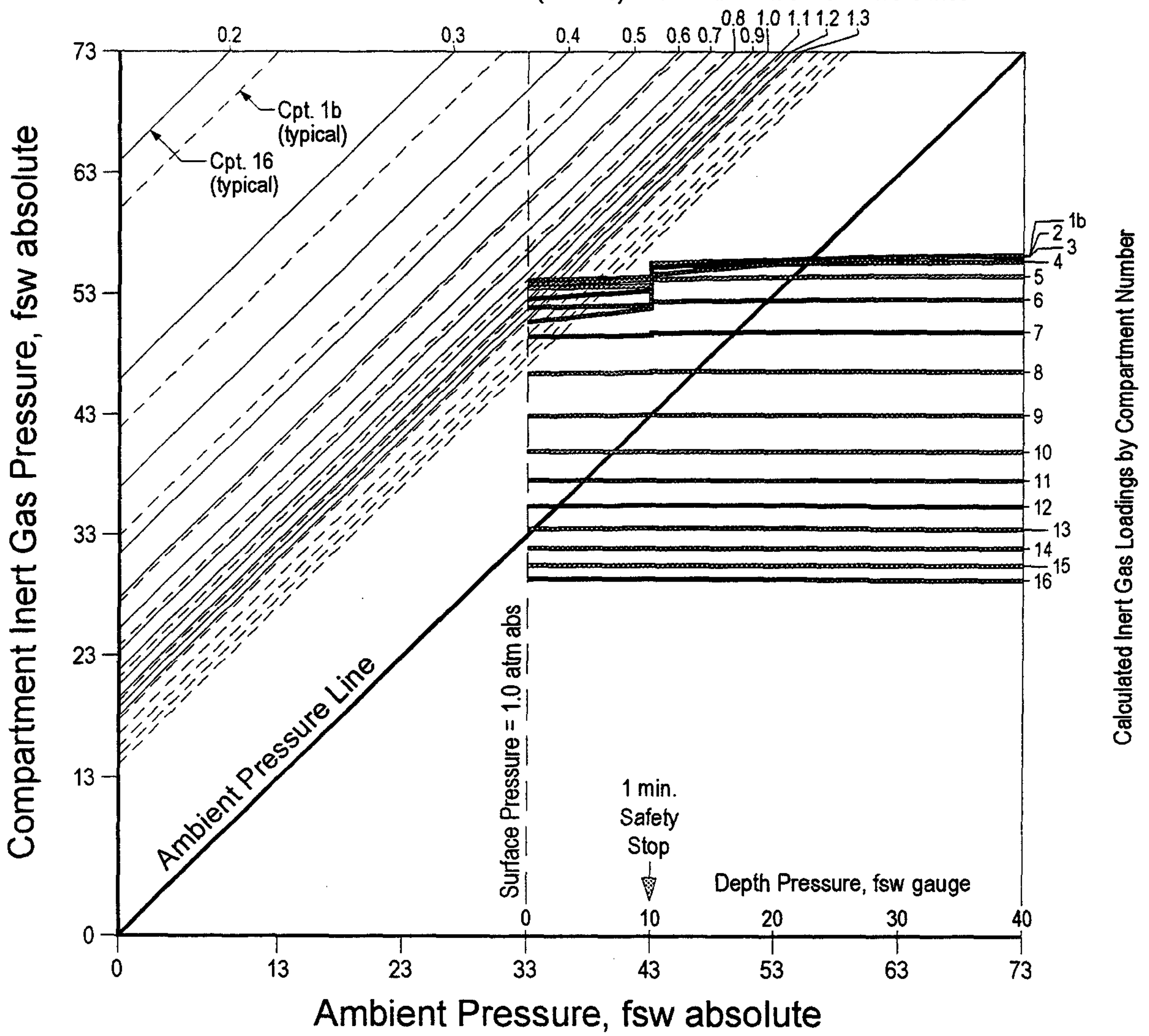
1. M-values for fast compartments permit large overpressure gradients and thus allow profuse bubble formation.
2. Upon surfacing from this dive, Compartments 6 and 7 are leading (gas loadings closest to M-values).
3. The one minute safety stop at 10 fsw has only a mild effect in terms of dropping gas loadings.

Figure 17.

Pressure Graph:

Ascent Profile For Repetitive Dive Of Forward Dive Series 2B
Inert Gas Loadings Versus VPM Criterion for Bubble Formation

Shown Upon Surfacing: Lines of Fixed Gradient = Isopleths of Constant Bubble Number
Calculated Based on Minimum Initial Radius (microns) of Gas Nuclei at Start of Dive Series



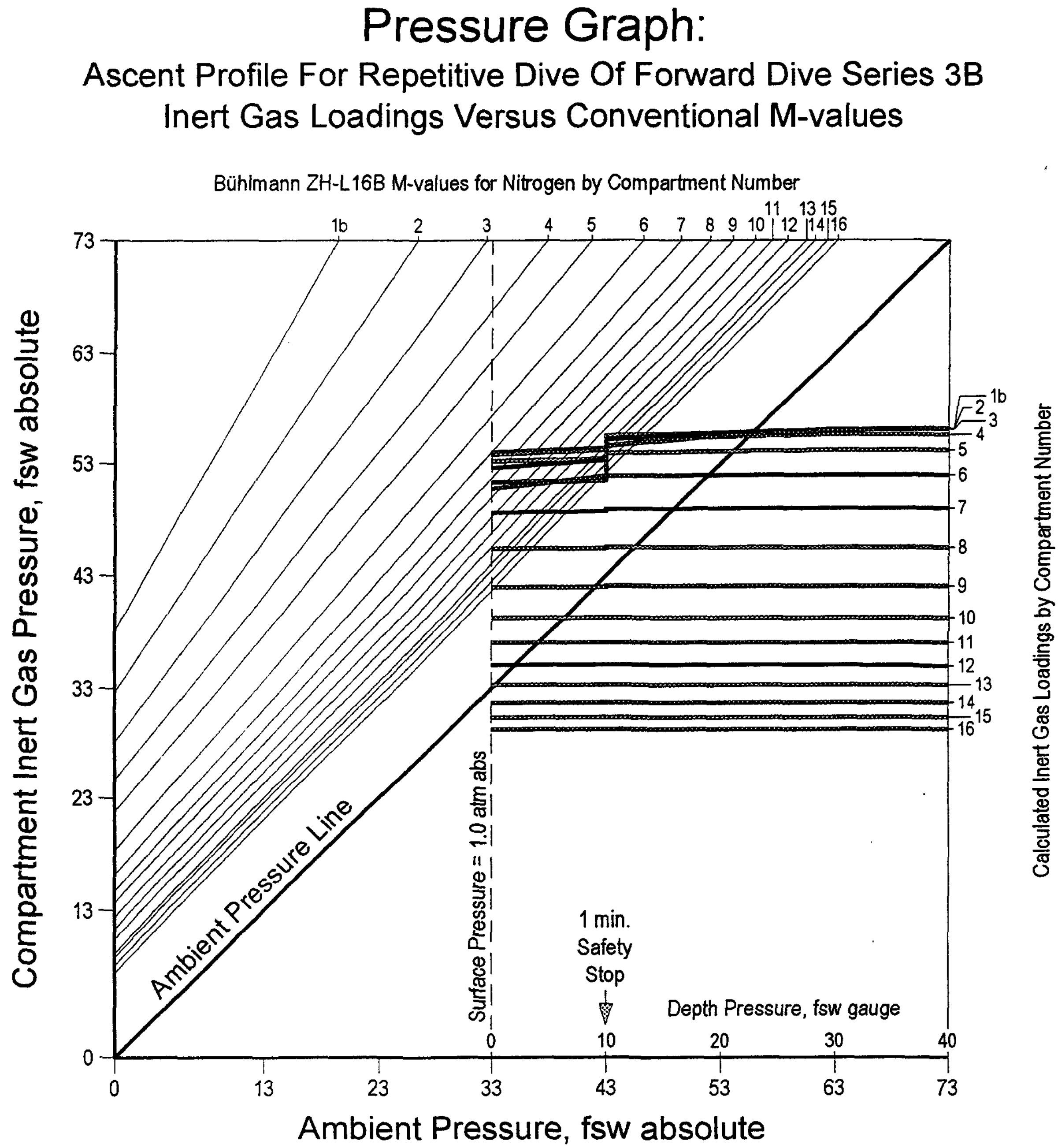
Notes:

1. After surface interval of 60 minutes, repetitive air dive to 40 fsw for 106 minutes bottom time (no-deco limit).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

Observations:

1. Bubbles are formed in Compartments 1b thru 7 upon surfacing from this dive.
2. Overpressure (supersaturation) gradients will exist for over 30 minutes after this dive to drive bubble growth.
3. There is a difference of 4.0 fsw in allowable gradients between Compartments 1b and 16.

Figure 18.



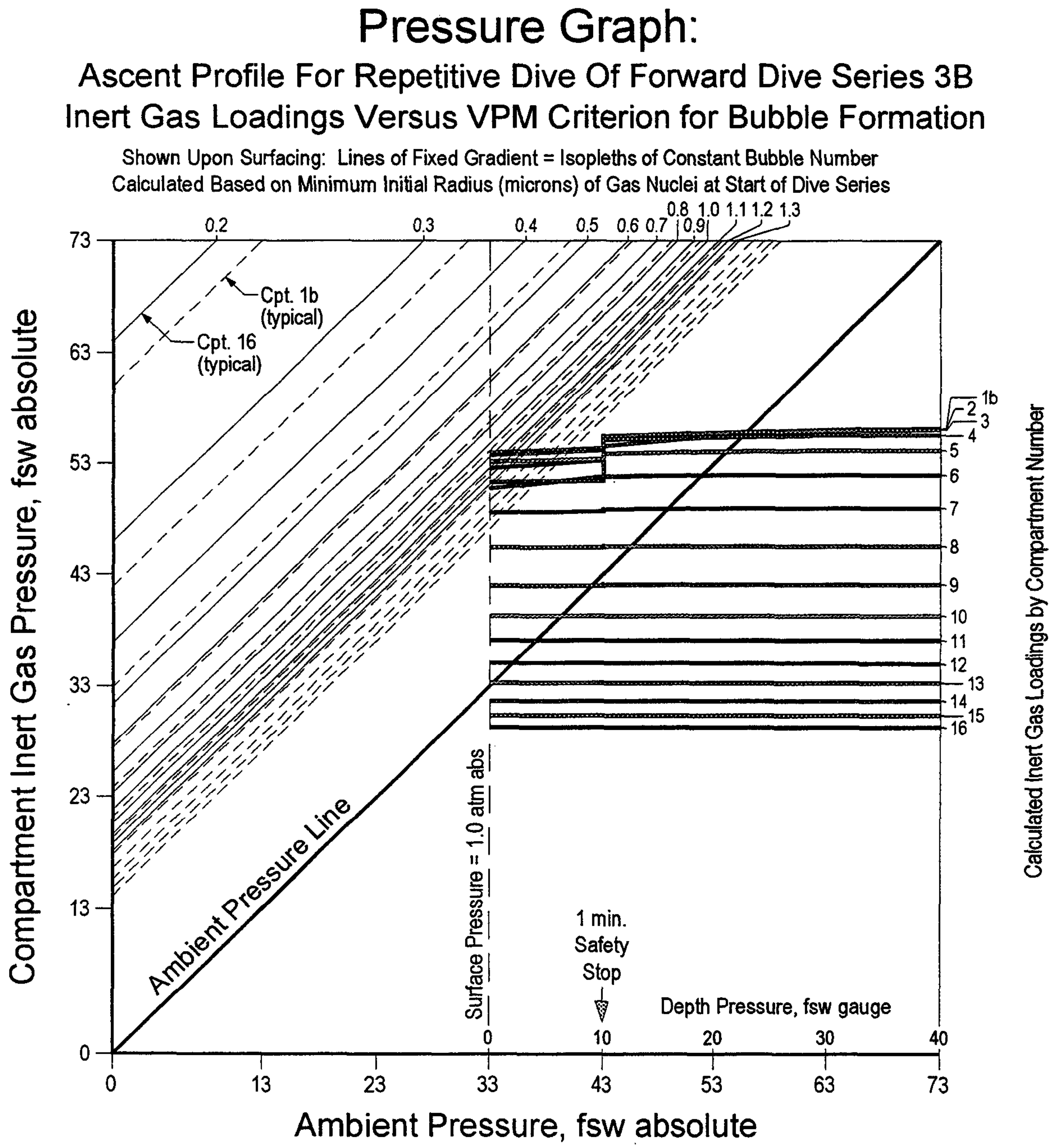
Notes:

1. After surface interval of 120 minutes, repetitive air dive to 40 fsw for 106 minutes bottom time according to no-deco limit of Bühlmann ZH-86 Air Diving Tables.
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. A one minute safety stop is required by the table.

Observations:

1. M-values for fast compartments permit large overpressure gradients and thus allow profuse bubble formation.
2. Upon surfacing from this dive, Compartments 6 and 7 are leading (gas loadings closest to M-values).
3. The one minute safety stop at 10 fsw has only a mild effect in terms of dropping gas loadings.

Figure 19.



Notes:

1. After surface interval of 120 minutes, repetitive air dive to 40 fsw for 106 minutes bottom time (no-deco limit).
2. Inert gas is nitrogen. Gas loadings are shown leaving the bottom at the end of the bottom time.
3. Ascent rate is 30 fsw/min. Descent rate is 75 fsw/min and descent is included in the bottom time.
4. VPM criterion is computed with varying differential crushing and supersaturation pressures across the 16 compartments.

Observations:

1. Bubbles are formed in Compartments 1b thru 7 upon surfacing from this dive.
2. Overpressure (supersaturation) gradients will exist for over 30 minutes after this dive to drive bubble growth.
3. There is a difference of 4.0 fsw in allowable gradients between Compartments 1b and 16.

Figure 20.

COMPUTATIONAL REVERSE DIVE PROFILES: CONTRASTS AND COMPARISONS

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Though the manifestations of Decompression Illness (DCI) are statistically distributed, tables and meters employ deterministic models to stage reverse dive profiles, with models broadly categorized as Haldane (dissolved phase) or bubble (combinations of dissolved and free phases). A summary of models and their underpinnings, correlations with data, and predictions for the 100/60 and 60/100 reverse dive profiles applying variable surface intervals are given. Suggestions for experiments are tendered, and in related vein, extreme statistics on reverse dive profiles gathered at Nuclear Emergency Strategy Team (NEST) exercises on various gas mixtures are sketched.

Introduction

We first discuss DCI risk and coupled statistics, return to broad base description of gas transfer models used in decompression applications, apply these models to the reverse dive profiles, contrast staging regimens, denote differences, suggest testing, and then summarize experience with NEST reverse dive profiles on mixed gases.

Decompression algorithms

Diving models address the coupled issues of gas uptake and elimination, bubbles, and pressure changes in different computational frameworks. Application of a computational model to staging divers is called a diving algorithm. Consider the computational models and staging regimens for six popular algorithms, namely, the perfusion limited, diffusion limited, thermodynamic, varying permeablity, reduced gradient bubble, and tissue bubble diffusion algorithms. The first two are Haldane models (workhorse algorithms in most tables and computers), while the remaining four are bubble models in the generic sense (coming online in tables and computers, often driven by technical diving). The first two track just dissolved gas transfer, using critical tissue tensions as limit points, while the latter four treat both dissolved and free phase transfer, using free phase volumes as limit points.

Though the systematics of gas exchange, nucleation, bubble growth or collapse, and decompression are so complicated that theories only reflect pieces of the DCI puzzle, the risk and statistics of decompressing divers are fairly straightforward. The folding of DCI risk and statistics over data and model assumptions is perhaps the most satisfying means to safety and model closure. Some Workshop papers and presentations center on probabilistic decompression, risk, and parameter fitting, using variants of the models discussed.

Decompression Risk and Statistics

Computational algorithms, tables, and manned testing are requisite across a spectrum of activities. The potential of electronic devices to process tables of information or detailed equations underwater is near maturity, with virtually any algorithm or model amenable to digital implementation. Pressures for even more sophisticated algorithms are expected to grow.

Still, computational models enjoy varying degrees of success or failure. More complex models address a greater number of issues, but are harder to codify in decompression tables. Simpler models are easier to codify, but are less comprehensive. Some models are based on first principles, but many are not. Application of models can be subjective in the absence of definitive data, the acquisition of which is tedious, sometimes controversial, and often ambiguous. If deterministic models are abandoned, statistical analysis can address the variability of outcome inherent to random occurrences, but only in manner indifferent to specification of controlling mechanisms. The so-called dose-response characteristics of statistical analysis are very attractive in the formulation of risk tables. Applied to decompression sickness incidence, tables of comparative risk offer a means of weighing contributing factors and exposure alternatives. At the basis of statistical and probabilistic analyses of decompression sickness is the binomial distribution. The binomial distribution is the fundamental frequency distribution governing random events:

1. Binomial Distribution

Decompression sickness is a hit, or no hit, situation. Statistics are binary, as in coin tossing. Probabilities of occurrence are determined from the binomial distribution, which measures the numbers of possibilities of occurrence and nonoccurrence in any number of events, given the incidence rate. Specifically, the probability, P, in a random sample of size, N, for n occurrences of decompression sickness and m non-occurrences, takes the form,

$$P(n) = \frac{N!}{n!\, m!}\, p^n q^m \ , \tag{1}$$

with,

$$n + m = N \ , \tag{2}$$

p the underlying incidence rate (average number of cases of decompression sickness), and q,

$$q = 1 - p \ , \tag{3}$$

the underlying nonincidence. The discrete probability distributions, P, are the individual terms of the binomial expansion of $(p+q)^N$,

$$(p+q)^N = \sum_{n=0}^{N} P(n) = 1 \ . \tag{4}$$

In risk analysis, p and q are also the failure and success rates, gleaned, for instance, from random or strategic sampling of arbitrary lot sizes. Obviously, the larger the sample size, the better are the estimates of p or q. Once p or q is determined, the binomial statistics and probabilities are also fixed. The statistical mean, M, and variance, s, are given by,

$$M = \sum_{n=1}^{N} nP(n) = pN \ , \tag{5}$$

$$s = \sum_{n=1}^{N} (n-M)^2\, P(n) = pqN \ , \tag{6}$$

the usual measures of a statistical distribution. The square root of the variance is the standard deviation. The cumulative probability for more than n cases of decompression sickness, $P_>(n)$, is written,

$$P_>(n) = \sum_{j=n+1}^{N} P(j) = 1 - \sum_{j=0}^{n} P(j) \ , \tag{7}$$

and the probability of less than n cases, $P_<(n)$, is similarly,

$$P_<(n) = \sum_{j=0}^{n-1} P(j) = 1 - \sum_{j=n}^{N} P(j) \ . \tag{8}$$

The probability of nonoccurrence in any set of N trials is simply,

$$P(0) = q^N \ , \tag{9}$$

while the probability of total occurrence in the same number, N, of trials is given by,

$$P(N) = p^N \ . \tag{10}$$

The binomial distribution is a special case of the multinomial distribution describing processes in which several results having fixed probabilities, p_l, q_l, for $l = 1, L$, are possible. Separate probabilities are given by the individual terms in the general multinomial expansion,

$$(p_1 + q_1 + ... + p_L + q_L)^N = \sum_{n_1,...,n_{L-1}=0}^{N} P(n_1,...,n_{L-1}) = 1 \ , \tag{11}$$

as in the binomial case. The normal distribution is a special case of the binomial distribution when N is very large and variables are not necessarily confined to integer values. The Poisson distribution is another special case of the binomial distribution when the number of events, N, is also large, but the incidence, p, is small.

2. Normal Distribution

The normal distribution is an analytic approximation to the binomial distribution when N is very large, and n, the observed value (success or failure rate), is not confined to integer values, but ranges continuously,

$$-\infty \leq n \leq \infty \ . \tag{12}$$

Normal distributions thus apply to continuous observables, while binomial and Poisson distributions apply to discontinuous observables. Statistical theories of errors are ordinarily based on normal distributions.

For the same mean, $M = pN$, and variance, $s = pqN$, the normal distribution, P, written as a continuously varying function of n,

$$P(n) = \frac{1}{(2\pi s)^{1/2}} \, exp \, [- \, (n - M)^2/2s] \ , \tag{13}$$

is a good approximation to the binomial distribution in the range,

$$\frac{1}{N+1} < p < \frac{N}{N+1} \ , \tag{14}$$

and within three standard deviations of the mean,

$$pN - 3 \, (pqN)^{1/2} \leq n \leq pN + 3 \, (pqN)^{1/2} \ . \tag{15}$$

The distribution is normalized to one over the real infinite interval,

$$\int_{-\infty}^{\infty} P dn = 1 \ . \tag{16}$$

The probability that a normally distributed variable, n, is less than or equal to b is,

$$P_<(b) = \int_{-\infty}^{b} P dn \ , \tag{17}$$

while the corresponding probability that n is greater than or equal to b is,

$$P_{>}(b) = \int_{b}^{\infty} P dn \ . \tag{18}$$

The normal distribution is extremely important in statistical theories of random variables. By the central limit theorem, the distribution of sample means of identically distributed random variables is approximately normal, regardless of the actual distribution of the individual variables.

3. Poisson Distribution

The Poisson distribution is a special case of the binomial distribution when N becomes large, and p is small, and certainly describes all discrete random processes whose probability of occurrence is small and constant. The Poisson distribution applies substantially to all observations made concerning the incidence of decompression sickness in diving, that is, $p << 1$ as the desired norm. The reduction of the binomial distribution to the Poisson distribution follows from limiting forms of terms in the binomial expansion, that is, $P(n)$.

In the limit as N becomes large, and p is much smaller than one, we have,

$$\frac{N!}{(N-n)!} = N^n \ , \tag{19}$$

$$q^m = (1-p)^{N-n} = exp\ (-pN) \ , \tag{20}$$

and therefore the binomial probability reduces to,

$$P(n) = \frac{N^n p^n}{n!} exp\ (-pN) = \frac{M^n}{n!} exp\ (-M) \ , \tag{21}$$

which is the discrete Poisson distribution. The mean, M, is given as before,

$$M = pN \tag{22}$$

and the variance, s, has the same value,

$$s = pN \ , \tag{23}$$

because q is approximately one. The cumulative probabilities, $P > (n)$ and $P < (n)$, are the same as those defined in the binomial case, a summation over discrete variable, n. It is appropriate to employ the Poisson approximation when $p \leq .10$, and $N \geq 10$ in trials. Certainly, from a numerical point of view, the Poisson distribution is easier to use than the binomial distribution. Computation of factorials is a lesser task, and bookkeeping is minimal for the Poisson case.

In addition to the incidence of decompression sickness, the Poisson distribution describes the statistical fluctuations in such random processes as the number of cavalry soldiers kicked and killed by horses, the disintegration of atomic nuclei, the emission of light quanta by excited atoms, and the appearance of cosmic ray bursts. It also applies to most rare diseases.

Probabilistic Decompression

Table 1 lists corresponding binomial decompression probabilities, $P(n)$, for 1% and 10% underlying incidence (99% and 90% nonincidence), yielding 0, 1, and 2 or more cases of decompression sickness. The underlying incidence, p, is the (fractional) average of hits.

As the number of trials increases, the probability of 0 or 1 occurrences drops, while the probability of 2 or more occurrences increases. In the case of 5 dives, the probability might be as low as 5%, while in the case of 50 dives, the probability could be 39%, both for $p = .01$. Clearly, odds even percentages would require testing beyond 50 cases for an underlying incidence near 1%. Only by increasing the number of trials for fixed incidences can the probabilities be increased. Turning that around, a rejection procedure for 1 or more cases of decompression sickness at the 10% probability level requires many more than 50 dives. If we are willing to lower the confidence of the acceptance, or rejection, procedure, of course, the number of requisite trials drops. Table 1 also shows that the test practice of accepting an exposure schedule following 10 trials without incidence of decompression sickness is suspect, merely because the relative probability of nonincidence is high, near 35%.

Questions as to how safe are decompression schedules have almost never been answered satisfactorily. As seen, large numbers of binary events are required to reliably estimate the underlying incidence. One case of decompression sickness in 30 trials could result from an underlying incidence, p, bounded by .02 and .16 roughly. Tens more of trials are necessary to shrink those bounds.

Table 1. Probabilities of Decompression Sickness for Underlying Incidences.

N (dives)	n (hits)	$P(n)$ $p = .01$ $q = .99$	$P(n)$ $p = .10$ $q = .90$
5	0	.95	.59
	1	.04	.33
	2 or more	.01	.08
10	0	.90	.35
	1	.09	.39
	2 or more	.01	.26
20	0	.82	.12
	1	.16	.27
	2 or more	.02	.61
50	0	.61	.01
	1	.31	.03
	2 or more	.08	.96

Biological processes are highly variable in outcome. Formal correlations with outcome statistics are then generally requisite to validate models against data. Often, this correlation is difficult to firmly establish (couple of percent) with fewer than 1,000 trial observations, while ten percent correlations can be obtained with 30 trials, assuming binomial distributed probabilities. For decompression analysis, this works as a disadvantage, because often the trial space of dives is small. Not discounting the possibly small trial space, a probabilistic approach to the occurrence of decompression sickness is useful and necessary. One very successful approach, developed and tuned by Weathersby and others for decompression sickness in diving, called maximum likelihood, applies theory or models to diving data and adjusts the parameters until theoretical prediction and experimental data are in as close agreement as possible.

Validation procedures require decisions about uncertainty. When a given decompression procedure is repeated with different subjects, or the same subjects on different occasions, the outcome is not constant. The uncertainty about the occurrence of decompression sickness can be quantified with statistical statements, though, suggesting limits to the validation procedure. For instance, after analyzing decompression incidence statistics for a set of procedures, a table designer may report that the procedure will offer an incidence rate below 5%, with 90% confidence in the statement. Alternatively, the table designer can compute the probability of rejecting a procedure using any number of dive trials, with the rejection criteria any arbitrary number of incidences. As the number of trials increases, the probability of rejecting a procedure increases for fixed incidence criteria. In this way, relatively simple statistical procedures can provide vital information as to the number of trials necessary to validate a procedure with any level of acceptable risk, or the maximum risk associated with any number of incidences and trials.

One constraint usually facing the statistical table designer is a paucity of data, that is, number of trials of a procedure. Data on hundreds of repetitions of a dive profile are virtually nonexistent, excepting bounce diving perhaps. As seen, some 30-50 trials are requisite to ascertain procedure safety at the 10% level. But 30-50 trials is probably asking too much, is too expensive, or generally prohibitive. In that case, the designer may try to employ global statistical measures linked to models in a more complex trial space, rather than a single profile trial space. Integrals of risk parameters, such as bubble number, supersaturation, separated phase, etc., over exposures in time, can be defined as probability measures for incidence of decompression sickness, and the maximum likelihood method then used to extract appropriate constants:

1. Maximum Likelihood
   We can never measure any physical variable exactly, that is, without error. Progressively more elaborate experimental or theoretical efforts only reduce the possible error in the determination. In extracting parameter estimates from data sets, it is necessary to also try to minimize the error (or data scatter) in the extraction process. A number of techniques are available to the analyst, including the well-known maximum likelihood approach.

The measure of any random occurrence, p, can be a complicated function of many parameters, $x = (x_k, k = 1, K)$, with the only constraint,

$$0 \leq p(x) \leq 1 \ , \tag{24}$$

for appropriate values of the set, x. The measure of nonoccurence, q, is then, by conservation of probability,

$$q(x) = 1 - p(x) \ , \tag{25}$$

over the same range,

$$0 \leq q(x) \leq 1 \ . \tag{26}$$

Multivalued functions, $p(x)$, are often constructed, with specific form dictated by theory or observation over many trials or tests. In decompression applications, the parameters, x, may well be the bubble-nucleation rate, number of venous gas emboli, degree of supersaturation, amount of pressure reduction, volume of separated gas, ascent rate, or combinations thereof. Parameters may also be integrated in time in any sequence of events, as a global measure, though such measures are more difficult to analyze over arbitrary trial numbers.

The likelihood of any outcome, Φ, of N trials is the product of individual measures of the form,

$$\Phi(n) = p^n q^m = p^n (1-p)^m \ , \tag{27}$$

given n cases of decompression sickness and m cases without decompression sickness, and,

$$n + m = N \ . \tag{28}$$

The natural logarithm of the likelihood, Ψ, is easier to use in applications, and takes the form,

$$\Psi = \ln \Phi = n \ln p + m \ln (1-p) \ , \tag{29}$$

and is maximized when,

$$\frac{\partial \Psi}{\partial p} = 0 \ . \tag{30}$$

In terms of the above, we then must have,

$$\frac{n}{p} - \frac{m}{1-p} = 0 \ , \tag{31}$$

trivially requiring,

$$p = \frac{n}{n+m} = \frac{n}{N} \ , \tag{32}$$

$$1 - p = q = \frac{m}{n+m} = \frac{m}{N} \ . \tag{33}$$

Thus, the likelihood function is maximized when p is the actual incidence rate, and q is the actual nonincidence rate. The multivalued probability functions, $p(x)$, generalize in the maximization process according to,

$$\frac{\partial \Psi}{\partial p} = \sum_{k=1}^{K} \frac{\partial \Psi}{\partial x_k} \frac{\partial x_k}{\partial p} = 0 \ , \tag{34}$$

satisfied when,

$$\frac{\partial \Psi}{\partial x_k} = 0 \ \ for \, k = 1, \, K \ . \tag{35}$$

In application, such constraints are most easily solved on computers, with analytical or numerical methods.

In dealing with a large number of decompression procedures, spanning significant range in depth, time, and environmental factors, an integrated approach to maximum likelihood and risk is necessary. Integral measures, $p(x,t)$ and $q(x,t)$, can be defined over assumed decompression risk, $\zeta(x,t)$,

$$p(x,t) = 1 - exp \left[- \int_0^t \zeta(x,t')dt' \right] \ , \tag{36}$$

$$q(x,t) = exp \left[- \int_0^t \zeta(x,t')dt' \right] \ , \tag{37}$$

with t' any convenient time scale, and ζ any assumed risk, such as bubble number, saturation, venous emboli count, etc. as mentioned. Employing $p(x,t)$ and $q(x,t)$ in the likelihood function, and then maximizing according to the data, permits maximum likelihood estimation of $\zeta(x,t)$. Such an approach can be employed in decompression table fabrication, yielding good statistical estimates on incidence rates as a function of exposure factors.

2. Saturation Bends Probability

Many factors contribute to bends susceptibility. Age, obesity, temperature, physical condition, alcohol, and cigarettes are a few. Whatever the contributing factors, the distribution of bends depths for saturation exposures has been characterized in terms of the saturation tension, Q, and ambient pressure, P, by Hills. This characterization is not only of academic interest, but is also useful in assigning formal risk to decompression formats.

The distribution of saturation bends depths, χ, fits a Weibull function. This is true for all breathing mixtures, nitrox, heliox, trimix, etc. If cumulative fraction of air bends cases up to G is χ, the survivor fraction, $1 - \chi$, satifies,

$$\ln \, (1 - \chi) = - \left[\frac{G - 14.3}{25.1} \right]^{4.73} \tag{38}$$

for cumulative bends probability, χ, the usual integral over bends risk, ζ, as a function of gradient, G,

$$\chi = \int_0^G \zeta(G')dG' \tag{39}$$

with saturation bends gradient, G, measured in fsw,

$$G = Q - P \tag{40}$$

As the gradient grows, the survivor function approaches zero exponentially. The smallest bends gradient is 14.3 fsw, which can be contrasted with the average value of 26.5 fsw. The root mean square gradient is 27.5 fsw. At 27 fsw, the survivor fraction is 0.96, while 67% of survivors fall in the range, 26.5 ± 7.6 fsw, with 7.6 fsw the standard deviation. For gas mixtures other than air, the general form is given by,

$$\ln(1-\chi) = -\varepsilon \left[\frac{(P_f - 20.5)}{(P_i - 33.0)} - \frac{1}{f_i} \right]^{\delta} \tag{41}$$

where f_i is the total volume fraction of inert breathing gases, for $G = P_f - P_i$, and with ε, δ constants.

The efficiency of the Weibull distribution in providing a good fit to the saturation data is not surprising. The Weibull distribution enjoys success in reliability studies involving multiplicities of fault factors. It obviously extends to any set of hyperbaric or hypobaric exposure data, using any of the many parameter risk variables described above.

3. Risk Tables

A global statistical approach to table fabrication consists of following a risk measure, or factor p, throughout and after sets of exposures, tallying the incidence of DCI, and then applying maximum likelihood to the risk integral in time, extracting any set of risk constants optimally over all dives in the maximization procedure. In analyzing air and helium data, Weathersby assigned risk as the difference between tissue tension and ambient pressure divided by ambient pressure. One tissue was assumed, with time constant ultimately fixed by the data in ensuing maximum likelihood analysis. The measure of nonincidence, q, was taken to be the exponential of risk integrated over all exposure time,

$$q(\kappa,\tau) = exp\left[-\int_0^{\infty} \zeta(\kappa,\tau,t')dt'\right] \ , \tag{42}$$

$$\zeta(\kappa,\tau,t') = \kappa \, \frac{p(t') - p_a}{p_a} \ , \tag{43}$$

with κ a constant determined in the likelihood maximization, p_a ambient pressure, and $p(t')$ the instantaneous Haldane tension for tissue with halftime, τ, also determined in the maximization process, corresponding to arbitrary tissue compartments for the exposure data. Other more complex likelihood functions can also employed, for instance, the separated phase volume according to the varying permeability and reduced gradient bubble models,

$$\zeta(\kappa,\xi,\tau,t') = \kappa\Delta nG(t') \ , \tag{44}$$

$$\Delta = \left[1 - \frac{r}{\xi}\right] \ , \tag{45}$$

with Δn the permissible bubble excess, r the bubble radius, G the bubble diffusion gradient (dissolved-free gas), and κ and ξ constants determined in the fit maximization of the data. Another risk possibility is the tissue ratio,

$$\zeta(\kappa,\tau,t') = \kappa \, \frac{p(t')}{p_a} \ , \tag{46}$$

a measure of interest in altitude diving applications.

Hundreds of air dives were analyzed using this procedure, permitting construction of decompression schedules with 95% and 99% confidence (5% and 1% bends incidence). These tables were published by U.S. Navy investigators, and Table 2 tabulates the corresponding nonstop time limits (p = .05, .01), and also includes the standard U.S. Navy (Workman) limits for comparison. Later re-evaluations of the standard set of no-stop time limits estimate an underlying incidence rate of 1.25% for the limits. In actual usage, the incidence rates are below .001%, because users do not generally dive to the limits.

Table 2. No-Stop Time Limits for 1% and 5% Incidence Rates.

depth d (fsw)	nonstop limit t_n (min) $p = .05$	nonstop limit t_n (min) $p = .01$	nonstop limit t_n (min) US Navy
30	240	170	
40	170	100	200
50	120	70	100
60	80	40	60
70	80	25	50
80	60	15	40
90	50	10	30
100	50	8	25
110	40	5	20
120	40	5	15
130	30	5	10

Implicit in such formulations of risk tables are the assumptions that a given decompression stress is more likely to produce symptoms if it is sustained in time, and that large numbers of separate events may culminate in the same probability after time integration. Though individual schedule segments may not be replicated enough to offer total statistical validation, categories of predicted safety can always be grouped within subsets of corroborating data. Since the method is general, any model parameter or meaningful index, properly normalized, can be applied to decompression data, and the full power of statistical methods employed to quantify overall risk. While powerful, such statistical methods are neither deterministic nor mechanistic, and cannot predict on first principles. But as a means to table fabrication with quoted risk, such approaches offer attractive pathways for analysis.

Model Validation

Validation procedures for schedules and tables can be quantified by a set of procedures based on statistical decompression analysis:

1. select or construct a measure of decompression risk, or a probabilistic model;
2. evaluate as many dives as possible, and especially those dives similar in exposure time, depth, and environmental factors;
3. conduct limited testing if no data are available;
4. apply the model to the data using maximum likelihood;
5. construct appropriate schedules or tables using whatever incidence of decompression sickness is acceptable; and,
6. release and then collect use statistics for final validation and tuning.

Questions of what risk is acceptable to the diver vary. Recreational and scientific divers would probably opt for very small risk (.01% or less), while military and commercial divers might live with higher risk (1$\%$), considering the nearness of medical attention in general. Many factors influence these two populations, but fitness and acclimatization levels would probably differ considerably across them. While such factors are difficult to fold into any table exercise or analysis, the simple fact that human subjects in dive experiments exhibit higher incidences during testing phases certainly helps to lower the actual incidence rate in the field, noted by Bennett and Lanphier.

Computational Models

Certainly there is considerable latitude in model assumptions, and many plausible variants on a theme. Many models are correlated with diving exposure data, using maximum likelihood to fit parameters or other valid statistical approaches, but not all. Most have been applied to profiles outside of tested ranges, when testing has been performed, in an obvious extrapolation mode. Sometimes the

extrapolations are valid, other times not. Reverse dive profiles represent just that sort of extrapolation process for the bulk of these models, since reverse dsive profiles testing has not been extensive. So, now consider the 6 models:

1. Perfusion Limited Algorithm (PLA)

   Exchange of inert gas, controlled by blood flow rates across regions of varying concentration, is driven by the gas gradient, that is, the difference between the arterial blood tension, p_a, and the instantaneous tissue tension, p. This behavior is modeled in time, t, by classes of exponential response functions, bounded by p_a and the initial value of p, denoted p_i. These multitissue functions satisfy a differential perfusion rate equation,

$$\frac{\partial p}{\partial t} = -\lambda(p - p_a) \tag{47}$$

   and take the form, tracking both dissolved gas buildup and elimination symmetrically,

$$p - p_a = (p_i - p_a)\ exp\ (-\lambda\, t) \tag{48}$$

$$\lambda = \frac{.693}{\tau} \tag{49}$$

   with perfusion constant, λ, linked to tissue halftime, τ. Compartments with 1, 2.5, 5, 10, 20, 40, 80, 120, 180, 240, 360, 480, and 720 minute halftimes, τ, are employed, and are independent of pressure.

   In a series of dives or multiple stages, p_i and p_a represent extremes for each stage, or more precisely, the initial tension and the arterial tension at the beginning of the next stage. Stages are treated sequentially, with finishing tensions at one step representing initial tensions for the next step, and so on. To maximize the rate of uptake or elimination of dissolved gases the *gradient*, simply the difference between p_i and p_a, is maximized by pulling the diver as close to the surface as possible. Exposures are limited by requiring that the tissue tensions never exceed M, written,

$$M = M_0 + \Delta M\ d \tag{50}$$

   at depth, d, for ΔM the change per unit depth. A set of M_0 and ΔM are listed in Table 3. In absolute units, the corresponding critical gradient, G, and critical ratio, R, are given by,

$$G = \frac{M}{.79} - P \tag{51}$$

$$R = \frac{M}{P} \tag{52}$$

   with P ambient pressure.

Table 3. Classical US Navy Surfacing Ratios And Critical Tensions

halftime τ (min)	critical ratio R_0	critical tension M_0 (fsw)	tension change ΔM
5	3.15	104	2.27
10	2.67	88	2.01
20	2.18	72	1.67
40	1.76	58	1.34
80	1.58	52	1.26
120	1.55	51	1.19

At altitude, some critical tensions have been correlated with actual testing, in which case, the depth, d, is defined in terms of the absolute pressure,

$$d = P - 33 \tag{53}$$

with absolute pressure, P, at altitude, z, given by (fsw),

$$P = 33\ exp\ (-0.0381z) = 33\ \alpha^{-1} \tag{54}$$

$$\alpha = exp\ (0.0381z) \tag{55}$$

and z in multiples of 1000 $feet$. However, in those cases where the critical tensions have not been tested nor extended to altitude, an exponentially decreasing extrapolation scheme, called *similarity*, has been employed. Extrapolations of critical tensions, below $P = 33\ fsw$, then fall off more rapidly then in the linear case. The similarity extrapolation holds the ratio, $R = M/P$, constant at altitude. Denoting an equivalent sea level depth, δ, at altitude, z, one has for an excursion to depth d,

$$\frac{M(d)}{d + 33\alpha^{-1}} = \frac{M(\delta)}{\delta + 33} \tag{56}$$

so that the equality is satisfied when,

$$\delta = \alpha d \tag{57}$$

$$M(\delta) = \alpha M(d). \tag{58}$$

Considering the minimum surface tension pressure of bubbles, G^{min} (near $10 fsw$), as a limit point, the similarity extrapolation should be limited to 10,000 $feet$ in elevation, and neither for decompression, nor heavy repetitive diving.

As described previously, depth-time exposures are often limited by a law of the form,

$$dt_n^{1/2} = H \tag{59}$$

with t_n the nonstop time limit, and $400 \leq H \leq 500\ fsw\ min^{1/2}$. One can obtain the corresponding tissue constant, λ, controlling the exposure at depth d, for nonstop time t_n, by differentiating the tissue equation with respect to depth, d, and setting the result to zero. With $p_a = .79(d + 33)$ at sea level, there results,

$$1 - exp\ (-\lambda t_n)(1 + 2\ \lambda t_n) = 0. \tag{60}$$

Corresponding critical tensions, M, are then easily obtained using d, λ, and t_n. In the above case, the transcendental equation is satisfied when,

$$\lambda t_n = 1.25 \tag{61}$$

Time remaining before a stop, time at a stop, or surface interval before flying can all be obtained by inverting the tissue equation. Denoting the appropriate critical tension at some desired stage, M, and the instantaneous tension at that time, p, at stage, p_a, the time remaining, t_r, follows from,

$$t_r = \frac{1}{\lambda} \ln \left[\frac{p - p_a}{M - p_a}\right] \tag{62}$$

for each compartment, λ. Obviously, the smallest t_r controls the ascent.

The PLA forms the basis for most table and meter algorithms, and has been extensively tested for different profiles and gas loadings. First tests on the modern approaches were performed by the US Navy.

2. Diffusion Limited Algorithm (DLA)

Exchange of inert gas, controlled by diffusion across regions of varying concentration, is also driven by the local gradient. As before, denoting the arterial blood tension, p_a, and instantaneous tissue tension, p, the gas diffusion equation takes the form in one-dimensional planar geometry,

$$D\frac{\partial^2 p}{\partial x^2} = \frac{\partial p}{\partial t} \tag{63}$$

with D a single diffusion coefficient appropriate to the media. Using standard techniques of separation of variables, with ω^2 the separation constant (eigenvalue), the solution is written,

$$p - p_a = (p_i - p_a) \sum_{n=1}^{\infty} W_n \, sin\,(\omega_n x) \, exp\,(-\omega_n^2 D t) \tag{64}$$

assuming at the left tissue boundary, $x = 0$, we have $p = p_a$, and with W_n a set of constants obtained from the initial condition. First, requiring $p = p_a$ at the right tissue boundary, $x = l$, yields,

$$\omega_n = \frac{n\pi}{l} \tag{65}$$

for all n. Then, taking $p = p_i$ at $t = 0$, multiplying both sides of the diffusion solution by $sin\,(\omega_m x)$, integrating over the tissue zone, l, and collecting terms gives,

$$W_{2n} = 0 \tag{66}$$

$$W_{2n-1} = \frac{4}{(2n-1)\pi} \tag{67}$$

Averaging the solution over the tissue domain eliminates spatial dependence, that is $sin\,(\omega_n x)$, from the solution, giving a bulk response,

$$p - p_a = (p_i - p_a) \sum_{n=1}^{\infty} \frac{8}{(2n-1)^2\,\pi^2} exp\,(-\omega_{2n-1}^2 D t). \tag{68}$$

The expansion resembles a weighted sum over *effective* tissue compartments with time constants, $\omega_{2n-1}^2 D$, determined by diffusivity and boundary conditions.

Diffusion models fit the time constant, K,

$$\kappa = \pi^2 D l^2 \tag{69}$$

to exposure data, with a typical value employed by the Royal Navy given by,

$$\kappa = 0.007928\,min^{-1}. \tag{70}$$

The approach is aptly single tissue, with equivalent tissue halftime, τ_D,

$$\tau_D = \frac{.693}{\kappa} = 87.5\,min\,, \tag{71}$$

close to the US Navy 120 *minute* compartment used to control saturation, decompression, and repetitive diving. Corresponding critical tensions in the bulk model, take the form,

$$M = \frac{709\,P}{P + 404}\,, \tag{72}$$

falling somewhere between fixed gradient and multitissue values. At the surface, $M = 53\,fsw$, while at $200 fsw$, $M = 259\,fsw$. A critical gradient, G, satisfies,

$$G = \frac{M}{.79} - P = \frac{P\,(493 - P)}{(P + 404)}. \tag{73}$$

The limiting features of bulk diffusion can be gleaned from an extension of the above slab model in the limit of thick tissue region, that is, $l \to \infty$. Replacing the summation over n with an integral as $l \to \infty$, we find

$$p - p_a = (p_i - p_a)\ \bar{erf}\ [l/(4Dt)^{1/2}] \tag{74}$$

with $\bar{erf}$ the average value of the $error - function$ over l, having the limiting form (Abramowitz and Stegun),

$$\bar{erf}\ [l/(4Dt)^{1/2}] = 1 - (4Dt)^{1/2} l \pi^{1/2} \tag{75}$$

for short times, and

$$\bar{erf}\ [l/(4Dt)^{1/2}] = \frac{l}{(4\pi Dt)^{1/2}} \tag{76}$$

for long times.

Unlike the perfusion case, the diffusion solution, consisting of a sum of exponentials in time, cannot be formally inverted to yield time remaining, time at a stop, nor time before flying. Such information can only be obtained by solving the equation numerically, that is, with computer or hand calculator for given M, p, and p_a.

If we wrap the above planar geometry around into a hollow cylinder of inner radius, a, and outer radius, b, we generate Krogh geometry. The hollow cylindrical model retains all the features of the planar model, and additionally includes curvature for small a and b, with $l = b - a$ from before. Assigning the same boundary conditions at a and b, namely, the tissue tension, p, equals the arterial tension, p_a, writing the diffusion equation in radial cylindrical coordinates,

$$D\frac{\partial^2 p}{\partial r^2} + \frac{D}{r}\frac{\partial p}{\partial r} = \frac{\partial p}{\partial t} \tag{77}$$

and solving yields,

$$p - p_a = (p_i - p_a) \sum_{n=1}^{\infty} X_n\ U_0(\varepsilon_n r)\ exp\ (-\varepsilon_n^2 Dt) \tag{78}$$

with X_n a constant satisfying initial conditions, U_0 the cylinder functions (Abramowitz and Stegun), and ε_n the eigenvalues satisfying,

$$U_0(\varepsilon_n a) = \frac{\partial U_0(\varepsilon_n b/2)}{\partial r} = 0\ . \tag{79}$$

Averaging over the tissue region, $a \le r \le b$, finally gives,

$$p - p_a = (p_i - p_a)\ \frac{4}{(b/2)^2 - a^2} \sum_{n=1}^{\infty} \frac{1}{\varepsilon_n^2} \frac{J_1^2(\varepsilon_n b/2)}{J_0^2(\varepsilon_n a) - J_1^2(\varepsilon_n b/2)}\ exp\ (-\varepsilon_n^2 Dt) \tag{80}$$

with J_1 and J_0 Bessel functions, order 1 and 0. Typical vascular parameters are bounded by,

$$0 < a \le 4\ microns \tag{81}$$

$$10 \le b \le 32\ microns. \tag{82}$$

The DLA was introduced and tested extensively by the Royal Navy, roughly on the same time scales as the US Navy tested the PLA.

3. Thermodynamic Algorithm (TA)

The thermodynamic model couples both the tissue diffusion and blood perfusion equations. Cylindrical symmetry is assumed in the model. From a boundary vascular zone of thickness, a, gas diffuses into the extended extravascular region, bounded by b. The radial diffusion equation is given by,

$$D\frac{\partial^2 p}{\partial r^2} + \frac{D}{r}\frac{\partial p}{\partial r} = \frac{\partial p}{\partial t} \tag{83}$$

with the tissue tensions, p, equal to the venous tensions, p_v, at the vascular interfaces, a and b. The solution to the tissue diffusion equation is given previously,

$$p - p_v = (p_i - p_v) \frac{4}{(b/2)^2 - a^2} \sum_{n=1}^{\infty} \frac{1}{\varepsilon_n^2} \frac{J_1^2(\varepsilon_n b/2)}{J_0^2(\varepsilon_n a) - J_1^2(\varepsilon_n b/2)} \, exp\,(-\varepsilon_n^2 Dt) \tag{84}$$

with ε_n eigenvalue roots of the boundary conditions,

$$J_0(\varepsilon_n a)\, Y_1(\varepsilon_n b/2) - Y_0(\varepsilon_n a)\, J_1(\varepsilon_n b/2) = 0 \tag{85}$$

for J and Y Bessel and Neumann functions, order 1 and 0. Perfusion limiting is applied as a boundary condition through the venous tension, p_v, by enforcing a mass balance across both the vascular and cellular regions at a,

$$\frac{\partial p_v}{\partial t} = -\kappa(p_v - p_a) - \frac{3}{a} S_p D \left[\frac{\partial p}{\partial r}\right]_{r=a} \tag{86}$$

with S_p the ratio of cellular to blood gas solubilities, κ the perfusion constant, and p_a the arterial tension. The coupled set relate tension, gas flow, diffusion and perfusion, and solubility in a complex feedback loop.

The thermodynamic trigger point for decompression sickness is the volume fraction, χ, of separated gas, coupled to mass balance. Denoting the separated gas partial pressure, P_{N_2}, under worse case conditions of zero gas elimination upon decompression, the separated gas fraction is estimated,

$$\chi\, P_{N_2} = S_c\, (p - P_{N_2}) \tag{87}$$

with S_c the cellular gas solubility. The separated nitrogen partial pressure, P_{N_2} is taken up by the inherent unsaturation, and given by (fsw),

$$P_{N_2} = P + 3.21 \tag{88}$$

in the original Hills formulation, but other estimates have been employed. Mechanical fluid injection pain, depending on the injection pressure, δ, can be related to the separated gas fraction, χ, through the tissue modulus, K,

$$K\chi = \delta \tag{89}$$

so that a decompression criteria requires,

$$K\chi \leq \delta \tag{90}$$

with δ in the range, for $K = 3.7 \times 10^4\ dyne\ cm^{-2}$,

$$0.34 \leq \delta \leq 1.13\ fsw. \tag{91}$$

Identification of the separated phase volume as a critical indicator is a significant development in decompression theory.

The TA has been applied to computational studies of air and helium deep saturation data, and was the first model to suggest deep stops to control bubble growth.

4. Varying Permeability Algorithm (VPA)

The critical radius, r_i, at fixed pressure, P_0, represents the cutoff for growth upon decompression to lesser pressure. Nuclei larger than r_i will all grow upon decompression. Additionally, following an initial compression, $\Delta P = P - P_0$, a smaller class of micronuclei of critical radius, r, can be excited into growth with decompression. If r_i is the critical radius at P_0, then, the smaller family, r, excited by decompression from P, obeys,

$$\frac{1}{r} = \frac{1}{r_i} + \frac{\Delta P}{158} \tag{92}$$

with ΔP measured in fsw, and r in *microns*. Table 4 lists critical radii, r, excited by sea level compressions ($P_0 = 33\ fsw$), assuming $r_i = .8$ *microns*. Entries also represent the equilibrium critical radius at pressure, P.

Table 4. Micronuclei Excitation Radii

pressure $P\ (fsw)$	excitation radius $r_s\ (\mu m)$	pressure $P\ (fsw)$	excitation radius $r_s\ (\mu m)$
13	.89	153	.49
33	.80	173	.46
53	.72	193	.44
73	.66	213	.41
93	.61	233	.39
113	.57	253	.37
133	.53	273	.36

The permissible gradient, G, is written for each compartment, τ, using the standard formalism,

$$G = G_0 + \Delta G d \tag{93}$$

at depth $d = P - 33\ fsw$. A nonstop bounce exposure, followed by direct return to the surface, thus allows G_0 for that compartment. One set G_0 and ΔG are tabulated in Table 5, with ΔG suggested by Bühlmann. The minimum excitation, G^{min}, initially probing r, and taking into account regeneration of nuclei over time scales τ_r, is (fsw),

$$G^{min} = \frac{2\,\gamma\,(\gamma_c - \gamma)}{\gamma_c\, r(t)} = \frac{11.01}{r(t)} \tag{94}$$

with,

$$r(t) = r + (r_i - r)\ [1 - exp\ (-\lambda_r t)] \tag{95}$$

γ, γ_c film, surfactant surface tensions, that is, $\gamma = 17.9\ dyne/cm$, $\gamma_c = 257\ dyne/cm$, and λ_r the inverse of the regeneration time for stabilized gas micronuclei (many days). Prolonged exposure leads to saturation, and the largest permissible gradient, G^{sat}, takes the form (fsw), in all compartments,

$$G^{sat} = \frac{58.6}{r} - 49.9 = .372\,P + 11.01. \tag{96}$$

On the other hand, G^{min} is the excitation threshold, the amount by which the surrounding tension must exceeed internal bubble pressure to just support growth.

Although the actual size distribution of gas nuclei in humans is unknown, experiments *in vitro* suggest that a decaying exponential is reasonable,

$$n = N\ exp\ (-\beta r) \tag{97}$$

with β a constant, and N a convenient normalization factor across the distribution. For small values of the argument, βr,

$$exp\ (-\beta r) = 1 - \beta r \tag{98}$$

as a nice simplification. For a stabilized distribution, n_0, accommodated by the body at fixed pressure, P_0, the excess number of nuclei, Δn, excited by compression-decompression from new pressure, P, is,

$$\Delta n = n_0 - n = N\beta r_i \left[1 - \frac{r}{r_i}\right]. \tag{99}$$

For large compressions-decompressions, Δn is large, while for small compressions-decompressions, Δn is small. When Δn is folded over the gradient, G, in time, the product serves as a critical volume indicator and can be used as a limit point in the following way.

The rate at which gas inflates in tissue depends upon both the excess bubble number, Δn, and the gradient, G. The critical volume hypothesis requires that the integral of the product of the two must always remain less than some limit point, $\alpha\, V$, with α,a proportionality constant,

$$\int_0^\infty \Delta n G dt = \alpha V\ , \tag{100}$$

for V the limiting gas volume. Assuming that gradients are constant during decompression, t_d, while decaying exponentially to zero afterwards, and taking the limiting condition of the equal sign, yields simply for a bounce dive, with λ the tissue constant,

$$\Delta nG\,(t_d + \lambda^{-1}) = \alpha V. \tag{101}$$

In terms of earlier parameters, one more constant, δ, closes the set, defined by,

$$\delta = \frac{\gamma_c\,\alpha\,V}{\gamma\beta\,r_i\,N} = 7180\,fsw\;min\;, \tag{102}$$

so that,

$$\left[1 - \frac{r}{r_i}\right]\,G\,(t_d + \lambda^{-1}) = \delta\,\frac{\gamma}{\gamma_c} = 500.8\,fsw\;min. \tag{103}$$

The five parameters, γ, γ_c, δ, λ_r, r_i, are five of the six fundamental constants in the varying permeability model. The remaining parameter, λ_m, interpolating bounce and saturation exposures, represents the inverse time contant modulating multidiving. Bubble growth experiments suggest that λ_m^{-1} is in the neighborhood of an hour. Discussion of λ_m follows in the next section (RGBA).

The depth at which a compartment controls an exposure, and the excitation radius as a function of halftime, τ, in the range, $12 \le d \le 220\;fsw$, satisfy,

$$\frac{r}{r_i} = .9 - .43\;exp\,(-\zeta\tau) \tag{104}$$

with $\zeta = .0559\;min^{-1}$. The regeneration constant, λ_r, is on the order of inverse days, that is, $\lambda_r = .0495\;days^{-1}$. Characteristic halftimes, τ_r and τ_h, take the values $\tau_r = 14\;days$ and $\tau_h = 12.4\;min$. For large τ, r is close to r_i, while for small τ, r is on the order of $.5\;r_i$. At sea level, $r_i = .8\;microns$ as discussed.

The VPA has been applied extensively to nitrox and heliox staging in ranges down to 250 fsw, with parameters fitted to exposures in this range.

5. Reduced Gradient Bubble Algorithm (RGBA)

The phase (limit) integral for multiexposures is written,

$$\sum_{j=1}^{J}\left[\Delta nG\,t_{d_j} + \int_0^{t_j}\Delta nG dt\right] \le \alpha\,V \tag{105}$$

with the index j denoting each dive segment, up to a total of J, and t_j the surface interval after the j^{th} segment. For the inequality to hold, that is, for the sum of all growth rate terms to total less than αV, obviously each term must be less the $\alpha\,V$. Assuming that $t_J \to \infty$, gives,

$$\sum_{j=1}^{J-1}\left[\Delta nG\,[t_{d_j} + \lambda^{-1} - \lambda^{-1}exp\,(-\lambda t_j)]\right] + \Delta nG\,(t_{d_J} + \lambda^{-1}) \le \alpha\,V. \tag{106}$$

Defining G_j,

$$\Delta nG_j\,(t_{d_j} + \lambda^{-1}) = \Delta nG\,(t_{d_j} + \lambda^{-1}) - \Delta nG\,\lambda^{-1}exp\,(-\lambda t_{j-1}) \tag{107}$$

for $j = 2$ to J, and,

$$\Delta nG_1 = \Delta nG \tag{108}$$

for $j = 1$, it follows that

$$\sum_{j=1}^{J}\Delta n\;G_j\,(t_{d_j} + \lambda^{-1}) \le \alpha\,V \tag{109}$$

with the important property,

$$G_j \leq G. \tag{110}$$

This implies we employ reduced gradients extracted from bounce gradients by writing,

$$G_j = \xi_j \, G \tag{111}$$

with ξ_j a *multidiving* fraction requisitely satisfying,

$$0 \leq \xi_j \leq 1 \tag{112}$$

so that, as needed,

$$\Delta n G_j \leq \Delta n G. \tag{113}$$

The fractions, ξ, applied to G always reduce them. As time and repetitive frequency increase, the body's ability to eliminate excess bubbles and nuclei decreases, so that we restrict the permissible bubble excess in time,

$$\Delta n(t_{j-1}^{cum}) = N\beta r_i \left[1 - \frac{r(t_{j-1}^{cum})}{r_i}\right] = \Delta n \; exp\; (-\lambda_r t_{j-1}^{cum}) \tag{114}$$

$$t_{j-1}^{cum} = \sum_{i=1}^{j-1} t_i \tag{115}$$

with t_{j-1}^{cum} cumulative surface interval time. A reduction factor, η_j^{reg}, accounting for creation of new micronuclei is taken to be the ratio of present excess over initial excess, written,

$$\eta_j^{reg} = \frac{\Delta n(t_{j-1}^{cum})}{\Delta n} = exp\; (-\lambda_r t_{j-1}^{cum}) \tag{116}$$

For reverse profile diving, the gradient is restricted by the ratio (minimum value) of the bubble excess on the present segment to the bubble excess at the deepest point over segments. The gradient reduction, η_j^{exc}, is then,

$$\eta_j^{exc} = \frac{(\Delta n)_{max}}{(\Delta n)_j} = \frac{(rd)_{max}}{(rd)_j} \tag{117}$$

with rd the product of the appropriate excitation radius and depth. Because bubble elimination periods are shortened over repetitive dives, compared to intervals for bounce dives, the gradient reduction, η_j^{rep}, is proportional to the difference between maximum and actual surface bubble inflation rate, that is,

$$\eta_j^{rep} = 1 - \left[1 - \frac{G^{min}}{G}\right] exp\; (-\lambda_m t_{j-1}) \tag{118}$$

with t_{j-1} consecutive surface interval time, λ_m^{-1} on the order of an hour, and G^{min} the smallest G_0 in Table 5. Finally, for multidiving, the gradient reduction factor, ξ, is defined by the product of the three η,

$$\xi_j = \eta_j^{exc}\, \eta_j^{rep}\, \eta_j^{reg} = \frac{(\Delta n)_{max}}{(\Delta n)_j} \left[1 - \left(1 - \frac{G^{min}}{G}\right) exp\; (-\lambda_m t_{j-1})\right] exp\; (-\lambda_r t_{j-1}^{cum}) \tag{119}$$

with t_{j-1} consecutive interval time, and t_{j-1}^{cum} cumulative interval time, as noted. Since bubble numbers increase with depth, reduction in permissible gradient is commensurate. Multiday diving is mostly impacted by λ_r, while repetitive diving mostly by λ_m. Obviously, the critical tension, M, takes the form,

$$M = \xi(G_0 + \Delta G d) + P. \tag{120}$$

Table 5 tabulates a set of critical gradients, G_0 and ΔG.

Table 5. Critical Phase Volume Gradients

halftime τ (min)	threshold depth δ (fsw)	surface gradient G_0 (fsw)	gradient change ΔG
2	190	151.0	.518
5	135	95.0	.515
10	95	67.0	.511
20	65	49.0	.506
40	40	36.0	.468
80	30	27.0	.417
120	28	24.0	.379
240	16	23.0	.329
480	12	22.0	.312

The RGBA extends the VPA to multidiving and depths to roughly 500 fsw for nitrox, heliox, and trimix. Parameters are correlated with diving exposure date using maximum likelihood regression.

6. Tissue Bubble Diffusion Algorithm (TBDA)

Bubbles shrink or grow according to a simple radial diffusion equation linking total gas tension, Π, ambient pressure, P, and surface tension, γ, to bubble radius, r,

$$\frac{\partial r}{\partial t} = \frac{DS}{r}\left[\Pi - P - \frac{2\gamma}{r}\right] \tag{121}$$

with D the gas diffusion coefficient, and S the gas solubility. Bubbles grow when the surrounding gas tension exceeds the sum of ambient plus surface tension pressure, and vice versa. Higher gas solubilities and diffusivities enhance the rate. Related bubble area, A, and volume, V, changes satisfy,

$$\frac{\partial A}{\partial t} = 8\pi r \frac{\partial r}{\partial t} \tag{122}$$

$$\frac{\partial V}{\partial t} = 4\pi r^2 \frac{\partial r}{\partial t} \quad . \tag{123}$$

Using Fick's law, a corresponding molar current, J, of gas into, or out of, the bubble is easily computed assuming an ideal gas,

$$J = -\frac{DS}{RTh}\left[\Pi - P - \frac{2\gamma}{r}\right] \tag{124}$$

for R the ideal gas constant, T the temperature, and h an effective diffusion barrier thickness. And the molal flow rate is just the molal current times the interface area, that is,

$$\frac{\partial n}{\partial t} = JA \tag{125}$$

for n the number of moles of gas. The change in pressure and volume of the bubble, due to gas diffusion, follows simply from the ideal gas law,

$$\frac{\partial(PV + 2\gamma r^{-1} V)}{\partial t} = R\frac{\partial(nT)}{\partial t} \tag{126}$$

for V the bubble volume.

Obviously, the above constitute a coupled set of differential equations, solvable for a wide range of boundary and thermodynamic conditions connecting the state variables, namely, P, V, Π, r, n, and T.

In the TDBA, a bubble dose, based on the hypothetical volume of an expanding test bubble, is linked to decompression data for the exposure. Maximum likelihood regression is used to correlate bubble dose with DCI risk.

Comparative Reverse Dive Profiles

Employing the above described algorithms, we consider model predictions for Reverse dive profiles, extract underlying features and tendencies, and draw comparisons. The code, *DECOMP*, containing a number of model kernels, is employed for calculations.

The reverse dive profiles (100/60 and 60/100) are normalized to roughly the same NDLs so that the nonstop time limits at 100 fsw and 60 fsw are 15 min and 50 min, respectively. This normalization leans slightly toward the conservative side as far as NDLs are concerned. Table 6 encapsulates the results for the PLA, DLA, TA, VPA, RGBA, and TBDA. Typically, tracking bubble growth and dissolved gas buildup and elimination, phase models require slightly more decompression times for the reverse dive profiles. The PLA and DLA are comparable, the TA, VPA, and TBDA also track closely, and the RGBA is most conservative. These profiles are relatively shallow, and the reverse dive profiles increment is small (Δd = 40 fsw). Generally, bubble models affect deep and prolonged exposures the most, requiring deeper stops, but usually shorter overall decompression times. The effect is not seen here trendwise, but will reappear as the reverse dive profiles increments increase. Bubble and Haldane models overlap for short and shallow exposures, such as these reverse dive profiles, and entries in Table 6 are no exception. The observation has often been made that not much free gas phase has been excited during short and shallow exposures, and then, bubble models should collapse to dissolved gas phase models in the limit.

When exposures are deeper and reverse dive profiles increments are greater than 40 fsw, model differentiations between dissolved gas and dual phase models appear in the staging regimens, as seen in Table 7, contrasting the PLA and RGBA only for 160/40 and 40/160 reverse dive profiles. Clearly phase models (RGBA) require deeper staging but shorter times, as seen in Table 7 for the same surface intervals in Table 6. The bottom times are 7 min and 100 min at 160 fsw and 40 fsw respectively in Table 7.

NEST Reverse Dive Profiles Data

The Nuclear Emergency Strategy Team (NEST) is involved in counterterrorism and countermeasures related to nuclear and biological threats. Exercises and tests have yielded scattered data about reverse dive profiles across a spectrum of breathing gas mixtures (nitrox, heliox, trimix). Recent activities have settled on trimix as the bottom and ascent gas, with pure oxygen breathed at 20 fsw. Mixture range 13-17% helium, 53-61% nitrogen, and 26-30% oxygen. Reverse dive profiles increments, Δd, vary from 40 - 120 fsw, and surface intervals are nominally greater than 60 min. The RGBA is the staging algorithm.

Table 8 tabulates results of NEST field activities, with nominal surface intervals of an hour or more. Maximum bottom depth is 250 fsw, and exposures are near trimix NDLs. Dives are grouped in reverse dive profiles categories of 40 fsw. The NDLs computed from the RGBA for trimix in the range down to 250 fsw are roughly:

100 fsw	8 - 10 min
150 fsw	5 - 7 min
200 fsw	4 - 6 min
250 fsw	2 - 3 min

similar in duration to Haldane trimix NDLs. The ascent profile is different under the RGBA, as compared to standard Haldane staging. And this is well known. The incidence rate, p, in Table 8 is 6.7%, with highest count in the 40 - 120 fsw increment range. There are many variables here, such as staging depth, gas mixture, exposure time, and surface interval not tabulated separately.

Practices for the deeper increments may border the yo-yo category, though no prior history of repetitive diving existed. Exercises continue, and data will grow. Trends are apparent in the above Table 8, but further analysis is required.

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Table 6. Comparative Reverse Dive Profiles and Algorithms.

Algorithm	Dive 1	Deco 1	Surface Interval	Dive 2	Deco 2
PLA	100/15	none	30	60/30	10/2
DLA		none			10/2
TA		none			10/1
VPA		none			10/2
RGBA		none			10/4
TBDA		none			10/3
PLA	60/30	none		100/15	10/2
DLA		none			10/2
TA		none			10/2
VPA		none			10/3
RGBA		none			10/5
TBDA		none			10/3
PLA	100/15	none	60	60/30	10/1
DLA		none			10/1
TA		none			10/1
VPA		none			10/2
RGBA		none			10/4
TBDA		none			10/2
PLA	60/30	none		100/15	10/1
DLA		none			10/1
TA		none			10/1
VPA		none			10/3
RGBA		none			10/6
TBDA		none			10/2
PLA	100/15	none	120	60/30	none
DLA		none			none
TA		none			10/1
VPA		none			10/1
RGBA		none			10/3
TBDA		none			10/1
PLA	60/30	none		100/15	10/1
DLA		none			10/1
TA		none			10/1
VPA		none			10/2
RGBA		none			10/4
TBDA		none			10/2
PLA	100/15	none	240	60/30	none
DLA		none			none
TA		none			none
VPA		none			none
RGBA		none			10/1
TBDA		none			10/1
PLA	60/30	none		100/15	none
DLA		none			none
TA		none			none
VPA		none			10/1
RGBA		none			10/2
TBDA		none			10/1

Table 7. Comparative PLA and RGBA (Deep) Reverse Dive Profiles.

Algorithm	Dive 1	Deco 1	Surface Interval	Dive 2	Deco 2
PLA	160/7	10/3	30	40/100	none
RGBA		10/1			10/4
PLA	40/100	none		160/7	10/11
RGBA		none			30/1,20/1,10/2
PLA	160/7	10/3	60	40/100	none
RGBA		10/1			10/3
PLA	40/100	none		160/7	10/3
RGBA		none			20/1,10/2
PLA	160/7	10/3	120	40/100	none
RGBA		10/1			10/2
PLA	40/100	none		160/7	10/3
RGBA		none			20/1,10/1
PLA	160/7	10/3	240	40/100	none
RGBA		10/1			10/1
PLA	40/100	none		160/7	10/3
RGBA		none			20/1,10/1

Table 8. NEST Reverse Dive Profiles Risk Table.

Dives	Reverse Dive Profiles Increment (fsw)	Probable DCS Hits
36	0 – 40	0
18	40 – 80	2
6	80 – 120	2

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REVERSE DIVING AND PRECURSORS OF DECOMPRESSION SICKNESS BUBBLES: QUESTIONS IN NEED OF ANSWERS.

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This communication reviews some fundamental questions about the bubbles that cause decompression sickness: Are micronuclei necessary precursors of bubbles in the body? If so, are the micronuclei always in excess, in which case the quantity of supersaturated gas, rather than micronuclei, would be the limiting factor? Are micronuclei so plentiful that after decompression there are many small bubbles which take up all the excess gas in the tissue, or do only a few bubbles form so that most of the tissue remains supersaturated? Are the micronuclei "crushable," meaning that they can be eliminated by pressurization? The reverse diving situation dramatizes the lack of answers. Theoretical considerations can give different predictions, depending on which assumptions one starts from. Consider a pattern in which asymptomatic bubbles form after the first, shallow dive. If there are many bubbles per unit of tissue, gas washout after the decompression is slower than with only a few bubbles. On the second, deeper dive, the bubbles from the first dive can either serve as a rapid source of supersaturated gas for the tissue (if there are many bubbles) or can have little effect on the gas washout (if there are few bubbles). Also, if micronuclei are crushable and are not regenerated before the second dive, a first deep pressurization could eliminate micronuclei so fewer bubbles would form for both the first and second dive. In the absence of answers to the fundamental questions about bubble formation, it seems that theories about gaseous micronuclei will not be helpful for predicting the consequences of reverse diving.

Introduction

The purpose of this communication is to explore some ideas about bubble precursors in the context of "reverse" diving. The conclusion reached is that there is not sufficient information about bubble precursors to allow recommendations about safety or desirability of reverse diving. Although provocative, the line of reasoning presented below does not have a solid enough experimental base to warrant application to practical situations.

It is conventional to assume that tissues of the body vary in the rate they exchange gas with blood during washin when the diver breathes dense gas at depth and washout after decompression from depth. To simplify the more realistic idea of a spectrum of tissue exchange rates, we will speak of "fast" and "slow" tissues. In a repetitive dive sequence known as a "reverse" dive profile, the diver makes a shallow dive followed by a deeper dive; the shallow dive is likely to be long in duration because it is possible to remain at a shallow depth for a relatively long time. Fast tissues can be expected to take up gas rapidly on both deep, short dives and shallow, long dives. In contrast, slow tissues take up appreciable amounts of gas only in shallow, long dives and because their exchange rate is slow, do not lose much gas during a surface interval between repetitive dives. Gas taken up in the first dive of a pair of dives poses a threat for the second dive, so the second dive should be less stressful than if it were the first dive. This can often be accomplished by shortening the second, shallow dive in a conventional dive pattern. However, deep second dives are relatively short, so decompression stops are often necessary to take care of the N_2 taken up by slow tissues in the first dive.

Numbers of Bubbles

Realistically, there can probably be a wide variance in the number of bubbles that form in a tissue, depending on the characteristics of the dive. To simplify, we will speak of "few bubbles" or "many bubbles." Van Liew and Burkard (1993) explored consequences of varying numbers of bubbles in tissue by simulations of growth and decay of decompression bubbles. Suppose that a few bubbles (say 10 bubbles per ml of tissue) form as a consequence of the first decompression in a pair of dives. The bulk of the tissue remains supersaturated; most of the tissue is so far from the few bubbles that there is no diffusive exchange between that faraway tissue and any of the bubbles. Therefore, washout of gas from the tissue during a surface interval or decompression stop remains exponential in nature, similar to what it would have been had no bubbles formed.

The situation is quite different when there are many bubbles (say 10,000/ml); distances are so short that all excess gas diffuses into the bubbles. This results in a drastic decrease of the gradient for tissue washout. In addition to the lowered gradient, the bubbles serve as depots that gradually discharge gas into the tissue. Thus if many bubbles form due to the first decompression, washout of the tissue-bubble complex during the surface interval is considerably slowed as the bubbles are gradually absorbed (Van Liew and Burkard, 1993; Thalmann *et al.*, 1997).

With few bubbles, compression for the second dive hastens the absorption of bubbles, although some may remain until the decompression after the second dive and therefore be a source of trouble. However, the presence of many bubbles in a tissue after a first dive makes a qualitative difference. With many bubbles, gas in the bubbles immediately diffuses into tissue; as was the case during decompression, the nearness of tissue to bubbles makes the exchange rapid. The result can be called a "bubble-depot" gas load in the tissue immediately after compression; the gas uptake expected during the second dive receives a head start.

There are two interrelated disadvantages of many bubbles in the first dive. The slow washout during the surface interval and the bubble-depot gas load both tend to give the tissue a gas load at the time of decompression from the second dive that is larger than would be the case with few or no bubbles. This larger gas load means that bubbles are more likely and may be bigger after the second decompression. These disadvantages may be more harmful with shallow-first dives because there is more gas in slow tissues due to the long time for the shallow first dive.

Bubble Precursors

It is obvious that for a bubble to form, there has to be enough excess gas dissolved in tissue to fill the bubble. A second necessary condition has been postulated (Strauss, 1974; Yount and Strauss, 1976): a gaseous precursor. The concept of a gaseous precursor seems to be necessary because of surface tension, which raises hydrostatic pressure inside any spherical bubble. Pressure due to surface tension, P, is inversely proportional to radius of the bubble, R, by the law of Laplace: $P = 2\gamma/R$, where γ is the surface-tension constant. According to the law, if radius were vanishingly small, pressure inside the bubble would approach infinity. This makes small spherical bubbles very unlikely since the high internal pressure would cause rapid diffusion of gas out of the bubble. If small bubbles are precluded, how can bubbles large enough to cause damage in decompression sickness ever develop? The "quick and easy solution" to this conundrum has been to assume that decompression bubbles always grow from pre-existing gaseous entities. The name "gaseous micronuclei" is given to these putative entities; note however that assigning a name does not prove that such entities exist or give any knowledge as to their properties. It is possible that gaseous micronuclei are pockets of gas in a non-spherical shape in the body (Tikuisis, 1986) or are very small spherical bubbles that are stabilized by some sort of structure (Van Liew and Raychaudhuri, 1997).

If micronuclei are necessary precursors, it follows that the number of bubbles to form in a decompression is strongly dependent on the number of micronuclei. If there are always many micronuclei, many bubbles will always form; the many-bubble case described above will always prevail. Conversely, if there are few micronuclei, there will always be few bubbles.

Crushing of Micronuclei

The final point of concern here is the possibility that the number of gaseous micronuclei can vary, depending on conditions of the dive profile. The idea is that micronuclei can be "crushed," meaning that they can be inactivated permanently or temporarily by compression. It is reasonable to assume, as was done previously (Strauss, 1974; Yount and Strauss, 1976; Vann *et al.*, 1980; Van Liew and Raychaudhuri, 1999), that higher pressure crushes more micronuclei. Therefore, in a deep-first dive, many micronuclei would be crushed, with the consequence that few bubbles would be formed after the first decompression. This would mean that washout during the surface interval would be exponential and would tend to prevent a bubble-depot gas load at the beginning of the second, shallow dive. Compression for the second, shallow dive would not be expected to crush many micronuclei. However, if the crushing effect lasts for the duration of the two dives together, the crushing of many micronuclei on the first, deep dive could offer protection from bubble formation on both dives.

In the contrasting case of a shallow-first dive pair, few micronuclei would be crushed on the first dive, increasing the probability that many bubbles, slow washout, and a bubble-depot gas load would occur. However, the more-extensive crushing that would occur on the second, deep dive could protect the subject from bubble formation.

Discussion

It is seen that there are arguments in favor of both traditional and reverse dive pairs. The defect in all that has been said above is that very little is known about numbers of bubbles that form after a decompression and about gaseous micronuclei. Descriptions of populations of micronuclei that may occur in the body are purely theoretical (Van Liew and Raychaudhuri, 1999). It is not clear whether a many-bubble, few-bubble, or no-bubble scenario is more realistic after any particular dive. Very few experiments support the possibilities that micronuclei in mammalian tissues are important and that they are "crushable" (Vann *et al.*, 1980; Dervey *et al.*, 1997). The duration of a crushing effect in mammals or man has not been carefully explored. The lack of fundamental information means that our discussion of micronuclei and reverse diving is highly speculative.

It is instructive to list the seven assumptions that are the basis of the logical development above.

1. Tissues vary in rate of exchange with blood - the idea that there are fast and slow tissues.
2. If many bubbles form, all excess dissolved gas in tissue goes into bubbles, and thereby slows washout.
3. If few bubbles form, there is little effect on washout.
4. With many bubbles, a second compression gives a "bubble-depot gas load."
5. Gaseous precursors (micronuclei) are necessary for bubble formation.
6. Micronuclei may be crushable.
7. The effect of crushing may last for a period of time, which could be minutes or weeks.

Some of the assumptions are generally accepted and some are supported by mathematical simulations. However, it can be argued that all are deficient in direct experimental validation, partly because experimental methods are lacking for making the desired measurements and perhaps partly because of lack of focus or interest in the questions raised.

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ANALYSIS OF REVERSE DIVE PROFILES USING THE DCIEM BUBBLE EVOLUTION MODEL PART I: MODEL DEVELOPMENT

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The DCIEM bubble evolution model, calibrated against Doppler-detected bubble scores, is used to calculate the growth and decay of bubbles generated by a dive/decompression profile. The maximum bubble radius attained can be used as a measure of the risk of decompression sickness. Application of the model to reverse dive profiles suggests that these profiles do not present a markedly higher risk of DCS compared to conventional repetitive profiles.

Introduction

The DCIEM bubble evolution model, calibrated against Doppler-detected bubble scores, is used to calculate the growth and decay of bubbles generated by a dive/decompression profile. The maximum bubble radius attained can be used as a measure of the risk of decompression sickness (DCS). In Part 1, we outline the development of the model and compare its prediction to the risk of DCS for a wide range of dive profiles.

Model Development and Calibration

The bubble evolution model originated from an investigation to correlate bubble incidence in divers to a probabilistic model prediction of bubble evolution (Gault *et al.*, 1995). The bubble model incorporates a finite inert gas availability constraint for the formation of the bubble, perfusion-limitation of gas exchange between the blood and tissue, and a gas diffusion barrier at the bubble boundary. The method of maximum likelihood was applied to the original model against bubble grade data based on the Kisman-Masurel classification of Doppler-detected bubbles (Nishi, 1993). The data were comprised of 2,064 man-dives involving 276 air and 86 heliox dives. Air dives included single and repetitive exposures, standard decompression dives, dives with oxygen decompression at 9 msw, and surface decompression dives involving surfacing from 9 msw and recompressing back to 12 msw to complete the decompression. Heliox dives were mostly 84% He:16% O_2 with air decompression to 9 msw followed by O_2 decompression at 9 msw.

Maximum bubble grade data were used for the model calibration of the maximum bubble size (R_{max}) predicted. Bubble grades were categorized according to no bubbles detected (42.5% of cases), light bubble activity (BG's of 1 and 2; 28.1%), and heavy bubble activity (BG's of 3 and 4; 29.4%). Key model parameters fitted by maximum likelihood included the time constants of N_2 and He (τ_{N2} and τ_{He}, respectively), the gas flux coefficient at the bubble boundary (k_{N2} and k_{He}, where gas flux = $k \cdot \Delta$conc), and the Ostwald gas solubility coefficient in the tissue compartment (L_{N2} and L_{He}). Subsequently, the model has been expanded (Nishi *et al.*, 1997) to include two compartments and calibrated against a larger data set (original plus 464 nitrox man-dives). The resultant percentages of BG cases were 44.0% (0), 28.3% (1, 2), and 27.7% (3, 4). Common to both model compartments are the tissue volume (10^{-4} mL), tissue surface tension (30 dyne$\cdot$cm^{-1}), H_2O vapor tension (0.0619 atm), and CO_2 or metabolic gas tension (0.0625 atm). The estimated parameters are listed in the table below.

Table 1: Bubble model parameter estimates; τ = time constant; k = bubble boundary gas flux rate coefficient; and L = Ostwald gas solubility coefficient.

Parameter	Compartment 1		Compartment 2	
	N_2	He	N_2	He
τ (min)	27.8	21.7	158.9	72.0
k ($cm \cdot s^{-1}$)	7.033×10^{-5}	1.690×10^{-2}	4.639×10^{-5}	11.839×10^{-2}
L	0.0215	0.0110	0.0463	0.0138

Figure 1 shows the predicted bubble evolution in both model compartments for a standard air decompression dive (150 fsw for 30 min). In this example, the predicted bubble formation for the 2nd compartment lags the formation in the 1st compartment because of a lower gas tension. However, the subsequent growth of the bubble in the 2nd compartment after further decompression is larger because of a longer retention of the excess gas tension.

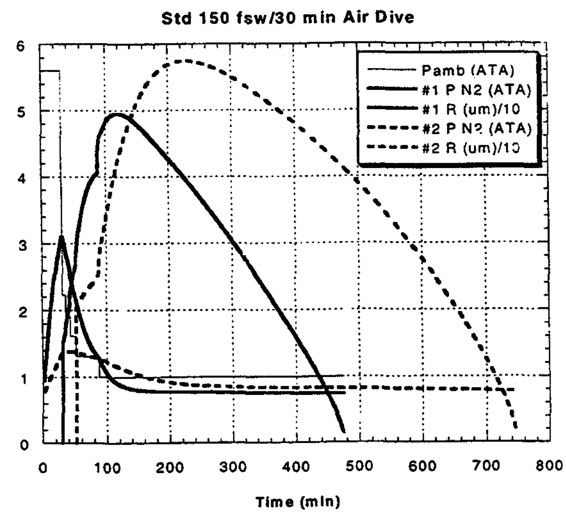

Fig. 1. Predicted N_2 tension and bubble evolution in the two model compartments for a 150 fsw/30 min air dive.

It is emphasized that the predicted bubble radius should not be interpreted literally, but rather as an index of the decompression stress, similar to the Bubble Grade Index (BGI) introduced by Gernhardt (1991). In fact, the maximum bubble radius predicted by the DCIEM model and the BGI for NoD dives is remarkably similar (Nishi and Tikuisis, 1999). Further, there appears to be a close correlation between R_{max} and the risk of DCS, as presented below.

Model Comparison to DCS Prediction

To substantiate the application of the bubble model to reverse air dive profiles, we first established the correspondence between the predicted maximum bubble size and the risk of DCS. For this purpose, we applied the bubble model to various air and nitrox dives comprising single and repetitive excursions extracted from the recent experimental dive compilation of Temple *et al.* (1999). The selection criterion was arbitrarily based on the maximum DCS incidence for each dive series. Fourteen dive profiles were thus selected and tabled below. The t1 and t2 values correspond to the average of the recorded times when the divers were symptom-free and when symptoms first occurred, respectively. Predictions of R_{max} pertain to the compartment having the larger predicted maximum bubble radius.

Figures 2a - 2d show the predicted N_2 tension and bubble evolution for one profile from each dive type. In these cases, and in most of the profiles tabled above, the predicted time of the maximum bubble radius falls within the t1-t2 envelope. Further, there is a convincing correlation between the predicted risk of DCS and the predicted maximum bubble radius, as seen in Fig. 3. Accordingly, predicted R_{max} > 60 µm correspond to pDCS > 3%.

Table 2. Dive profiles and model predictions: Dive Type, sa = single air, sna = single non-air, ra = repetitive air, and rna = repetitive non-air; Dive Series, Profile Notation and Profile # are from Temple *et al.* (1999); pDCS = predicted risk of DCS from USN93 model (courtesy of K.A. Gault, NEDU); n = number of DCS occurrences; t1 = average of last symptom-free time; t2 = average of earliest time of symptom; t_{max} = average time of predicted maximum bubble radius; and R_{max} = predicted maximum bubble radius.

Dive Type	Dive Series	Profile Notation	Profile #	pDCS (%)	n	Depth (fsw)	Time (min)	t1 (min)	(min)	t_{max} (min)	R_{max} (µm)
sa	DC4D	DR0340A	133	6.2	3	148.0	40.0	150.3	280.9	255.0	66.9
	EDU885A	AN1013.OUT	22	7.0	3	60.0	182.7	283.7	403.9	400.0	74.0
	EDU849LT2	EDU849.DAT	43	5.2	19	150.0	30.0	64.8	143.5	98.4	61.1
	NMR97NOD	SIMPLIFIED	2	3.8	7	40.0	200.0	245.4	369.4	350.7	64.5
	EDU545	11/06/44 EDU	1	9.5	12	100.0	85.0	159.0	443.3	276.0	78.2
	PASA	PAA0E04	6	4.6	3	101.5	59.9	274.3	814.3	317.3	60.0
	EDU1157	EDU1157N	14	30.3	4	140.0	240.0	661.3	1025	726.3	103
sna	NMR8697	DRA4_8301	6	1.9	3	71.0	30.0	131.5	271.5	85.5	41.3
	EDI1180S	DIV562	7	10.4	3	150.0	72.3	220.5	401.7	324.4	87.4
ra	PAMLA	PAA1B01	2	10.1	2	81.5	240.1	411.8	651.8	451.1	78.6
	EDU885AR	AN2011.OUT	6	12.9	2	150.0	43.9	519.1	1092	227.7	62.8
	EDU657	11/20/56	42	22.4	2	140.0	60.0	467.6	621.6	501.4	85.0
rna	EDI184	MDC024.OUT	11	9.0	2	80.0	47.4	319.1	370.2	513.5	59.8
	PAMLAOS	PAAIIA03	6	7.4	3	81.5	242.9	497.1	546.1	514.2	71.0

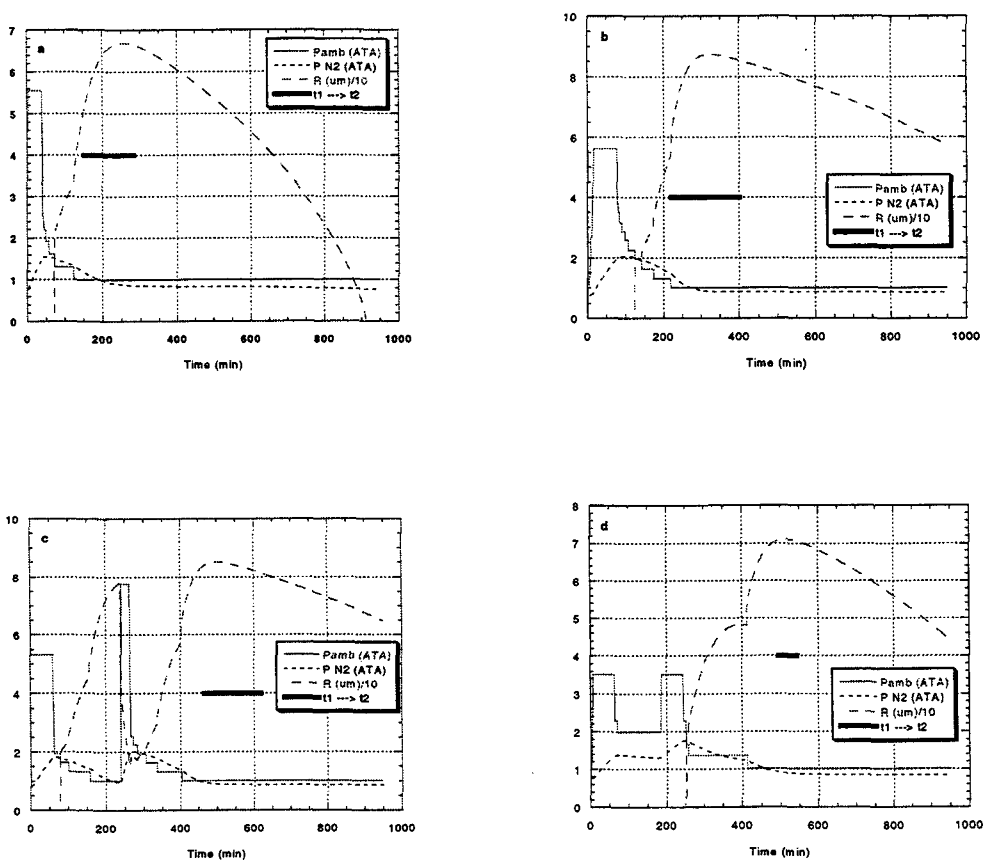

Fig. 2. Predicted N_2 tension and bubble size for dives a) DR4D, b) EDU1180S, c) EDU657, and d) PAMLAOS. The t2→t2 time bar represents the average recorded times between no symptoms and the occurrence of symptoms (see Table 2 for details).

Figure 2c is of particular interest since it represents one of the few reverse dive profiles available in the compilation record (Temple *et al.*, 1999). In this isolated case, the predicted R_{max} is 85.0 µm and pDCS is 22.4% with a 95% confidence interval of 18.5 - 26.1%.

Discussion

The bubble evolution model was developed with close adherence to the physical laws of gas kinetics and the conservation of mass, and most of the resultant parameter estimates are reasonable. Assuming that bubble size is a valid indicator of decompression stress, there is no fundamental reason why the model cannot be applied to reverse dive profiles, nor any reason why the predictions should be interpreted differently from those for normal dives. Further, the model is intuitively appealing since bubble size is particularly sensitive to pressure changes. This aspect may be especially important when comparing the effects of a large pressure change imposed by a reverse dive profile versus a more modest change with a shallower repetitive dive (see Nishi and Tikuisis for detailed examples).

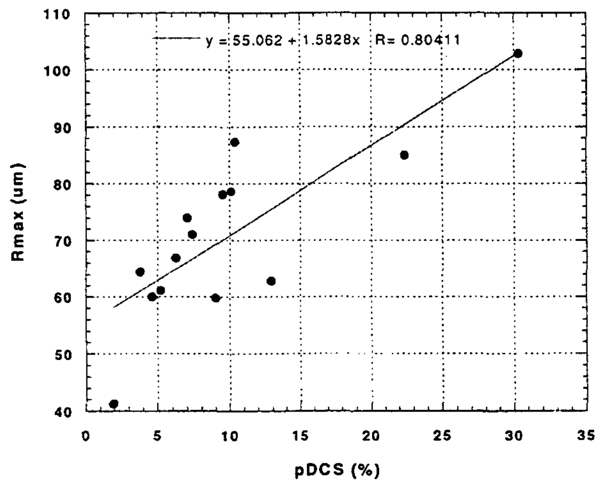

Fig. 3. Comparison of the bubble model prediction of maximum size and the USN93 model prediction of the risk of DCS (see Table 2 for details).

Comparisons of the bubble model predictions to DCS risk predictions suggest that a predicted R_{max} value > 60 µm is associated with a 3% risk of DCS. We conclude that this association can be used to judge the severity of decompression stress for dives within the range of those examined herein, whether normal or reversed.

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ANALYSIS OF REVERSE DIVE PROFILES USING THE DCIEM BUBBLE EVOLUTION MODEL PART II. RISK ASSESSMENT

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The DCIEM Bubble Evolution Model was used for a risk assessment analysis of a number of real and computed reverse and conventional repetitive dive profiles. The results suggest ways of managing and reducing the risk of reverse dive profiles.

Introduction

The DCIEM Bubble Evolution Model is a probabilistic model that has been calibrated with observed levels of venous gas emboli detected with the Doppler ultrasonic bubble monitor. It is used to calculate the growth and decay of bubbles generated by a dive/decompression profile. The predicted maximum bubble radius (max BR) attained can be used as a measure of the risk of decompression sickness (DCS). The model will be used to look at a number of calculated and real dive profiles to determine if reverse dive profiles are inherently more risky than normal repetitive dive profiles, which consist of a deeper dive followed by a shallower dive.

Repetitive Dive Models

In any analysis of repetitive dives, it is important to consider what was used to calculate the repetitive requirements. Calculation of repetitive dives either by means of tables or dive computers depends on the "decompression model" (or, more correctly, decompression algorithm) that was used to generate the tables or that is embodied within the dive computers.

There are two types of models for calculating repetitive dives. Ideally, the "decompression model" or dive computer should base the requirements of the repetitive dive on a continuous monitoring of all the compartment pressures. Figure 1 shows an example of repetitive dives being done with such a dive computer (Kidd and Stubbs, 1969). These types of dives were used to test and develop the Kidd-Stubbs "decompression model," the precursor of the present-day DCIEM model.

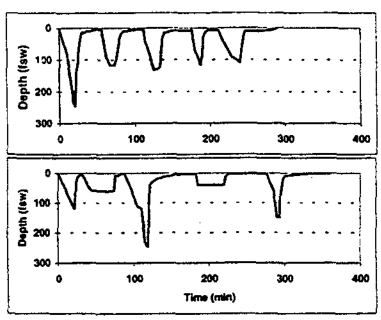


Figure 1. Examples of dives used to test original DCIEM model (Kidd-Stubbs, 1964-1969).

The other type of model is the Haldane/Workman/Schreiner (H/W/S) model that is the basis of most of the tables and dive computers that are available. This model uses a Residual Nitrogen Time (RNT) concept by looking at the compartment pressure in the 120 min half-time compartment, for example, in the case of the U.S. Navy decompression tables and in the 60 min half-time compartment in the case of the PADI/DSAT Recreational Dive Planner (Hamilton *et al.*, 1994). The RNT model has severe limitations and will give completely different results under certain conditions. Attempting to use the H/W/S model directly to compute repetitive dive requirements by monitoring the pressure values in all compartments generally results in very liberal repetitive dive times, and it is necessary to make numerous adjustments and modifications to the model to obtain safe repetitive dives (Hamilton, 1995).

Analysis of Real Dive Data with the Bubble Model

One of the first major applications of the bubble model was for the analysis of multiple repetitive dive profiles that were being conducted by the pearl divers of Western Australia (Wong, 1996). Figure 2 shows a typical daily routine: 10 repetitive dives a day for 8 continuous days. The depth for each excursion is 19 msw with a bottom time of 40 minutes, with some decompression stops on oxygen at 9 msw. The original profiles were empirical dives that had been developed over the years.

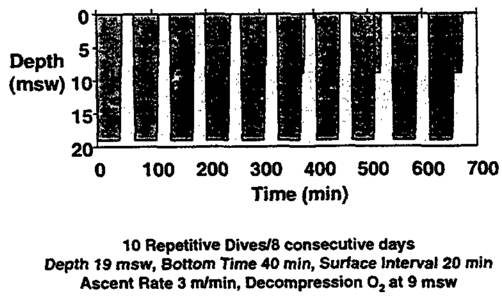


Figure 2. Pearl divers' multiple repetitive dive schedule

Figure 3 shows a more typical "at sea" operational dive and shows that some of the pearl diving involves reverse dives. This is not necessarily a result of the diver moving into deeper water. It is caused by tidal variations. The tides in northwestern Australia are among the greatest in the world, and there could be a change as great as 9 metres. Also shown in the figure are the calculated bubble evolution curves for both the first and second compartments in the model.

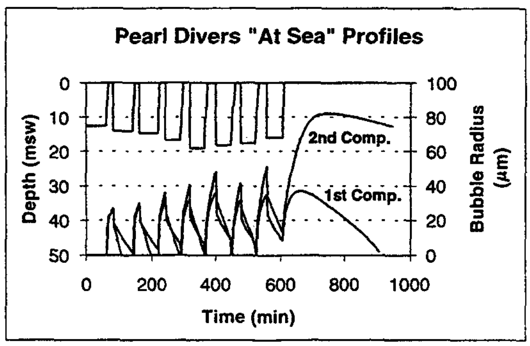


Figure 3. Calculated bubble evolution for multiple repetitive dives

An analysis of this particular series of dives shows that bubbles are generated during the surface interval between each dive, then redissolve and collapse during the next dive, form again and so on. During the surface interval, the growth is limited because of the short surface interval that helps explain the inherent safety of such procedures. Mike Gernhardt has used this concept of limiting the bubble growth to develop successful surface decompression tables with his Bubble Growth Index Model (Gernhardt, 1991). The most dangerous part of the dive is at the end, because the final bubble can grow considerably and it is important to provide sufficient decompression at the end.

Figure 4 shows the results obtained from a series of dive profiles from 11 to 23 metres depth that were tested in a hyperbaric chamber by Dr. Robert Wong, medical consultant to the pearl diving industry. The purpose of these dives was to evaluate the dive schedules that were being used in the industry and to determine how they could be improved by implementing additional decompression stops on oxygen. The DCIEM air diving model was used to determine the decompression requirements. The results (Nishi, 1999) show that for those profiles where the max BR at the end of the dives were greater than 70 µm, DCS always seemed to occur. High bubble levels, Doppler Grades 3 and 4, occurred at 60 µm or greater and below that, low bubble grades were observed. Grade 3 and 4 bubbles are associated with high decompression stress and an increased risk of DCS (Nishi, 1993). These results give us a good idea as to what to expect when analyzing repetitive dives. A good guideline for this type of diving would appear to be to keep the max BR produced by any dive profile below 60 µm. However, a potential problem with these predictions might arise with acclimatization since the pearl divers conduct many dives per day for 8 consecutive days.

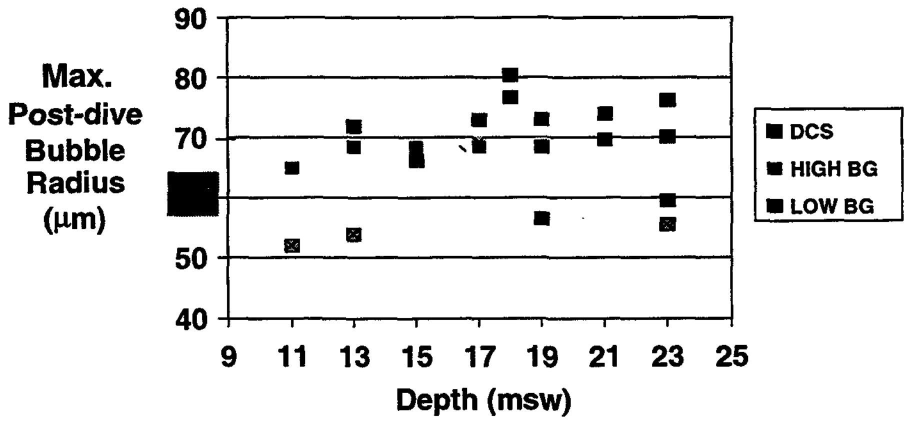


Figure 4. DCS bubble radius threshold for pearl divers' profiles (1992-1997).

Figure 5 shows another example from the pearl diving industry that shows multiple repetitive dives demonstrating both shallow subsequent dives and also increasingly deeper repetitive dives. There are a few interesting features. Normally, we think of a longer surface interval between dives as being safer than shorter surface intervals. However, in a case like this where there is a large gas loading, a longer surface interval such as observed after the fifth dive allows the bubble to grow considerably before the next dive begins and can put the diver at risk of DCS.

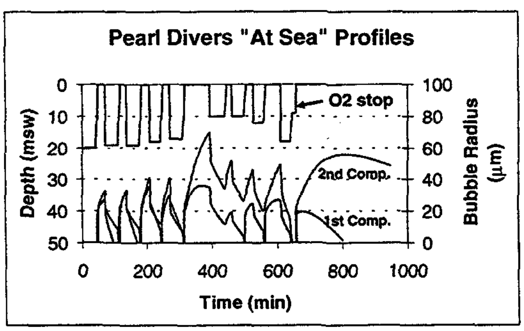


Figure 5. Calculated bubble evolution for multiple repetitive dives.

It is also interesting to note that a deep dive followed by a shallow dive may not be sufficient to cause the bubbles generated by the previous dive to redissolve and collapse and may lead to larger bubbles being formed during the next surface interval. Finally, it can be seen that providing more decompression for the last dive, either by giving oxygen or more decompression time can reduce the maximum bubble size and bring it down to a lower risk range.

One of the handicaps in developing decompression models and relating them to real dive and DCS information is the difficulty in obtaining large quantities of DCS data to accurately define the model. Recent work by the U.S. Navy and Dr. Charles Lehner at the University of Wisconsin (Lehner *et al.*, 1997) using probabilistic modeling has shown that sheep appear to be a good analogue for human diving (Ball *et al.*, 1999). The sheep data set is for single dives and comprises a considerable number of DCS cases.

Figure 6 shows observed DCS incidence versus max BR for part of this data set in two pressure ranges. For pressures in the range of 50 to 100 fsw, DCS occurred at around 60 µm and, as the bubble size increased, more and more subjects were observed to have DCS. This is consistent with the results shown in Part I. However, for depths greater than 100 fsw and less than 140 fsw, DCS occurred at a lower max BR, starting at about 45 µm. In addition, the observed DCS incidence increased more rapidly with increasing bubble size. So for non-acclimatized subjects, the threshold between low risk and high risk should perhaps be set at around 40 µm for reverse dives. For the shallower depths, the threshold could possibly be set at a higher value.

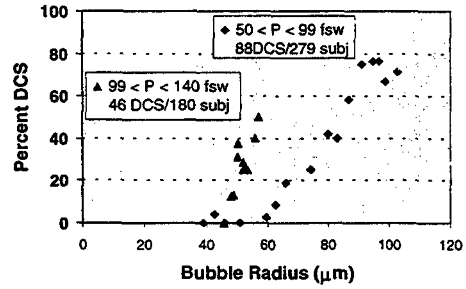


Figure 6. Percent observed DCS versus BR – Sheep Large Animal Model (Lehner et al., 1997)

Using the Bubble Model for Prediction of Risk

Tables 1 and 2 show the results of no-decompression limit (NDL) predictions for the DCIEM model and tables, the PADI/DSAT H/W/S model and tables, and the USN H/W/S model and tables. Both the PADI and USN H/W/S models were used directly as designed for first dives and no adjustments or modifications were made to the half-times or M-values. The dive conditions were 40 and 60 fsw to the NDL followed by a second dive to the NDL at 100 fsw after several different surface intervals, and a first dive of 100 fsw to the NDL followed by second dives at the NDL for 40 and 60 fsw.

Table 1. Calculated NDL's and Maximum Bubble Radii for Normal and Reverse Dive Profiles at 40 fsw and 100 fsw.

1st Dive		SI	2nd Dive	2nd Dive Bottom Time for different models											
				dciem				dsat				usn.air			
Depth	BT		Depth	model		table		model		table		model		table	
ft	min	hours	ft	NDL	BR	NDL	BR	NDL	BR	NDL	BR	NDL	BR	NDL	BR
40	30	0.5	100	10	*32.2*	10	*31.8*	18	*40.6*	12	*34.1*	22	*44.9*	11	*32.8*
40	30	1.0	100	11	*31.2*	11	*30.8*	19	*39.4*	14	*34.5*	23	*43.0*	11	*30.8*
40	30	2.0	100	12	*30.9*	11	*29.8*	19	*38.7*	17	*36.7*	23	*42.2*	15	*34.5*
40	30	4.0	100	12	*30.9*	13	*32.0*	19	*38.5*	17	*36.4*	23	*42.0*	22	*41.1*
40	60	0.5	100	9	*38.5*	9	*38.3*	18	*49.5*	6	*33.9*	21	*53.2*	n/a	
40	60	1.0	100	11	*36.6*	9	*34.1*	19	*47.2*	11	*37.2*	23	*51.5*	3	*27.9*
40	60	2.0	100	11	*31.7*	10	*30.0*	19	*41.8*	14	*35.6*	23	*46.9*	11	*31.3*
40	60	4.0	100	12	*30.6*	11	*29.2*	19	*38.5*	17	*36.4*	23	*42.1*	15	*34.3*
40	90	0.5	100	8	*46.7*	7	*45.1*	16	*55.3*	2	*42.0*	19	*57.9*	n/a	
40	90	1.0	100	10	*43.4*	8	*42.1*	19	*54.0*	8	*42.1*	23	*57.8*	n/a	
40	90	2.0	100	11	*38.7*	9	*38.5*	19	*48.1*	14	*41.8*	23	*52.3*	3	*39.2*
40	90	4.0	100	12	*30.2*	10	*28.4*	19	*40.1*	17	*37.6*	23	*45.2*	15	*34.4*
40	120	0.5	100	8	*52.9*	n/a		14	*59.1*	n/a		18	*62.3*	n/a	
40	120	1.0	100	9	*52.7*	7	*52.2*	19	*59.1*	6	*52.0*	23	*62.7*	n/a	
40	120	2.0	100	11	*50.2*	8	*49.8*	19	*53.4*	12	*50.4*	23	*57.2*	n/a	
40	120	4.0	100	11	*39.6*	9	*39.6*	19	*45.5*	17	*42.6*	23	*49.8*	11	*39.5*
40	150	0.5	100	7	*59.7*	n/a		12	*61.9*	n/a		17	*65.7*	n/a	
40	150	1.0	100	9	*59.8*	n/a		19	*63.3*	5	*59.0*	23	*66.9*	n/a	
40	150	2.0	100	10	*57.9*	7	*57.3*	19	*59.8*	12	*58.2*	23	*61.3*	n/a	
40	150	4.0	100	11	*49.1*	9	*48.9*	19	*50.6*	17	*50.1*	23	*54.2*	11	*49.0*
100	10	0.5	40	125	*57.6*	115	*55.6*	123	*57.2*	118	*56.3*	179	*65.9*	163	*64.0*
100	10	1.0	40	128	*57.4*	125	*56.8*	128	*57.5*	124	*56.6*	184	*66.0*	163	*63.4*
100	10	2.0	40	133	*57.2*	125	*55.6*	135	*57.6*	131	*56.9*	190	*66.3*	175	*64.2*
100	10	4.0	40	138	*56.9*	136	*56.5*	139	*57.2*	131	*55.5*	196	*65.8*	193	*65.5*
100	15	0.5	40	112	*57.3*	100	*54.9*	113	*57.5*	109	*56.7*	168	*66.0*	151	*63.9*
100	15	1.0	40	118	*57.2*	107	*55.0*	122	*58.0*	118	*57.2*	176	*66.4*	163	*64.6*
100	15	2.0	40	124	*56.7*	115	*54.8*	132	*58.2*	131	*58.0*	186	*66.5*	175	*65.0*
100	15	4.0	40	133	*56.3*	125	*54.8*	139	*57.5*	131	*56.0*	194	*66.2*	183	*64.6*
100	20	0.5	40	n/a		n/a		102	*57.9*	100		157	*66.4*	139	*64.0*
100	20	1.0	40	n/a		n/a		116	*58.8*	113		168	*66.7*	151	*64.5*
100	20	2.0	40	n/a		n/a		129	*59.1*	124		181	*66.9*	163	*64.5*
100	20	4.0	40	n/a		n/a		136	*58.3*	131	*56.9*	193	*66.5*	183	*65.2*
100	25	0.5	40	n/a		n/a		n/a		n/a		145	*66.5*	113	*62.1*
100	25	1.0	40	n/a		n/a		n/a		n/a		160	*67.0*	127	*62.6*
100	25	2.0	40	n/a		n/a		n/a		n/a		177	*67.3*	151	*63.9*
100	25	4.0	40	n/a		n/a		n/a		n/a		191	*66.9*	175	*64.8*

Table 2. Calculated NDL's and Maximum Bubble Radii for Normal and Reverse Dive Profiles at 60 fsw and 100 fsw.

1st Dive		SI	2nd Dive	2nd Dive Bottom Time for different models											
				dciem				dsat				usn.air			
Depth	BT		Depth	model		table		model		table		model		table	
ft	min	hours	ft	NDL	BR	NDL	BR	NDL	BR	NDL	BR	NDL	BR	NDL	BR
60	30	0.5	100	9	35.3	9	35.3	18	45.3	8	34.9	22	49.8	3	33.14
60	30	1.0	100	11	33.3	9	32.7	19	43.1	12	33.9	23	48.0	7	27.9
60	30	2.0	100	12	30.9	10	28.8	19	39.1	14	34.0	23	43.3	11	30.32
60	30	4.0	100	12	30.7	11	29.2	19	38.5	17	36.5	23	42.1	18	37.34
60	40	0.5	100	8	39.1	8	38.7	17	49.1	4	37.2	20	52.5	n/a	
60	40	1.0	100	10	37.5	9	31.0	19	48.4	9	36.7	23	52.5	3	34.67
60	40	2.0	100	11	32.6	10	31.0	19	42.9	14	36.7	23	47.8	11	32.27
60	40	4.0	100	12	30.6	11	29.7	19	38.6	17	36.5	23	40.9	15	34.37
60	50	0.5	100	8	43.7	8	43.9	15	52.1	2	39.4	18	55.2	n/a	
60	50	1.0	100	10	41.6	8	39.4	19	53.3	7	39.0	23	56.5	n/a	
60	50	2.0	100	11	36.7	9	35.2	19	46.9	14	40.4	23	51.1	7	35.3
60	50	4.0	100	12	30.8	10	28.3	19	38.9	17	36.6	23	43.7	15	34.44
100	10	0.5	60	26	33.6	31	36.8	46	46.9	41	43.3	56	51.9	36	40.12
100	10	1.0	60	29	33.4	35	37.8	50	47.8	44	43.5	60	52.6	36	38.44
100	10	2.0	60	31	33.4	35	35.1	53	47.2	49	44.2	63	52.5	43	40.49
100	10	4.0	60	32	33.5	40	36.5	54	45.2	49	41.6	65	51.2	49	41.57
100	15	0.5	60	23	35.9	27	38.9	43	48.8	36	45.0	51	53.0	30	40.82
100	15	1.0	60	27	36.1	29	37.6	49	50.0	41	45.7	57	54.5	36	42.14
100	15	2.0	60	29	33.3	31	34.5	53	49.1	49	47.0	62	54.3	43	42.91
100	15	4.0	60	31	33.3	35	34.9	54	46.2	49	42.7	65	52.0	49	42.66
100	20	0.5	60	n/a		n/a		38	50.5	30		46	54.8	24	41.92
100	20	1.0	60	n/a		n/a		47	52.4	38		55	56.4	30	42.59
100	20	2.0	60	n/a		n/a		53	51.7	44		62	56.4	36	41.48
100	20	4.0	60	n/a		n/a		54	47.9	49	44.5	65	53.8	49	44.49
100	25	0.5	60	n/a		n/a		n/a		n/a		41	56.1	8	43.2
100	25	1.0	60	n/a		n/a		n/a		n/a		52	58.2	16	41.27
100	25	2.0	60	n/a		n/a		n/a		n/a		61	58.2	30	41.14
100	25	4.0	60	n/a		n/a		n/a		n/a		65	55.4	43	42.89

The NDL varies greatly depending on what model is being used. With a 120 min halftime RNT, the U.S. Navy tables do not allow a reverse dive profile for short surface intervals. The PADI tables, based on a 60 min RNT compartment, are more liberal and will allow dives that the USN will not. The DCIEM model, which does not work on RNT's, allows a greater bottom time for shorter surface intervals than the other two tables. However, it is a more conservative model for repetitive no-decompression dives and gives shorter NDL's than the other two tables for longer surface intervals. The DCIEM (1992) repetitive dive tables give longer NDL's because some adjustments have been made to approach the first dive no-decompression limits at long surface intervals. The H/W/S models give very liberal NDL's that quickly approach the first dive's NDL's.

The max BR calculated for these dives shows that for a reverse dive, the first dive should not be done at or close to the NDL, if we assume a 40 µm max BR as a threshold for high risk. If a reverse dive is planned, then in order to control the risk, it will be necessary to back off from the NDL for the first dive. For a reverse dive, the bottom time of the first dive is important.

On the other hand, a deep dive followed by a shallower dive shows a different response. All models and tables now predict that the second dive is possible. The 60 min halftime RNT gives more liberal NoD times. The DCIEM model is probably too conservative and does not allow much time for long surface intervals at 60 fsw. If we look at the maximum bubble radii, it is more consistent with our belief that longer bottom times will give greater risk. In this case, it may not be wise to select the table or computer that will give the longest bottom time on the second dive.

An interesting observation for reverse dives is that regardless of whether or not bottom time of the second dive is long or short, the calculated max BR does not vary greatly when the gas loading on the first dive is high. For example, a first dive of 40 fsw for 90 minutes and a second dive of 100 fsw after a 2 hr surface interval shows that regardless of whether the NDL is 3 minutes as in the USN predictions or 14 min as in the PADI predictions, the max BR is approximately the same. However, the time to reach max Br is different. Figure 7 shows the detailed bubble evolution for these dives. A short deep second dive that is only 3 minutes long is not sufficient to collapse the bubbles generated by the first dive, and, hence, the starting base for a gas bubble from the second dive is much higher than expected. On the other hand, a longer bottom time second dive gives the bubbles generated by the first dive the time to be compressed and dissolved away. In this particular case, both the 3 min USN dive and the 14 min PADI dive give about the same maximum bubble size.

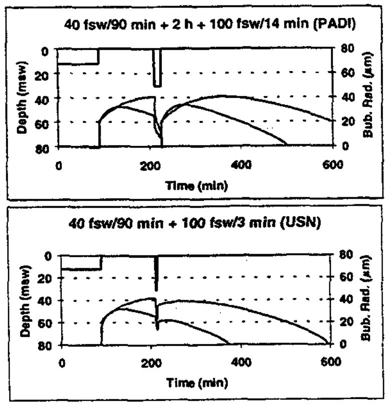
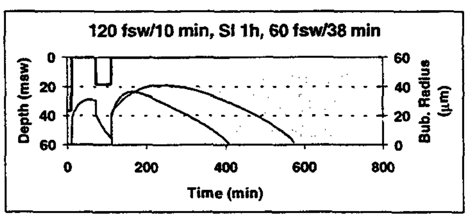


Figure 7. Comparison of short and longer deep dives.

This is not a problem peculiar to deep dives following a shallow dive. The same thing could happen with a short shallow dive following a long deep dive where the gas loading from the first dive can be substantial. Another factor comes into play for a shallow second dive. The depth of the second dive may not be sufficient to allow all the bubbles arising from the first dive to be dissolved away. Both of these conditions are illustrated in Figure 5.

Comparison of Predictions with Real Dive Data

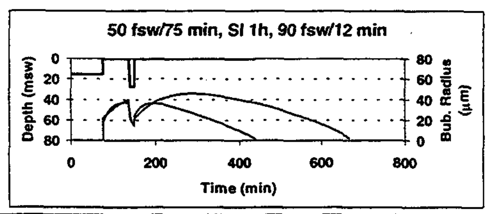
During the development of the DCIEM air diving tables, two repetitive dive profiles, a normal deep first dive followed by a shallow second dive, and a reverse dive profile were tested. Figure 8 shows the normal repetitive dive sequence, a dive to 120 fsw for 10 min followed by a dive to 60 fsw for 38 minutes after 1 hour. The max BR after the dives was around 40 µm. This sequence resulted in a relatively moderate stress sequence with one of 17 subjects reporting Grade 3 bubbles. There were no cases of DCS.



Maximum Bubble Grades Observed					
DCIEM Model	No. of Subjects				
Bubble Grades	0	1	2	3	4
1st Dive (14 subj)	12	1	0	1	0
2nd Dive (14 subj)	10	1	2	1	0

Other Tables	
DSAT RDP	USN 57
120/10	120/10
60/44	60/35

Figure 8. Results of experimental deep/shallow dive.



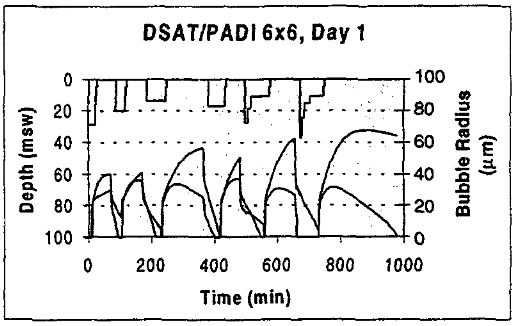
Maximum Bubble Grades Observed					
DCIEM Model	No. of Subjects				
Bubble Grades	0	1	2	3	4
1st Dive (17 subj)	11	1	2	3	0
2nd Dive (17 subj)	9	1	1	5	1

Other Tables	
DSAT RDP	USN 57
50/75	50/75
90/9	N/A

Figure 9. Results of experimental shallow/deep dive.

Figure 9 shows a reverse dive profile, a dive to 50 fsw for 75 minutes followed by a 90 fsw dive for 12 minutes. The max BR after the second dive was around 45 µm. This was a somewhat more stressful dive with three divers on the first dive with Grade 3 bubbles and 5 divers on the second dive with Grade 3 bubbles, suggesting that the second dive was more stressful than the first. The PADI tables allowed only 9 minutes for the second dive and the USN tables did not allow a repetitive dive. Although this is a very limited comparison, it does suggest that the choice of 40 µm may be appropriate as the threshold between low-risk and high-risk repetitive dives.

A third example (Figure 10) has been taken from the PADI/Diving Science and Technology trials for the Recreational Dive Planner (Hamilton *et al.*, 1994). Phase II of the trials involved 6 dives a day for 6 days. Only the first day is shown here with the last three dives being reverse dive profiles. A similar sequence was conducted on the second day and the third day of trials was discontinued because of a case of DCS. Of the six dives, the third to the sixth dives all resulted in max BR of greater than 40 µm. After all these dives, Grade 3 bubbles were reported in some of the subjects. So this is also consistent with dives that have a predicted max BR greater than 40 being of high decompression stress. More decompression would have been desirable for the last dive since the max BR was about 65 µm.



Grade 3 Doppler bubbles after 3rd, 4th, 5th and 6th dives

Figure 10. Bubble evolution for PADI experimental dives.

Summary

The risk of reverse dive profiles depends on what decompression algorithm is used to predict the second dive requirements. This same comment can be made for all repetitive dives, not only reverse dives. If reverse dive profiles are planned, it should be planned to dive conservatively, and the first dive should not be done at or near the NDL. An alternative would be to consider the use of oxygen decompression such as used by pearl divers. It should be kept in mind that there may be additional risks involved when doing a very short deep dive. However, this could also be true for a shallow dive following a deeper first dive.

In closing, analysis tools, like the bubble model described here, give us a more intuitive insight into the risks involved in reverse dives.

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II. Physics/Physiology Session Discussion. Charles E. Lehner, Moderator

H. Van Liew: Bruce, would you be more precise about phasing out Haldane models? Do you mean phasing out M-value type models?

B. Wienke: Yes. I think that clearly one of the most important things is that in diving it is not always the best thing to bring the diver up as fast as you can, á la Haldane staging. It just is not the best way to do it. Models that do phase dynamics tend to drop a decompression stop much lower. I think if you look at the experiences of the technical diving community, they are doing that. Jim Bowden, who has set the world's record for deep excursions, is diving a phase model-phasing algorithm, and he has come up. I think it is time for us to look at how to change our tables and the way we do diving. Haldane has been a great guide. He has allowed us to do a lot of things with diving, but I think it is time to change. It is really time to start building in some modern ideas and some modern approaches to what is going on. I am not saying that we have all the answers, that is for sure. The body is so complicated, to even try to model it to any appreciable degree is beyond our capabilities. But we do know that there is a basic physics law here that is working independent of how complex bubble formation is, where the sites are and how the biochemistry and all the rest feeds into it. There is a simple fact that once you form a bubble, it is better to keep it down there than it is to bring it up. That is all I am saying about phasing out. I hope I haven't offended anybody by saying that.

J. Lewis: Hugh, I wonder what the implications are for repetitively deep dives. It would seem as though if I followed out this reasoning and believed it, that would be the safest of all because it would be crushing micronuclei on both dives. Yet we know from experimental evidence that that is not so.

H. Van Liew: Please don't believe my theory.

R. Vann. Hugh, the study that we did about crushing nuclei or reducing decompression sickness in rats was really to test observations that other people had already made. First of all, Walder's theory that was pointed out from 1968, and which he tested in Evans and Walder in 1969, was followed up by additional work by Daniels and Hemmingsen and others. So there is quite a body of literature out there that supports the notion that you can eliminate gas nuclei by applying a crushing pressure. This was in shrimp and in living tissue *in vivo*. The difference between our studies and previous studies was that the previous studies had looked at visible bubbles, whereas we looked at the incidence of decompression sickness and inferred that the mechanism was decompression bubbles.

H. Van Liew: I appreciate experiments in shrimp and in gelatin and in various microorganisms or other invertebrates, but I think we have to say we don't really know for sure until we have dealt with mammalian tissue.

R. Vann: That was our goal with the rat experiments.

H. Van Liew: Yes, indeed. That is what I meant to imply.

R. Vann: One other notion that you might want to consider in your paradox that the bubbles can't exist is that maybe they behave exactly as Laplace's law would state and they have limited lifetimes. So that what you have is a dynamic equilibrium between the creation and the disruption of these precursors or gas nuclei. Deep dives perhaps might have an effect on the elimination or the reduction in the generation of gas nuclei, as NASA is currently testing for the development of the Space Station decompression procedures. We have noted that there is microgravity itself or gravity appears to be a risk factor for decompression sickness, which might indeed influence the generation of gas nuclei. The dynamic equilibrium may be an explanation, and a very simple one, that you don't require any fancy support through either surfactants or crevice nuclei.

H. Van Liew: I hope you will agree with me that what we need is studies that can prove some of these points.

R. Vann: I agree with you.

H. Van Liew: Ron, I think that the DCIEM bubble model is what I call the few bubble case. You aren't considering many bubbles per unit of tissue.

P. Tikuisis: Actually, our bubble model can be extrapolated to a many bubble case. It is just that we are looking at bubbles singly versus the cluster. But many of the dynamics that go into the prediction should be applicable. We do constrain bubble growth by imposing a finite volume condition, and that is analogous to having a cluster of bubbles, where each bubble is in essence confined to a finite volume.

H. Van Liew: The point I was trying to make was that I think that you have few bubbles per ml of tissue in the model that you presented, and the correspondence with reality seemed to be pretty good. And, that would be evidence that maybe my analysis can forget about the many bubble case.

V. Flook: I wanted to make a comment following Hugh's paper. First of all, I thank him for introducing my paper. But I also suggest that we are limiting ourselves if we try to think only in terms of gas micronuclei. There could be solid micronuclei. That was my main comment. I also wanted to endorse Dick Vann's statement that if it is gas micronuclei that are important, then we should keep an open mind on the possibility that they are continuously being produced in the body and that we have a dynamic equilibrium which we simply disturb when we use a crushing dive.

D. Yount: I want to make several comments. First, micronuclei are spherical. These are some photographs of micronuclei. Secondly, when you crush micronuclei, they get smaller. They do not go away. They just get smaller. Number three, old bubbles never die, they just become stable gas nuclei. The reason is that if they are formed in tissue, they are immediately surrounded by surfactants. The fourth comment is we should consider the possibility that instead of one micronucleus making one large bubble, that one primary bubble actually generates many secondary bubbles. There is a famous paper or book actually by Albano, where he sees rosaries of bubbles or chains of bubbles, and an experiment by Cowley, Allegra and Lambertsen where they watched a time course of this. I mentioned this in a paper I gave at the Inert Gas Counter Diffusion Workshop. So, rather than one nucleus making one bubble, maybe one nucleus makes ten small bubbles.

G. Beyerstein: I hear through all these papers talk about the formation of a bubble through some sort of an application of decompression stress. But I think it is an obvious statement that it is not the exposure that creates the bubble, it is the quality of the decompression. Nobody said anything about the quality of the individual exposures as they are undergoing decompression, even if it is a NoD dive, and no mention of ascent rates. I think that is a critical element we have to consider that keeps a bubble from forming. The other point that I hear is that we have no data. The data are scarce. I think it becomes a question then between practicality and scientific endeavor, where scientists are used to thinking of the quality of data, whereas we in the commercial industry can give you quantity of data, which may not conform to laboratory standards but can still, and allusion was made to that in one of the papers, supply some very useful results.

E. Baker: Bruce had used the term 'phasing out Haldane models' and in fact we are doing that, primarily the M-value aspect of the Haldanean models. We still certainly rely on the exponential behavior of gas loadings in our calculation of gas loadings. What we are comparing those against now are a different set of criteria being, for example, the varying permeability model as opposed to traditional M-values. I also wanted to comment on the role of technical diving in our evolution of decompression modeling in the last few years. Our experience has shown that a lot of the model predictions of the Varying Permeability Model seem to be pretty close to what we are experiencing in the field. For example, the practice of deep stops has become prevalent. There is still an issue about how do you determine what those deep stops are and where they should be. But just the fact that we are doing them seems to support predictions of the Varying Permeability Model. What I find interesting is the fact that if you do a properly executed deep stop profile, it requires less time at the shallow stops, which runs completely counter to your traditional M-value and your practical experience. But, in fact, people are doing these profiles and getting away with it. That is an area that should probably be looked at a little more. From the pressure graphs, what we are finding is that the ideal profile according to VPM would be basically parallel to the ambient pressure line. Your gas loadings are tracking a fixed gradient that corresponds with a certain minimum initial radius and bubble number, and as long as you don't exceed that, you don't have problems. You don't form a lot of bubbles. My own practical experience with repetitive cave diving (I run my own VPM tables for that) are dives to 95 and 100 feet of seawater depth for anywhere from 40 to 90 minutes. You can do those day after day after day with no problems. This is using oxygen for decompression. So basically my take on it is if you don't allow the bubbles to form in the first place, you don't have problems. In the technical diving community, we are not physiologists and we are not physicists. I happen to be an engineer, but we are opportunists and are going to look to all the models and the evolution that has taken place and we are going to pick out what seems to work the best. We have had some pretty good results with the VPM so far.

H. Van Liew: Bruce, if I understood your talk properly, towards the end you said that you had run through all the different models - that they all gave the same answer in certain regions of the possibility for dives, but that they diverged from each other in some other region. Well, I think that is great. Where they diverge, you begin to learn something. Where they are all together, you don't learn something. I wanted you to tell just what region it was where they diverged.

B. Wienke: The model predictions that I had on the screen and from the calculations I ran, the results shown were only for the profiles that were appropriate for this workshop (per Michael Lang). The deltas make model differences. By the deltas, I mean increments between the first and second dive. You start to see model differences around 50, 60 or 70 feet of seawater. The Haldane models essentially clustered and required roughly the same decompression time. The phase models also clustered in that region and also required similar decompression schedules. The particular model that I use, the RGBM, you will notice that it required slightly greater decompression stops. That comes about, because the phase, if you increase the surface interval or a decompression, will grow because you have decompressed it. But gas will then, as the surface interval gets longer, diffuse out and the bubble will shrink. That was built into the RGBM, but it wasn't built into the calculations that I ran for the other two models. So what I am saying is that the delta increments and model differences start to show up when the deltas are on the order of 50 or 60 feet of seawater and we start going deeper. John pointed out that it is a waste of time to worry about deltas when you are diving in 50 or 40 feet of seawater unless you are taking about rapid, explosive decompression. I haven't finished that analysis, and I didn't get a chance to bring it here because I wanted to focus just on these dive profiles. Since we only had 20 minutes, I figured I couldn't cover it. I will finish this write it up in some kind of report or memo, and will be glad to send it to you folks if you want to see what those are. What I will do is essentially take the same approach that I did here, and I will start the stage deeper and then look at what happens.

H. Van Liew: Can I ask if you are talking about bubbles in general?

B. Wienke: The whole business of changing pressure regimes on bubbles that are moving we can look at in the laboratory. We can take a fluid, shock it, have it under a certain pressure, generate cavitation nuclei (because of bends and weird configurations in a pipe), and we can watch them in the flow pattern. Some of them will, after initial shocking, go away very quickly, but some of them will persist. Then, if we reduce the pressure, we form new cavitation nuclei. Not all the old ones go away. New ones are formed. My colleagues' inference in looking at cavitation nuclei, under high-speed flows and high pressure/high temperature regimes (not the kind of stuff that most divers are subjected to) is that it doesn't really matter whether your first shock imparts a certain high pressure and the second shock is less or whether the second shock is stronger and the first shock is less corresponding to a reverse dive profile. The production of cavitation nuclei under those circumstances is sort of transparent to what is going on. I am saying people feel that for the reverse dive profiles we are looking at for this range of recreational or scientific diving, it probably doesn't matter. I would suggest that experiments in the laboratory with cavitation nuclei suggest that this is probably true, even at higher temperatures and higher pressures. But the body is a lot more complex than a flowing fluid, and we have got all kinds of things going on which makes it hard for us.

J. Lewis: Bruce, I want to go back to the models. You said you have taken the four or five models, and I remember you distinctly using the word 'tweaking parameters.' But what is the reason then that they all coalesce in predictions? Is it because they are all using NoD limits on single dives as the basis and is it more than just NoD dives or are they using some broader basis?

B. Wienke: For the phase models, it is the short amount of time that allows the phase to expand. Ron's slide showed multiple deep diving, where the phases are allowed to expand. If I were to run this analysis out to four or five dives, we might see some model differences even in this rather shallow area.

J. Lewis: But the empirical basis, they all have empirical parameters. Is that based on acceptable no decompression times. Is that already set?

B. Wienke: Yes, that is a good point, John. What I did was to normalize all the parameters in the model to the decompression limits that I indicated, 100 feet for 15 minutes, and then I could compare features to features when I develop the models.

J. Lewis: Right. And having done that on single dive NoD limits, the question is how does the repetitive control work, is there any empiricism involved in that?

B. Wienke: No, because I let these profiles go and decompression was required. You saw that slide.

J. Lewis: So the repetitive controls then are really a test for the difference between the models. If the only empiricism is involved with the no-decompression limit agreement, then that is really quite interesting if the repetitive controls have any resemblance to one another.

B. Wienke: They do. And this is just once. But, as I say, I really think that if we went further and further out, we would start to see things. This particular model that I have been referring to has sprung out of a lot of different things; it will be available on the Net. Suunto has encoded a version in their new dive computer called the Vyper. What we have done is to tweak parameters so that the analysis we do for the parameters is consistent, say, with Doppler scores peaking an hour or so after repetitive dives. Consistent maybe, if you want to make it that way, with delta P's for reverse dive profiles on the order of 60 feet. Nothing happens. But until you hit 60 feet, there are no modifications to the central Vyper algorithm. So we have tweaked parameters there. But in this comparison issue, I wanted to make it as simple as possible.

D. Yount. This is a quick response to John's question. With any model, you have some parameters. Generally, models are adjusted so that they fit the commonplace dives. So they should all agree in the region where they have adjusted their parameters. The real test of the model is how well does it extrapolate to some unknown region, and that is why it is so interesting with Bruce's data to look at those extreme cases, that is where you can really test the models.

J. Lewis: I think it is quite profound that if you test the NoD limits to the needs for the empiricism, that the repetitive control, at least moderate repetitive controls, are all consistent with each other.

D. Yount: The parameters were not adjusted for repetitive control. In a way, that is an interesting extreme case.

R. Moon. Bruce, could I get you to elaborate on what I think I have heard? What I heard you say, I think, is that within relatively small delta P's that all of the models that you have tested produce under any circumstances deep versus shallow first, or shallow first and then deep about the same predicted decompression requirements. Under larger delta P's, what is the difference between deep versus shallow, versus shallow versus deep? In other words, I understand that the models may behave differently, but leaving that aside, is there any suggestion that those two circumstances may produce different decompression requirements?

B. Wienke: I have the feeling that the Haldane models will cluster together no matter what I do for delta P, and the phase models will also cluster together. But the Haldane models and the phase models, as I increase the delta P, are going to diverge in the decompression formats that they suggest at the end of the repetitive dives, whether it is four, five, six or eight dives. I have actually run this. I just haven't collated it in a coherent fashion that I want to throw it up on the board. What you are going to see is Haldane models going one way for these repetitive dives, and you will see phase models going the other way. But the phase models are typically going to be what everybody here has been saying, deeper stops and shorter decompression times overall, because they are focusing on different dynamics as far as staging divers than Haldane is. So I think you will see essentially the same kinds of phenomena, but I think you are going to see that the classes of models will diverge as delta P gets larger.

B. Wienke: On these exercises that we do at the laboratory, we have a lot of leeway into how we schedule diving. Our concern is not to validate schedules and things like that. We may have to look at a potential nuclear device or a biological canister, and we have to assess, first of all, what is in there. So we have to take some measurements and we also bring some instruments down to see what is coming out of it. Then we call on the expertise of other people who know about this type of terrorist activities. Our experiences have been that whether we are diving nitrox or trimix or whether it is a deco dive or a number of repetitive insertions with a bunch of us, we generally don't exceed delta P's of about 50 or 60 feet of seawater, because the data we show for the 60 dives was an incidence rate of 4 out of 60, about 6 or 7 percent. As delta P went to 80 and 120, we had DCI incidence rates that were high enough that we couldn't live with. Generally, we don't do that, but we may have to. The delta P on the order of 60 feet of seawater is probably something that we have found to be important. When I do modeling work or when I concoct schedules, I try to keep that in mind. You will see model divergences once the increments, the reverse dive profile increments, are 60 or 70 feet. This is built into the Suunto implementation for recreational diving and actually uses some of the data from that table that I showed you.

W. Gerth: It is important in considering this divergence of model predictions or prescriptions for how to do decompression that we have to separate the issue of decompression efficiency versus the safety of a decompression. Different decompressions can be scheduled that are longer than necessary, but they are still safe, or shorter, and still safe. So it depends on how you allocate stops most efficiently.

ACCORDING TO A PHYSIOLOGICAL MODEL

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This model is based entirely on data available in the physiological and physical literature. It has been used to study the effect of reversing the order of a 100 ft dive and a 60 ft dive. Two patterns of bottom time have been studied: 100 ft for 15 min and 60 ft for 30 min, for bottom times determined by the USN Tables NoD limits for repetitive dives. The conclusion is that reverse diving does not routinely carry a risk of more decompression bubbles - in some situations the reverse order results in less bubbles.

Introduction

The model that I use to study decompression is simple in concept but to be used to its full potential requires considerable knowledge of physiology. The basis is a simple model of gas dynamics well proven in terms of uptake and distribution of inert gases (Mapleson, 1963). This approach treats the body as if it were a number of compartments each containing tissues that have identical properties of gas dynamics. Onto this is grafted, for each compartment, the Van Liew-Burkard model of bubble dynamics (Van Liew and Burkard, 1993). The minimum number of compartments required to give satisfactory simulation of gas dynamics is 8. However the model is designed in such a way that it is easy to divide any of the 8 to allow any tissue (or indeed any small section of tissue) to be treated as a separate compartment to study the effects of changes in conditions. For example, an extra compartment can be added to take account of areas of body surface subjected to heating through use of a hot water suit. Taking a step further in complexity, given patience and persistence to amass and evaluate the relevant data, it can be used to study the effect of differential skin temperatures such as might arise in a less than perfect suit.

In addition to looking at what happens within the compartments, the model can be used to predict what happens in the venous blood draining the compartment and by using appropriate weighting, what happens in pulmonary artery blood. This is very useful for comparison with precordial bubble counts.

All parameter values required by the model are drawn from the physiological literature. This effectively sets limitations in that, given the complexity of the human body and the lack of detailed experimental data about relevant aspects of its function, the model should always be used wisely. That is accepting the fact that we cannot reproduce reality, accepting that results from it can refer only to what will happen on average for groups of divers undergoing identical experiences. These limitations can be offset by, for example, estimating the confidence limits based on known ranges of normal physiological values and perhaps, most importantly, by always presenting and interpreting results relative to what is known. For example, if a particular exposure is known to give few bubbles, then does the predicted performance for an unknown procedure suggest a few more or lots more bubbles? It is easy to believe that the numbers that come out from a model tell the truth, especially if you have confidence in every number which has gone into the calculation. It takes an effort to remember that each human body has a very wide range of variability built in and that no person is identical to any other person.

In terms of decompression procedures that this model can simulate, the scope is limited only by the data and the time available to build the profiles. To date it has been used to study: no-decompression dives (both planned and accidental), surface supplied air dives, Sur-D decompressions, heliox saturation decompressions, excursions during heliox saturation dives, nitrox and mixed gas exposures, treatment tables, submarine escape exposures and, at the other extreme, compressed air exposures in caisson workers that approximately correspond to saturation air dives with severely accelerated decompressions.

Confidence in the model's ability to predict what might happen in the average person has increased over the four years of use as the opportunity has been taken to compare predictions with actual outcomes. The first comparisons were made with average bubble counts, recorded by trans-oesophageal ultrasonic scanning, in animals exposed to experimental hyperbaric profiles. Several of the commonly used operational profiles contributed to that study together with some more experimental procedures. Agreement was good enough to make it possible to convert from model prediction to bubble counts for anaesthetised pigs. It has also been used to rank outcome, in terms of predicted pulmonary artery bubbles, for experimental exposures in humans, with good agreement with the experimental data once the exact physiological conditions in the experiments were allowed for. It predicted bubbles in compressed air workers for profiles believed to be bubble free; later measurement of bubbles using both Doppler and ultrasonic scanning confirmed the model's prediction. The gas dynamics part of the model has been tested in a number of situations by comparison with inert gas content of blood with very close agreement. This has been done for both the uptake and washout phase in mixed venous blood for a range of decompression profiles, in arterial blood of humans during the rapid compression of a submarine escape procedure, in animals, venous and arterial blood, during the rapid decompression of submarine escape both during air breathing and after a switch to oxygen. More recently the model was used to assist in the design of human trials of Sur-D decompressions aimed at reducing variability between subjects. This trial was successful in that objective and median pre-cordial bubble scores were within one grade of predicted values on the Kisman-Masurel scale. Unfortunately, most of this work is published, at the moment, only as confidential reports to the clients, but all details can easily be supplied in a non-confidential format to interested parties. Ultimately, this will all be written up and put into the public domain.

Results

For the purposes of this work, I have chosen to look at what happens in individual tissue types rather than at pulmonary artery gas that, though ideal for comparing with Doppler or scanning bubble assessment, is after all only a whole-body average. The four compartments that I want to focus on are:

- **time constant 1.9 minutes,** which represents viscera and in particular could be taken to represent the grey matter of the brain;
- **time constant 5.3 minutes** representative of brain white matter;
- **time constant 51 minutes** for resting muscle and skin under normal thermal conditions; and
- **time constant 211 minutes** to represent fatty marrow and fat.

Table 1 gives the predicted volume of gas carried as bubbles per ml of tissue, or of venous blood draining that tissue, for Series 2 100ft 15 minutes and 60ft 30 minute exposures. Both the 100-60 and 60-100 exposures are given. The final column gives the ratio of the volume of gas carried as bubbles for the 60-100 exposure compared to the 100-60. The first conclusion from these numbers is that in the average diver all tissues are likely to form bubbles. The second conclusion is that, for the slower compartments, less gas is carried in bubbles when the surface interval is longer. The surface interval makes no difference to the gas in bubbles in the fast compartments, and this is because even the shortest surface interval, 1 hour, is long enough to ensure that each of the two exposures is a new event for these tissues. Because of this, the surface interval has no effect on the consequences of reversing the order of the dives. In fact for the fast tissues, the second dive is always the one that determines the formation of bubbles in these tissues; doing the deepest dive second will always give more bubbles at the end.

The ratios for the slower compartments also show that the deepest dive second will give more gas in bubbles, but, for example, for resting muscle the extra gas is only on the order of 20%. Again, the benefit of the increased surface interval is apparent. For the slowest tissue, the fat, the order in which the dives are done is more important. Almost twice as much gas is carried as bubbles if the deepest dive comes second. For these tissues the apparent effect of increasing the surface interval is to make the consequences of the reverse dive worse. In fact, what happens is that the beneficial effect of the increased surface interval is greater for the 100ft – 60ft than for the 60ft – 100ft dives. This is so because 15 minutes at 100ft does not give a sufficient gas load in the slow tissue for bubbles to form on the first decompression, and gas washout during the surface interval takes place at the appropriate rate for the tissue time constant. The 30-minute dive to 60ft does give enough gas for bubbles to form so when the

60ft dive is the first dive, there are bubbles in the tissue throughout the surface interval and removal of inert gas is considerably slower. Therefore, the second dive is started with a very high gas load.

Table 1. 100ft for 15 mins, 60ft for 30 mins. Gas carried in bubbles (ml/ml * 10⁴)

Time constant (mins)	100-60	60-100	Ratio
Surface interval 1 hour			
1.9	2.05	4.3	2.08
5.3	14.3	30.4	2.13
51	105.0	129.9	1.24
211	68.8	133.6	1.94
Surface interval 2 hours			
1.9	2.05	4.3	2.08
5.3	14.3	30.4	2.13
51	97.1	117.4	1.21
211	62.6	127.1	2.03
Surface interval 3 hours			
1.9	2.05	4.3	2.08
5.3	14.3	30.4	2.13
51	89.4	105.2	1.18
211	56.6	120.7	2.13

Figure 1 is presented to demonstrate the extent to which the formation of bubbles influences removal of gas from the body. This is for muscle at rest. The dotted line at the top of the figure shows the predicted bubble radius starting from the beginning of the initial decompression from 100ft. The solid line on the lower graph shows the arterial inert gas partial pressure and the shape corresponds to the pressure profile. The bubbles form at the end of the decompression and after reaching a maximum size decrease very slowly throughout the surface interval and are reduced very little by the start of the next compression. The line with the long dashes on the lower graph shows the tissue and venous blood inert gas partial pressure dropping as the bubbles form, reaching an equilibrium just above arterial partial pressure once bubbles have reached the maximum size. The tissue partial pressure then remains unchanged throughout the time that the bubbles decrease in size, and a dynamic equilibrium has been reached.

On the second compression the bubbles are squashed; the inert gas in them is expelled back into the tissue or blood, and this gives an immediate rise in inert gas partial pressure that increases further during the second dive, almost to saturation for that depth. The line with the shorter dashes shows what would happen if no bubbles formed and inert gas removal from the body was governed by the same factor that determines gas uptake. When no bubbles form, inert gas load at the end of the second dive is much less than when bubbles do form. Removal of gas from the body is proportional to the tissue (or venous blood) to arterial inert gas partial pressure gradient. On the figure this is displayed as the area bound by the solid line representing arterial partial pressure and the dashed line representing tissue (or venous) partial pressure. This area is obviously very much greater when there are no bubbles (short dashes) than when there are bubbles (long dashes).

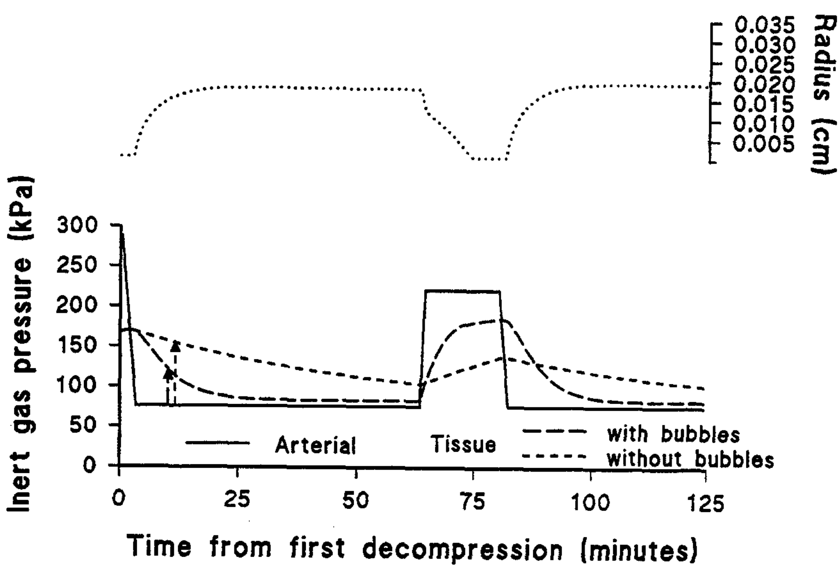


Figure 1. Bubble growth, arterial inert gas partial pressure and tissue inert gas partial pressure for decompression with bubbles and decompression without bubbles

Table 2 shows the same information as Table 1 but this time for 100ft and 60ft dives, each to the no decompression limits. Again, for the faster tissues, the amount of gas carried as bubbles is determined entirely by the second dive, but of course the duration of the second dive depends on the duration of the surface interval.

Table 2. 100ft NDL, 60ft NDL. Gas carried in bubbles (ml/ml * 10⁴)

Surface interval 1 hour			
Time constant (mins)	100-60	60-100	Ratio
1.9	2.18		
5.3	14.4		
51	119.7		
211	171.1		
Surface interval 2 hours			
1.9	2.05	4.02	1.96
5.3	14.3	13.9	0.97
51	122.6	132.3	1.08*
211	173.1	312.5	1.81
Surface interval 3 hours			
1.9	2.05	4.59	2.24
5.3	14.3	25.1	1.75
51	119.8	129.4	1.08**
211	173.7	316.2	1.82
Exercising muscle			
11/51	250.9	230.6	0.92
11/51	173.7	316.2	1.82

I used the USN dive tables to determine the duration of the second dive. These require you to reduce the duration of the second dive according to the estimated amount of gas remaining in the body at the end of the surface interval. That estimate takes no account of the way in which bubbles, once formed, slow down the removal of gas. Thus, the residual gas is underestimated, and the example shown in Figure 1 demonstrates the magnitude of the underestimation for one situation. If the volume of residual gas as used in the USN tables were "correct," as judged by a model that takes account of the effect of bubbles, the predicted gas carried in bubbles for each compartment would be the same for any repetitive dive combination. Table 2 shows this not to be the case. Where the value for the ratio exceeds 1, the estimate of residual gas following the 60ft dive as the first dive, is a greater under-estimate than that when the 100ft dive was taken as the first dive.

Following a surface interval of 2 hours for the 5.3 minute tissue, reversing the order of the dives appears to be beneficial.

Of course no diver dives in order to lie on the seabed and gaze at the stars. The dives usually involve some physical activity and this influences gas uptake and removal in many parts of the body. I have taken a very quick look at how physical activity might affect the outcome for the muscle. I have assumed that throughout the dives and the decompression there is a level of physical activity equivalent to heart rate of 100 to 120 beats per minute. In normal conditions, this would be taken as low level activity for somebody of average fitness. The appropriate increase in muscle blood flow has the effect of reducing the muscle time constant to about 11 minutes. This means that the 100ft NDL almost saturates the muscle and the 60ft NDL does saturate the muscle. During the surface interval muscle blood flow returns to normal resting levels. The penultimate row on Table 2 shows the outcome. Reversing the order of the dives is certainly beneficial. The reason of course is that the duration of the second dive is too short to allow more than a small increase in gas load even with the short time constant of the exercising muscle.

A different picture emerges when we do the same for the 3-hour surface interval. The final row in Table 2 shows why in this case reversing the order is not a good idea. Why does this differ from what happens for the 2-hour surface interval? The increased duration of the second dive (an extra 4 minutes) more than offsets the extra hour of the surface interval. Again, this is a consequence of the apparent under-estimation of the residual gas.

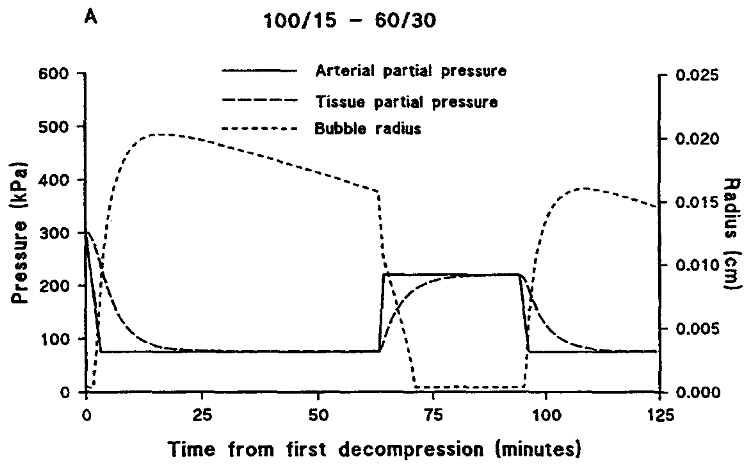
Discussion

In addition to the complexity of what happens in the different tissues of the body and the infinite range of dive time/surface interval combinations, there is the question of what is worse and by how much? Table 1 shows that for the short time-constant tissues making the 100ft dive, the second one gives approximately twice as many bubbles after the pair of dives than when the 60ft dive is second. Is the reverse order really twice as bad, twice as damaging? Figure 2 shows the pattern of bubble growth and decay predicted to occur in brain white matter for both combinations of 100ft for 15 minutes and 60ft for 30 minutes, with a surface interval of 1 hour. When the deeper dive is made second, the maximum bubble size after the dives is 0.0206 cm. When the deep dive is made first, the maximum bubble size after the first dive of the pair is 0.0203 cm. There is an equivalent similarity after the 60ft dive whether it comes first or second. There is a difference in the time taken for the bubbles to decay, in that when the less deep dive is second, bubbles are predicted to last for 82 minutes after the final decompression; when the deeper dive is second, bubbles last for 128 minutes. Is the reverse order of the dives really twice as bad, twice as dangerous, as doing the deep dive first?

Conclusions

The work presented here has been limited by the terms of reference of the workshop, but even within these limits we begin to see that there might not be a simple answer to the question: Is it better to do the deeper or the shallower dive first? What seems to be clear is that if you are going to make a second dive, it is probably better to work from tables that give some allowance for residual gas even if that allowance is an under-estimate.

The use of a physiological model draws attention to the complexity of the problem and illustrates the need for more clear and precise thinking about what we mean when we try to assess the risk of alternative procedures. Once such terms have been defined, the physiological model can be used to compare the alternatives and can guide the design of trials for experimental evaluation of procedures.



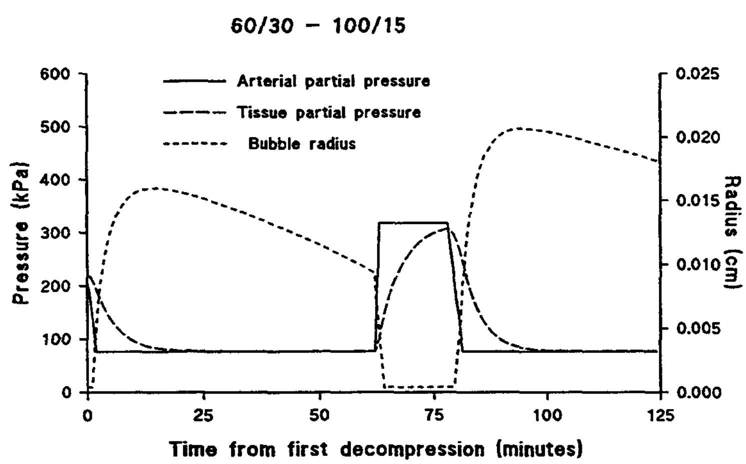


Figure 2. Arterial and tissue inert gas pressures with bubble growth for (A) the 100ft dive followed by a 60ft dive, and (B) the 60ft dive followed by the 100ft dive.

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EVALUATION OF REVERSE DIVE PROFILES

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The use of clinical symptoms as an endpoint for evaluating decompression procedures, in this case, reverse dive profiles, is based on the assumption that the incidence and severity of clinical symptoms can be used to determine which profile is the "best." The most obvious problem related to this approach is that most modern diving procedures provoke a very low incidence of acute clinical symptoms, requiring a very large number of dives under identical conditions for validation trials. This is in particular a problem for procedures that are to be used in sport diving, as few of these tables will ever be tested under controlled conditions where all symptoms are observed and recorded by trained personnel. We have shown that a considerable underreporting is to be expected. Gas bubbles can be detected in the pulmonary artery both in man and in experimental animals. Under experimental conditions in animals, the number of bubbles can be quantified; in man a semiquantitative measurement can be performed. It is argued that a decompression profile that produces the lowest number of bubbles in the pulmonary artery is the "best" and that this approach is best tested using a biological model. A limited number of animal experiments will be sufficient to determine which profile produces the lowest amount of gas. The problems related to evaluation of reverse diving profiles are particularly suited to this approach.

Introduction

"Careful clinical observation is the best method for evaluating decompression table adequacy as long as all symptoms, no matter how minor or trivial, are recorded and evaluated first-hand by trained and experienced medical personnel. Minor symptoms such as fatigue or transient niggles must be considered as they probably indicate a higher level of decompression stress than completely asymptomatic tables."..."Assuming DCS occurs randomly, the binominal distribution would predict a DCS rate between 0.03% and 5.45% at the 95% confidence level for 1 case of DCS in 100 man-dives" - (Thalmann, 1996).

The question of what constitutes a safe decompression is central to how decompression tables must be validated. Curiously enough, there is no common acceptance as to what constitutes a safe decompression. In general terms, a safe decompression shall not lead to any acute or chronic changes in the organism. If one considers the effects of decompression on the organism, then several definitions of decompression-related problems can be put forward:

1. Acute clinical symptoms requiring treatment in individuals who have been exposed to a reduction in environmental pressure.
2. Acute clinical symptoms in individuals who have been exposed to a reduction in environmental pressure.
3. Organic and/or functional decrements in individuals who have been exposed to a reduction in environmental pressure.
4. Vascular gas bubbles without reported clinical symptoms in individuals who have been exposed to a reduction in environmental pressure.

The first definition is the one traditionally used and is incidentally the one used to evaluate the effectiveness of decompression procedures. This is probably quite accurate if serious symptoms occur. If, however, the symptoms are less marked, there may be a considerable under-reporting of symptoms (see below) and the second definition may prove to give a more accurate description. A wide variety of symptoms may be included in this; many of them may not be recognized as having anything to do with decompression at all.

The third definition includes both acute and chronic changes related to decompression. These may be related to acute clinical symptoms or may develop sub-clinically. A recent consensus conference determined that such changes, even in individuals with few or no reported symptoms, have been found in the bones, central nervous system and the lungs (Hope *et al.*, 1994)

The last definition is similar to the so-called "silent bubbles" described by Behnke (1951). Most will probably not regard this as decompression sickness (DCS). However, the fact that such bubbles are present during most decompressions (see below) is similar to the situation in many infectious diseases with detectable pathological flora and little or no symptoms. Experimentally, it has been demonstrated that these bubbles have an effect on the organism. However, the question still remains about the importance of these changes in human pathology.

Most, if not all, practical decompressions will lead to some degree of gas bubble formation in the organism. The exact threshold for this bubble formation is not known, but it is probably in the range of 50 - 70 kPa in the tissue (Daniels, 1984) and even lower in the vascular system. Eckenhoff *et al.* (1990) demonstrated that saturation at 3.7 msw on air was sufficient to produce bubbles in humans. In resting, anaesthetized pigs, we observed bubbles after 180 minutes at 5 msw on air (unpubl.). The conclusion from these studies must be that gas bubbles may form in the vascular system at any supersaturation and that the concept of a minimum tolerable limit of supersaturation only relates to clinical symptoms and not to bubble formation. Adding to this problem is the fact that it has been demonstrated repeatedly that a large inter- and intra-individual difference in bubble-forming "ability" exists. Factors like sex, age, body build, circulation, temperature, blood composition, and degree of exercise seem to play a role (Jones, 1950; Vann, 1989). Cavitation in joints, for example, has been demonstrated without any supersaturation following violent movements. Furthermore, there are data indicating that there is a large difference is susceptibility to decompression sickness not directly related to the amount of vascular gas bubbles observed (Ward *et al.*, 1987).

Decompression Sickness as Endpoint

The use of decompression sickness as an endpoint for the safety of procedures is based on the assumption that procedures that give no symptoms of decompression sickness will have no effects upon the health of the individual. Furthermore, it is assumed that if mild decompression sickness can be prevented, then more serious changes will not be found. There is no argument about the fact that procedures that have a considerable incidence of decompression sickness can represent a health hazard. However, modern decompression procedures have a low incidence of treated decompression sickness, probably in the range of 0.05 to 0.5 %. Assuming a binominal distribution, 750 dives will have to be performed without any symptoms in order to document that a procedure has a DCS incidence of 0.5% within a 95% confidence interval. This makes these procedures very difficult to test.

A large percentage of commercial divers have suffered decompression sickness (DCS) in spite of careful use of accepted procedures. In a survey performed in a Norwegian diving company, we showed that 19 out of 40 divers (48%) who answered our questions (65% of the divers asked) had suffered Type I DCS (Brubakk and Fyllingen, 1986). In another, much larger study, we studied a group of Norwegian commercial and sport divers (Brubakk *et al.*, 1993). A questionnaire was sent out to 1200 sport divers and 800 commercial divers; a total of 1252 divers responded. The group consisted of 740 sport divers, 365 commercial air divers and 112 saturation divers. All divers had considerable diving experience with about 40-50% of the divers in each group having performed 100 – 500 dives, the divers with saturation experience being the most experienced. As can be seen in Figure 1, this study showed that 3% of the sports divers, 13% of the air divers, and 28% of the saturation divers had been treated for decompression sickness. However, 19% of the sport divers, 50% of the commercial air divers, and 63% of the saturation divers had experienced clinical symptoms related to decompression that were not reported and hence not treated. The majority of these symptoms could be related to the central nervous system. The divers were also asked about frequent problems related to poor concentration, loss of memory, irritability, or depression. The answers to these questions were compared to those of a group of 344 office workers and 92 firemen. The results can be seen in Figures 1 and 2. As a group, all divers had significantly more problems than the office personnel, but only the saturation divers had more problems than the firemen. The commercial air divers and the saturation divers had significantly more problems than the sport divers. Untreated symptoms of decompression sickness were significantly correlated to symptoms from the central nervous system, while divers in all groups, who had never experienced any symptoms or had been treated, had no more problems than the control groups (Figure 2).

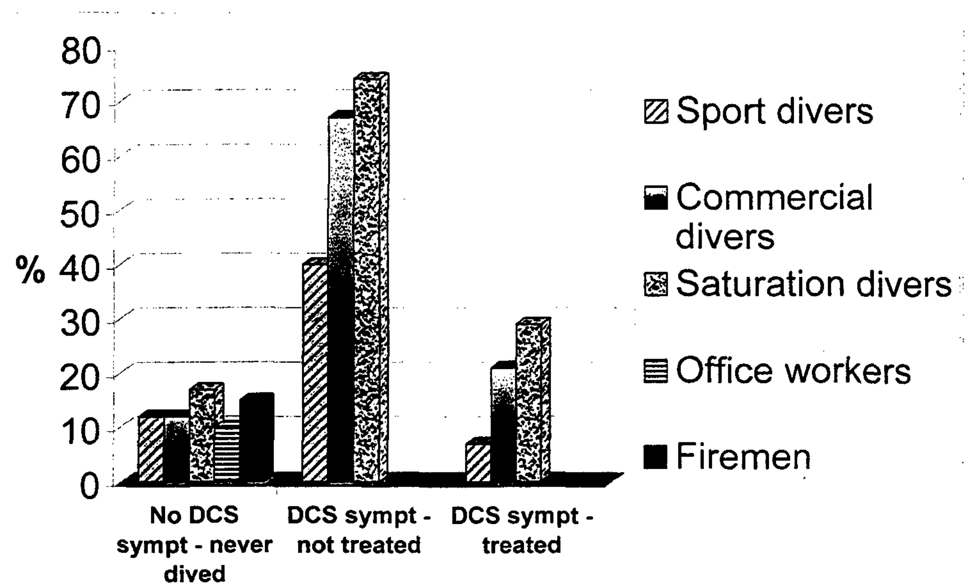

Figure 1. The incidence of treated DCS, clinical symptoms not treated and CNS symptoms in different groups of divers. From (Brubakk *et al.*, 1993).

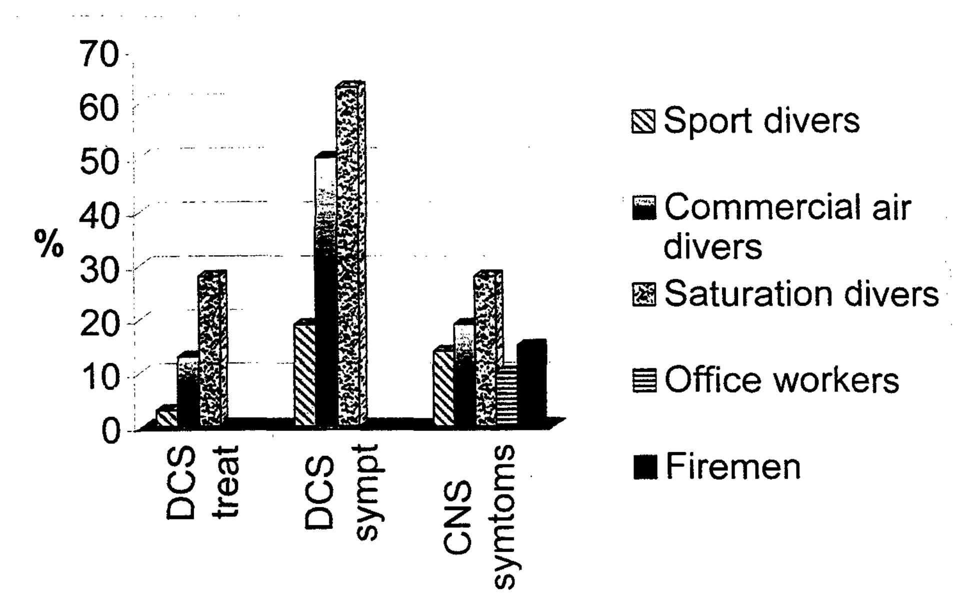

Figure 2. Central nervous problems (%) related to DCS, treated and untreated. From (Brubakk *et al.*, 1993).

In a different study, Todnem *et al.* (1990) showed that changes in the central nervous system are positively correlated with clinical signs related to decompression and with treated decompression sickness in saturation divers.

From the above studies we can conclude that there probably is a considerable under-reporting of clinical symptoms related to decompression and that such symptoms may have decremental effects upon the divers health. In the above study, 64% of the divers who had lost their diving license on medical grounds had been treated for DCS, while 79% had experienced symptoms without reporting them. In a recent study of saturation divers who had lost their diving license on medical grounds, 13 out of 15 reported that they had failed to report even quite serious symptoms (Moe and Bjelland, 1994).

In most testing schemes for decompression procedures, mild decompression sickness (muscle and joint pain only) is acceptable in a certain percentage of the cases (typically 1-5%), while serious decompression sickness (central nervous symptoms) is not acceptable. The acceptance of the procedure is thus dependent upon the diagnostic accuracy. Small areas of central nervous damage can for instance lead to very localized changes in skin sensitivity, easily missed even with careful investigations. This is perhaps most strikingly shown by the case reported by Palmer *et al.* (1981) where a diver with considerable degeneration of his spinal cord following a decompression accident had only minute clinical signs and in fact was allowed to continue diving. Recent studies have also shown that so-called "pain-only DCS" is a rare event, happening only in 8 (Kelleher *et al.*, 1993) to 13% (DeNoble *et al.*, 1993) of all cases. Diving can often be very heavy work, with considerable use of muscles of the upper body. It is to be anticipated that joint and muscle pain caused by decompression sickness easily can be missed in this situation. Furthermore, as documented above, many professional divers may be reluctant to report minor symptoms, as treatment of decompression sickness may have a negative effect upon their further employment prospects.

There are indications that the tables evaluated using decompression sickness as an endpoint can be unsafe. This is demonstrated by the striking change in the occurrence of neurological decompression sickness in the last 10 years, from 20% of all treated cases in 1975 (Kidd and Elliott, 1975) to 80% in 1987 (DAN, 1999). The reason for this is not quite clear, but is probably related to the development of better equipment, enabling the divers to go to the limit of the tables. Many centers with extensive experience in treating decompression sickness claim that about 1/3 of all treated divers have dived inside accepted limits (Edmonds, pers. comm., 1993). Furthermore, there seems to be a general consensus that most air diving tables are unsafe for long, deep exposures, clearly indicated by the restriction of such dives on commercial operations by British authorities. Incidentally, the British Health and Safety Executive has determined that decompression sickness is not any longer considered adequate for evaluating decompression procedures and in the future will use gas bubbles in the pulmonary artery as an endpoint (Robertson and Simpson, 1996; Simpson, 1999).

All the above seems to indicate that decompression sickness case reports can be an unreliable way of evaluating decompression procedures.

Vascular Gas Bubbles as an Endpoint

With ultrasonic techniques, it has been possible to detect gas bubbles in the vascular system of individuals undergoing decompression. Several studies have demonstrated that there is no linear relationship between gas bubbles found in the right heart and clinical decompression sickness. (Gardette, 1979; Nashimoto and Gotoh, 1978). However, dive procedures that produce many intravascular gas bubbles have a high incidence of decompression sickness. Thus, the occurrence of a large number of gas bubbles in the vascular system may function as an early warning sign.

It has often been claimed that gas bubbles, as can be detected in the pulmonary artery, are a poor predictor of DCS. The main reason for this is that gas bubbles have been detected without clinical signs of DCS (Nishi, 1990). However, these bubbles can lead to endothelial damage and a reduction in gas exchange (Nossum and Brubakk, 1999; Thorsen *et al.*, 1995).

There appears to be agreement that the risk of DCS increases with increasing number of bubbles. This is based on the following assumptions:

1. Endogenous gas bubbles are the cause of DCS.
2. Increased numbers of endogenous gas bubbles increase the risk of developing DCS.
3. The number of gas bubbles in the vascular system correlates with the number of gas bubbles elsewhere in the body.
4. The number of gas bubbles in the pulmonary artery correlates with the number of gas bubbles in the vascular system.
5. The number of gas bubbles detected by ultrasound in the pulmonary artery correlates with the number of gas bubbles actually present.

There is probably little argument about the first two statements. This is, in fact, the basis for all models describing the decompression process. There is to our knowledge no data that refutes the third statement. In our own experience, after carefully having monitored many hundreds of air dives and numerous saturation dives, we have never seen an individual without pulmonary artery gas bubbles who had clinical symptoms. The same observation was made by Davies (1983), who claims that clinical symptoms were never observed when gas bubbles could not be detected in the muscles of the thigh. Nishi (1993) points out that for air dives, decompression illness was always accompanied by bubbles if all monitoring sites are considered. Published data seem to support this (Table 1).

TABLE 1. Air dives, precordial bubbles at rest.

		Bubble Grade	
		0	**I-IV**
Nishi (1993)	**n**	**1265**	**331**
	DCS incidence (%)	**0.6**	**8**
Spencer & Johansen (1974)	**n**	**110**	**64**
	DCS incidence(%)	**1.0**	**22**
Nashimoto & Gotoh (1977)	**n**	**64**	**88**
	DCS incidence (%)	**0**	**19**

One interesting observation is the considerable difference in DCS incidence in the various studies. In divers with bubbles, the DCS incidence is considerably above what is considered acceptable today. It can be very difficult in many cases to distinguish between an occasional bubble and no bubbles using the Doppler method (Sawatzky and Nishi, 1991). Thus, it is possible that the few individuals with DCS and no observed gas bubbles actually had a few bubbles that were not detected.

One of the assumptions made in using ultrasound to evaluate decompression tables, is that a table producing few gas bubbles will be safer than one producing many bubbles. This is probably not an unreasonable assumption, but as far as we know, no one has been able to document that. However, we have been able to show experimentally that it is possible to use gas bubble content in the venous system to distinguish between two different profiles and that there is a relationship between the amount of gas and the "stress" of the dive (Flook *et al.*, 1993). The advantage of this method is that even small dive series can be sufficient to make this distinction.

Most studies using ultrasound have been performed in the right heart. It is generally assumed that the lung is a very good filter for gas bubbles down to a diameter of approximately 10 microns (Butler and Hills, 1979). However, we have shown that procedures considered safe will give rise to considerable gas bubble formation both on the venous and the arterial side of the circulation (Brubakk *et al.*, 1986). Arterial gas bubbles were also detected in another study during routine decompression from saturation (Hjelle *et* *al.*, 1987). These bubbles probably were transmitted through the pulmonary circulation, indicating that if many bubbles are present on the venous side, arterial gas emboli may occur even without a patent foramen ovale (PFO). Thus, if gas bubbles are to be monitored after a dive, it would be useful to monitor both the venous and arterial side of the circulation.

Methods for Evaluating Gas Bubble Content

Traditionally, the Doppler method has been used for evaluating circulating gas bubbles (Spencer, 1976). The advantage of this method is that the equipment is cheap and easy to use even in remote locations. The disadvantage is that the evaluation of the signals is very difficult and requires extensive training, in particular, if few bubbles are present (Sawatzky and Nishi, 1991). We have developed a method based upon the use of ultrasonic imaging (Eftedal and Brubakk, 1991; 1993a). Using this system, the bubbles are easy to identify and the classification is easy, using the grading system developed (E-B Grades) (Eftedal and Brubakk, 1993b). Furthermore, we have demonstrated that even untrained individuals can grade such images accurately (Eftedal and Brubakk, 1997)

In animal experiments, we have been able to actually count the number of bubbles in the pulmonary artery and have developed a system that does this automatically (Eftedal and Brubakk, 1991). This enables us to document the relationship between peripheral vascular gas bubbles and those in the pulmonary artery, in support of the above assumptions.

In a pig, we canulated the femoral vein and placed a proximal Doppler ultrasonic probe (Reinertsen *et al.*, 1994). Furthermore, the bubbles in the pulmonary artery were detected using a transoesophageal ultrasonic probe; bubble counting was performed using the method described previously (Eftedal and Brubakk, 1991). We then infused air bubbles of a constant size into the femoral vein in various doses as is indicated in Figure 3. In this figure, the reflected amplitude of the Doppler signal recorded immediately proximal to the probe is recorded. The reflected amplitude of the signal is proportional to the radius of the bubble and hence to the volume of gas if all bubbles are of the same size (Angelsen, 1980). As can be seen, there is no high correlation between the reflected amplitude and the volume of gas infused. This was surprising, but watching the field, we could clearly see that a large number of the gas bubbles moved retrograde in the blood stream and accumulated in the distal part of the vein.

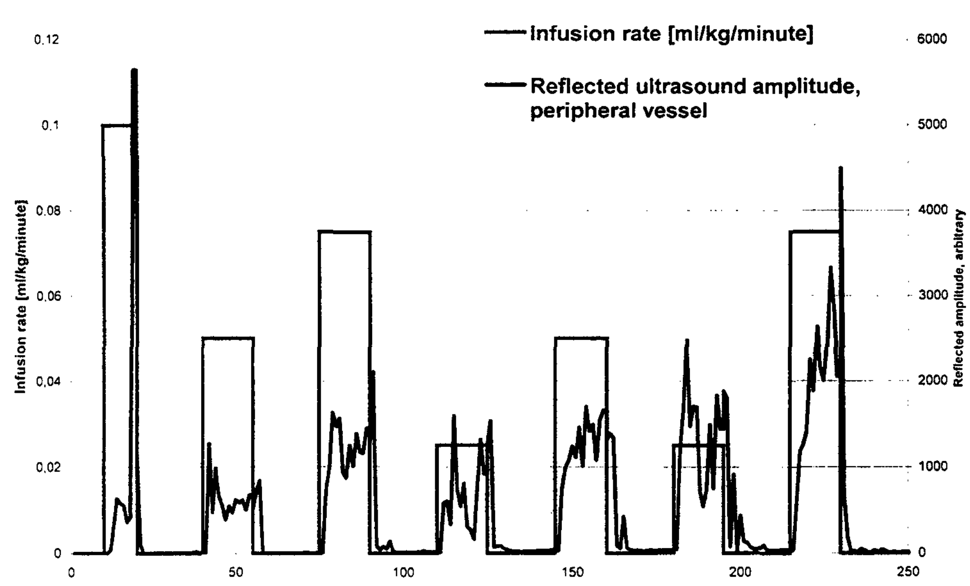

Figure 3. The relationship between infused gas volume and the reflected ultrasonic amplitude in the femoral vein.

Figure 4 shows the relationship between the reflected amplitude in the peripheral vein and the number of gas bubbles counted in the pulmonary artery. As can be seen, the correlation is excellent. This is further supported if we integrate both signals, as can be seen in Figure 5.

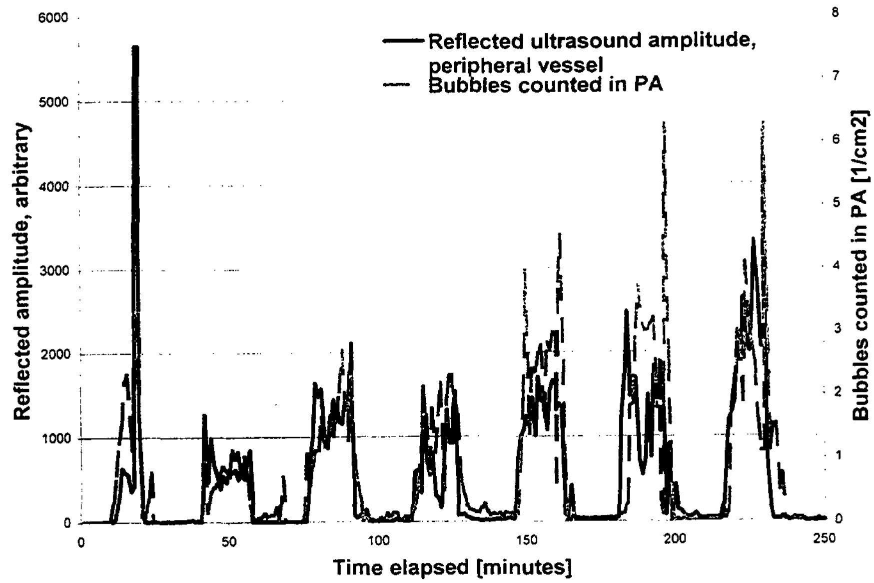

Figure 4. The relationship between reflected ultrasonic amplitude in the femoral vein and bubble numbers in the pulmonary artery.

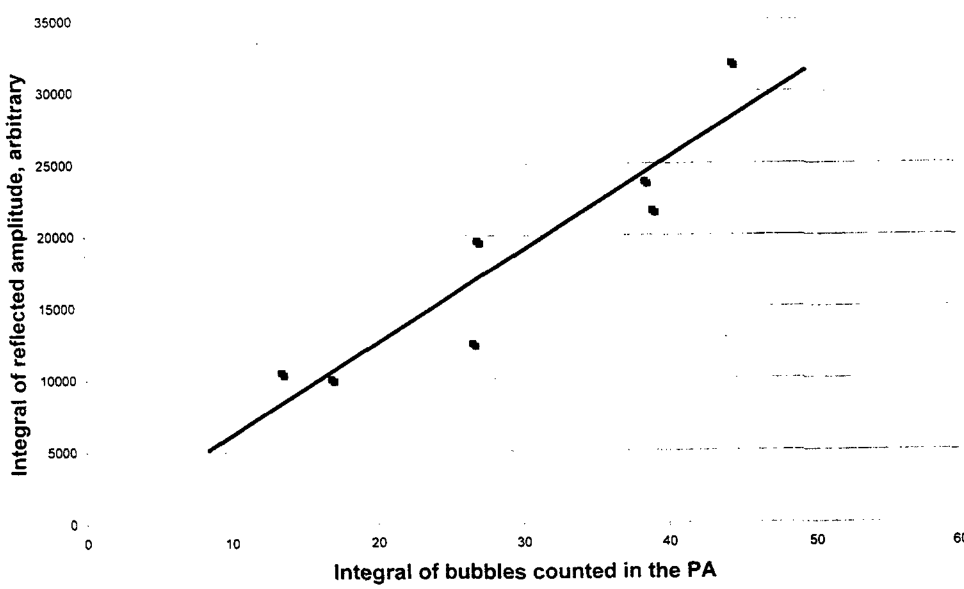

Figure 5. The relationship between integral of bubble numbers in the pulmonary artery and amplitude of the Doppler signal in the peripheral vein for the whole experiment. The regression line is $y = 641x - 295$, $r=0.93$.

Thus, this experiment seems to support the assumption that the number of bubbles counted in the pulmonary artery is indeed proportional to the volume of gas in bubbles arriving from the periphery.

The ability to count bubbles allows us to determine the relationship between the number of bubbles in the pulmonary artery and the bubble grades (Eftedal *et al.*, 1998). Table 2 is based upon data from several hundred separate experiments, but is obviously an approximation based on our evaluation on the data. From the table, it is quite obvious that the grading system is nonlinear. Going from Grade II to

Grade III gives a ten-fold increase in the number of bubbles, and hence in gas volume. In transforming the grading to a linear scale, one further advantage is that one can use parametric statistics for evaluating the results.

Table 2. Relationship between bubble count and bubble grade, K-M (Doppler), E-B (Images).

K-M Grade	E-B Grade	Bubble count bubbles/cm^2
0	0	0
I-	1	0.01
I	1	0.05
I+	1	0.1
II-	2	0.15
II	2	0.2
II+	2	0.3
III-	3	0.5
III	3	1
III+	3	2
IV-	4	5
IV	5	10

Even if this obviously is an approximation, it now becomes possible to convert the bubble grades to a linear scale. Initial analysis of data from dives where both Doppler grade and bends incidence are known indicates that this method may have considerable power for discriminating between "safe" and "unsafe" dives.

Use of pulmonary artery bubbles and animal experiments to evaluate reverse diving profiles

The previous findings indicate that counting the gas bubbles in the pulmonary artery can be used to compare two different profiles. There is at present no method for doing this accurately in man, thus for an initial comparison, animal experiments are needed. When evaluating reverse dive profiles, the question asked will be, "how will the depth-time combination of repeated dives influence the outcome, *e.g.*, the safety for the diver?" As demonstrated at this workshop, the usual approach to this is to test different depth-time combinations using mathematical models. There is probably no other field in biology or medicine where one relies so strongly on mathematical models for determining outcome.

The advantage of the mathematical model is its simplicity and the ease with which many combinations can be tested. The use of models combined with statistical techniques, *e.g.*, maximum likelihood, has been a powerful tool for developing decompression procedures (Thalmann *et al.*, 1997). However, the model's strength is also its weakness; it may not be easy to test all the assumptions made. We would argue that a biological model, using a quantitative endpoint, is better suited for determining which combination of dive depth and time actually produces less gas bubbles. This approach also overcomes another problem, namely how to correlate gas bubbles and decompression sickness. Animal experiments can actually give additional insight, as organs can be studied after the experiments have been terminated. It is important to remember that the proposal made here focuses on the comparison of the number of bubbles produced by two profiles; this does not require any information about the relationship between bubbles and injury to the organism.

One has to exercise caution when extrapolating from the results obtained in any model system to man. In designing animal experiments, a large animal model should preferably be used (Brubakk, 1996). However, if two procedures are to be compared, then the most "stressful" one will produce the largest amount of separated gas both in man and in any model, mathematical or biological.

Comparing decompression procedures in this way will obviously give considerable input to the mathematical modelers, who can use this approach for improving and calibrating the models and for simulations to suggest additional experiments. Thus, a combination of both approaches may be the most profitable way for comparing different profiles and for developing decompression procedures in the future.

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REVERSE DIVE PROFILES IN THE NMRI AIR AND N_2O_2 DIVING DATA BASE

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A central issue in the advisability of diving "reverse" profiles is whether such profiles incur DCS risk by different mechanisms from those governing DCS risk in other types of diving. Primary empirical information for DCS incidence and time of occurrence in a large number and variety of repetitive dive profiles has been obtained in U.S. Navy man-trials since 1974. Over 1200 repetitive and multilevel exposures are present in the published database (NMRC Technical Report 99-02, 1999). However, only a few dozen are "reverse" since Navy developers never considered "reverse" profiles worthy of special study. Nevertheless, all of these "reverse" data were included in the Primary Data used to calibrate the USN93, JAP98 and Duke BVM(3) gas and bubble dynamics probabilistic models. All the models provide estimates of DCS incidence and time of occurrence for these reverse profiles that are within the 95% binomial confidence limits of the observations. Available empirical data for reverse profiles has thus been successfully combined with data for other profiles under each probabilistic model. This ability is consistent with the view that DCS risk accumulates by the same mechanism in both types of profiles and that reverse profiles are not "special".

Introduction

In the history of U.S. Navy development of decompression tables and procedures, we can find no concern over "reverse" profiles. The investigators have always calculated and tested profiles now labeled as "reverse" as part of the repetitive or multilevel range needed at the time. Thus, the Navy would simply never have seen the need for this Workshop. However, the Navy has acquired some data directly relevant to "reverse" dives.

As part of a major effort to control decompression based on valid statistical treatment of human diving observations, the Naval Medical Research Institute (NMRI) amassed a collection of thousands of well controlled dives and relevant DCS outcome symptoms and onset timings. The compiled high quality modern data (since 1974) was published as "Primary Data" for decompression modeling (Weathersby *et al.*, 1992). More recently the data base has been doubled in size to over 8000 dives and expanded to include earlier controlled decompression trials (Temple *et al.*, 1999). Almost 1600 repetitive and multilevel exposures are present in the newer data base, and at least 1200 of them qualify as modern "Primary Data." Table 1 is an excerpt from a summary chart in the newer NMRI report. All of these profiles and outcomes are available for anyone desiring high-quality diving data. Several of the published profiles identified as "reverse," or illustrative of issues pertinent to consideration of DCS risk in reverse profiles, are illustrated in Figures 1 - 5.

Profiles

The profile shown in Figure 1 is a very long experimental profile (11 hours) in which 9 subjects made three downward excursions to 81.5, 61.5, and 81.5 fsw, respectively, but spent most of the day at 16.5 fsw. The downward excursions were made on air, while an oxygen-enriched gas (0.7 ata O_2; balance N_2) was breathed during the 16.5 fsw portion to simulate a dive on one of the Navy's rebreathers. Note that the dives to the deepest depth, 81.5 fsw, were made at the beginning and end of the profile, qualifying the profile as a "reverse" profile. Final surfacing was preceded by staged decompression prescribed by a controlled-risk real-time decompression algorithm, but the decompression time was modest by Navy standards. Very similar profiles following the same real-time algorithm were dived by an additional 52 subjects (Thalmann *et al.*, 1999). Overall, only 2 subjects reported decompression-related symptoms, but neither of them required recompression therapy according to the judgement of the on-scene Diving Medical Officer. Minor symptoms, referred to as "marginals" in the data, are rather common in closely monitored decompression trials, but are routinely ignored in field dives.

Table I. Sections III, IV of page 9 of NMRC 99-2.

TYPE OF DIVES		DATA SET	# Dives	DCS	Marginals
III. REPETITIVE & MULTILEVEL (AIR)	A.	PAMLA	236	13	12
	B.	EDU885AR	182	11	0
	C.	DC4DR	142	1	0
	D.	EDU657	142	4	0
	E.	PARA	135	7	3
	F.	DC4WR	12	3	0
		Totals	849	39	15
IV. REPETITIVE & MULTILEVEL (NON-AIR)	A.	EDU184	239	11	0
	B.	PAMLAOS	140	5	3
	C.	PAMLAOD	134	6	0
	D.	EDU1180R	128	2	0
	E.	EDU885S	94	4	0
		Totals	735	28	3

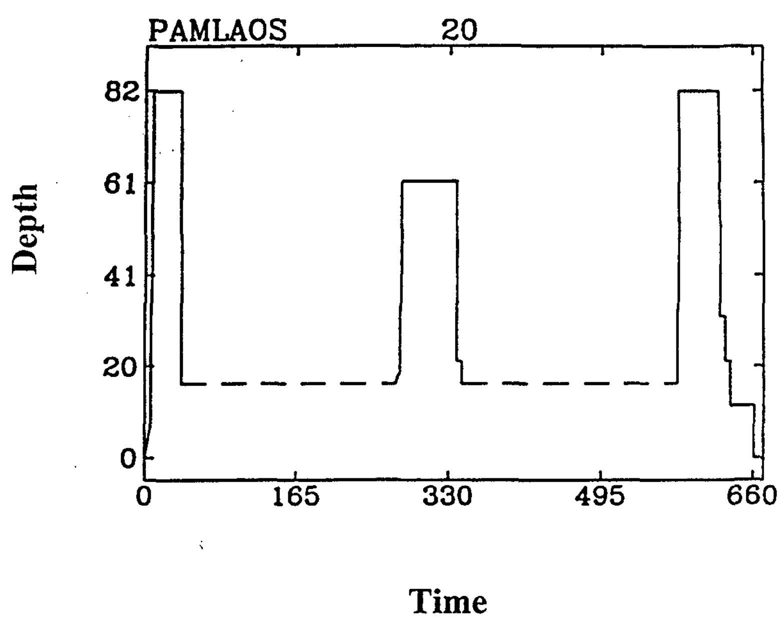

Figure 1. "PAMLAOS-20".

Figure 2 illustrates another experimental multilevel dive profile in which a 100 fsw downward excursion was made several hours after an 80 fsw excursion from the 20 fsw "main" depth. Air was breathed during the first and second dives, while an oxygen-enriched gas (0.7 ata PO_2; balance N_2) was breathed during the 20 fsw stages and during the second dive. This or similar profiles were dived by 38 test subjects with 4 reported cases of DCS (Thalmann, 1986). The decompression was specified by a (non-probabilistic) decompression algorithm that has since been modified.

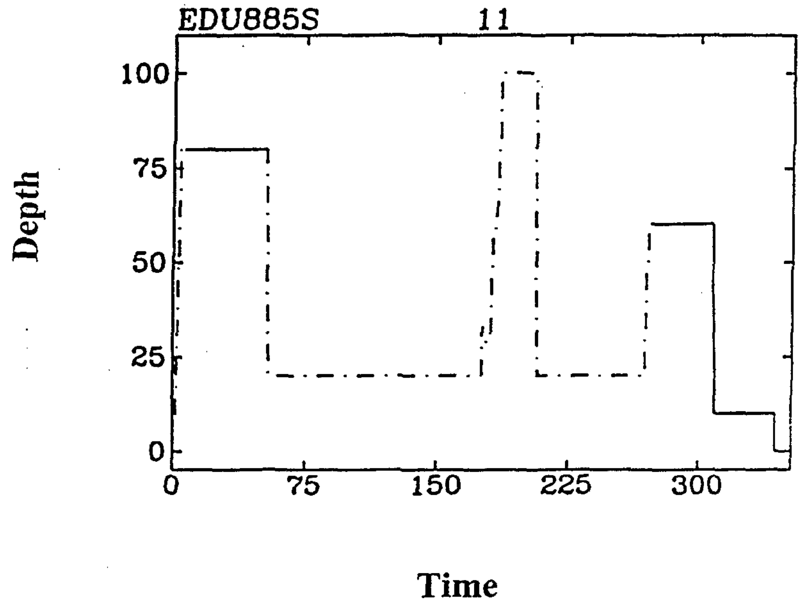

Figure 2. "EDU885S-11".

Figure 3 shows a Navy experimental dive from the early 1980's. Twenty subjects completed this "reverse" multilevel dive while breathing from a 0.7 ata constant PO_2 rig. None suffered DCS (Thalmann, 1984). The tables obtained from this trial are still in Navy use for scheduling both "regular" and "reverse" profiles.

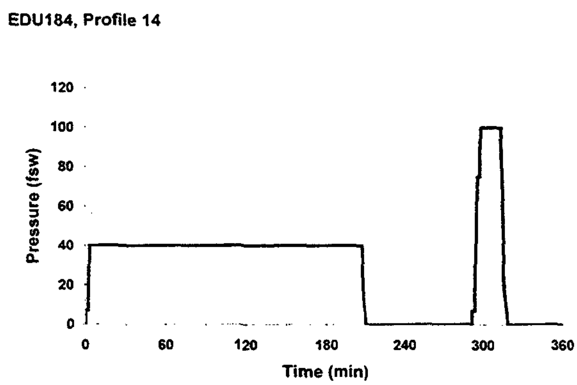

Figure 3. "EDU184-14".

The profile illustrated in Figure 4 is a "reverse" repetitive sequence from a 1957 Navy validation trial of a repetitive diving calculation method (des Granges, 1957). The two divers on this profile spent an hour at 140 fsw followed by a surface interval of just over an hour, and then completed a dive to 220 fsw with a 20 min bottom time. While both divers suffered DCS, a total of 140 other man-dives on a wide variety of different profiles prescribed by the same method were completed with only 2 additional cases of DCS. The trial was consequently declared a success. The Navy no longer authorizes routine air dives to 220 fsw, but it does authorize use of the repetitive scheme validated in this trial to plan dives in both "regular" and "reverse" profiles.

The final profile in Figure 5 is not formally "reverse", but is included to demonstrate the severity of repetitive air dives that can be successfully managed with a probabilistic model. This test subject went to 101.5 fsw three times over a 7 hour period, staying for the maximum no-decompression time allowed by a probabilistic model. Another 19 subjects made very similar dives, all with only a single marginal DCS symptom noted (Thalmann *et al.*, 1999).

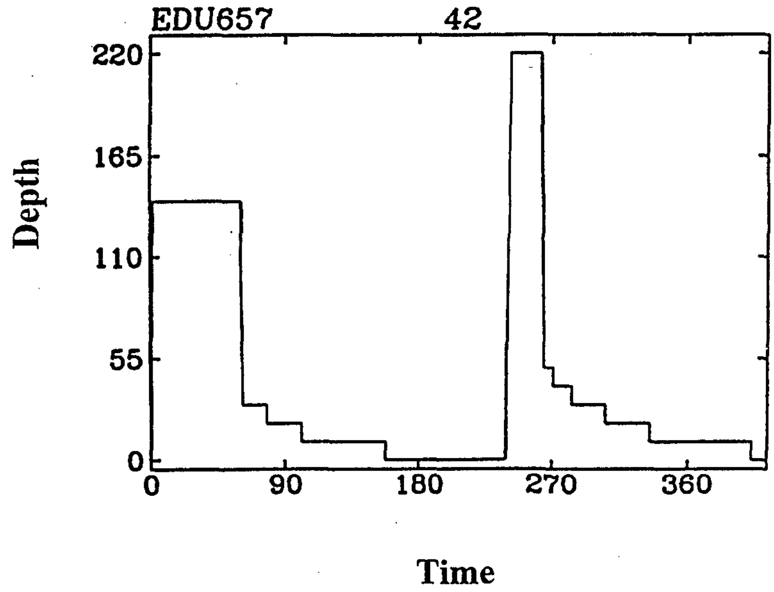

Figure 4. "EDU657-42".

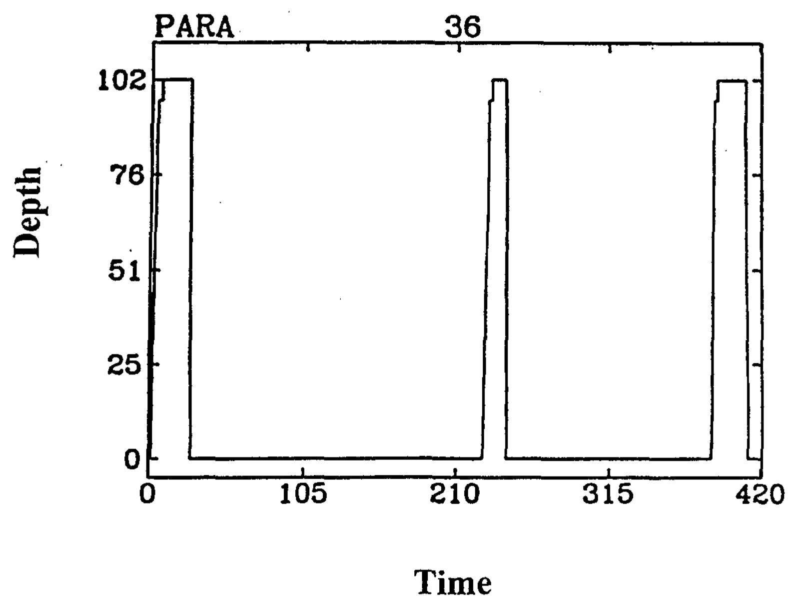

Figure 5. "PARA-36".

Discussion

A central question for diving "reverse" profiles is: Do such profiles incur DCS risk by different mechanisms from those governing DCS risk in other types of diving? We believe the answer is NO. We find no evidence that there is a "qualitatively" different operative mechanism. Instead, in concert with most of the Workshop speakers, we approach all diving questions with the same quantitative analysis.

The analysis we prefer is undertaken with a minimum number of questionable assumptions and with the strongest and most direct connection possible to human experimental data. Since the mid-1980s, a formal, statistically valid methodology has been available to combine observed DCS outcome information from a large number and variety of different profiles under a single probabilistic model, simultaneously

(Gerth and Vann, 1996; 1997; Parker *et al.*, 1992; 1998; Survanshi *et al.*, 1997; Temple *et al.*, 1999; Thalmann, 1984; 1986; Thalmann *et al.*, 1997; 1999; Weathersby *et al.*, 1992). The method ensures that each model provides its closest possible agreement with the observed data. The models are readily used to estimate the probabilities of DCS in different profiles and compute decompression schedules to keep estimated DCS probability within user-specified limits.

Three carefully constructed and tested probabilistic models for DCS incidence and time of occurrence in many forms of N_2-O_2 diving have been published (USN93: Parker *et al.*, 1992; Survanshi *et al.*, 1997; Thalmann *et al.*, 1997; Duke BVM(3): Gerth and Vann, 1996; 1997; JAP98-2: Parker *et al.*, 1998). All use hazard/risk functions of varying complexity with parameters estimated from over 3000 human dives. The "reverse" data discussed for Figures 1, 2, 3, and 5 were all included in the calibration data for these models. The performance of the models is documented in the literature cited.

Model predictions of DCS outcomes for the "reverse" profiles outlined above are compared with observed outcomes in Table 2. For each set of profiles (identified by Figure number), columns have: total number of divers, observed number of DCS and marginal cases, and the 95% binomial confidence limits for the observed number of DCS cases. The next columns have the upper and lower 95% confidence limits for the total number of DCS cases predicted by each of the three models. All the models provide estimates of DCS incidence for these reverse profiles that are within the 95% binomial confidence limits of the observations.

Available empirical data for reverse profiles has thus been successfully combined with data for other profiles under each probabilistic model. This ability is consistent with the view that DCS risk accumulates by the same mechanism in both types of profile and that reverse profiles are not "special." This model success indicates that comprehensive risk management of "all" dives - reverse or not - is feasible (see Weathersby paper in these Proceedings).

Table 2. Probabilistic Model Predictions for Tested Reverse Profiles

	Observed				Predicted, low - high 95% CL		
Profile	Divers	DCS	Marginal	95% CL on DCS cases	USN93D	BVM(3)	JAP98-2
Figure 1	54	0	2	0 - 3	1.6 - 2.5	1.2 - 4.9	1.4 - 2.4
Figure 2	38	4	0	1 - 10	1.6 - 2.3	1.6 - 2.1	1.6 - 2.4
Figure 3	20	0	0	0 - 3	0.7 - 1.1	0.7 - 0.9	0.8 - 1.2
Figure 4	2	2	0	0 - 2	0.4 - 0.5	0.3 - 0.4	0.4 - 0.6
Figure 5	20	0	1	0 - 3	1.0 - 1.7	0.9 - 1.6	0.9 - 1.6

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THEORETICAL, EXPERIMENTAL AND OPERATIONAL ASPECTS OF REVERSE DIVE PROFILES

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There have been no definitive laboratory studies to directly compare the decompression stresses associated with forward and reverse dive profiles. For this reason, assessment of the risks associated with reverse dive profiles will not be "hard science," but the result of thoughtful analysis of a variety of information sources including limited laboratory trials, well-documented operational records, field experience and theoretical predictions. This paper addresses the decompression stresses associated with reverse dive profiles, based on analysis with the Bubble Dynamics Model (Gernhardt, 1991). It also addresses a number of related special topics including: multi-gas, multi-depth, reverse dive profiles; the hang-off technique used in commercial diving; comparison of "Repet-Up" vs. "Repet-Down" dive profiles; and, the influence of exercise on decompression stress, as a function of dive profile.

Bubble Dynamics Model

The conceptual formulation of the bubble dynamics model assumes that DCS is not a localized threshold phenomenon that always occurs when some critical value of decompression stress is exceeded.

The observations that decompression can result in a spectrum of different symptoms that can occur at different sites in the body with different degrees of severity suggests that DCS is a generalized systemic phenomenon of graded degrees (Lambertsen, 1989). Specific symptoms of DCS would be local expressions of generalized DCS. There are also likely to be other forms of asymptomatic DCS that can occur at multiple sites and go unrecognized because the degree of gas phase separation and expansion is not severe enough to elicit detectable symptoms at a particular anatomical site (Lambertsen, 1989).

Since the specific tissue types and sites that result in the spectrum of DCS symptoms are not known with certainty, then the physical, physiological and biochemical parameters of those tissue sites cannot be precisely defined.

Given these limitations, it is not practical to model decompression stresses at specific anatomical sites. It is also not sensible to assume that there is one worst case theoretical tissue site that would apply to all types of decompression and at all points in a decompression profile. Instead, it is more reasonable to model decompression stress as a generalized systemic phenomenon resulting from gas phase separation, with bubble growth of multiple degrees and at multiple sites.

This is accomplished by modeling the growth of a single theoretical bubble, resulting from an assumed nucleus in each of a spectrum of tissue compartments that collectively provide an adequate description of the whole body's inert gas exchange. Prediction of gas phase growth and resolution is accomplished within an integrated system of tissue gas exchange, bubble dynamics and oxygen effect (Lambertsen *et al.*, 1991). The highest level of decompression stress (determined by the largest theoretical bubble) occurring in the spectrum of tissue compartments can then be used as a "worst case" general description of the levels of decompression stress resulting from the much more complicated and interrelated physical, physiological and biochemical phenomena that produce DCS symptoms.

Assumptions of the Model

The specific assumptions of the bubble dynamics model are:
1. Gas bubbles are the initial cause of DCS symptoms;
2. Gas nuclei are assumed to exist or form normally in tissues during decompression;
3. Gas bubbles grow prior to symptoms of DCS;
4. The inert gas exchange between a "well-stirred" tissue and a free gas bubble is limited by diffusion through a diffusion barrier;
5. The inert gas exchanges between the lungs and the tissues can be described with a multi-compartment, exponential inert gas exchange model;
6. The volume of gas in an extravascular bubble is much smaller than the volume of gas dissolved in the tissues, and initial pre-DCS bubble growth does not appreciably lower tissue inert gas tensions; and,
7. There is a worst case tissue for defining maximum decompression stress, but the specific tissue type depends on the dive profile and type of exposure.

The detailed rationale and supporting data for these assumptions and the mathematical derivation of the model are beyond the scope of this paper (Gernhardt, 1991; Lambertsen, 1989). A graphic illustration of the bubble dynamics model is shown in Figure 1.

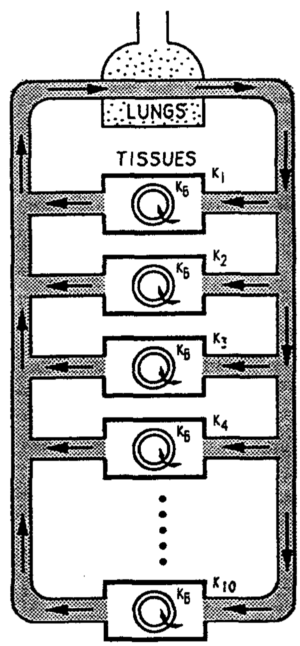

Figure 1. Bubble Dynamics Model.

Retrospective Validation of the Model

The bubble dynamics model was evaluated by comparing the decompression stress predictions of the model to DCS observations in a variety of laboratory decompression trials (Gernhardt, 1991; Lambertsen, *et al.*, 1991) using the logistic regression method (Lee, 1980). The statistical analysis involved analyzing 6457 decompression exposures, which resulted in 430 cases of DCS. The decompression data (provided by the International Diving, Hyperbaric Therapy and Aerospace Data Center) included a wide range of decompression techniques (Table 1).

Data sets were combined based on the likelihood ratio test (Lee, 1980). The results of the statistical analysis are shown below in Table 2.

The DCS incidence data associated with different degrees of theoretical bubble growth were plotted as a histogram. The x-axis denotes the bubble growth index (the maximum bubble radius in any tissue compartment divided by the initial radius) and the y-axis denotes the associated DCS incidence. The number of man dives associated with each interval is shown at the top of each bar.

Table 1. Summary of Laboratory Decompression Data

Decompression Procedure	Man Trials	DCS
No Stop Ascent	674	52
Submarine Escape	299	4
Air Decompression In-Water	2,687	133
N_2 - O_2 Decompression	488	33
O_2 Decompression "In-Water"	301	8
Surface Decompression		
With Oxygen	1,733	156
With Air	275	44
Total Numbers	**6,457**	**430**

Table 2. Summary of statistical analysis of nitrogen-based decompression data (Lambertsen *et al.*, 1991.).

Data Set: In-Water Decompression on Air		Test for Improvement		Test for Goodness of Fit	
Index	Log-Likelihood	x^2	p-value	x^2	p-value/ df
Null Set	-529				
Bubble Growth Index	-498	62.8	.000	4.8	0.77/8
Relative Supersaturation	-524	10.8	.001	19.4	0.08/12
Exposure Index	-505	47..9	.000	30.5	0.00/9

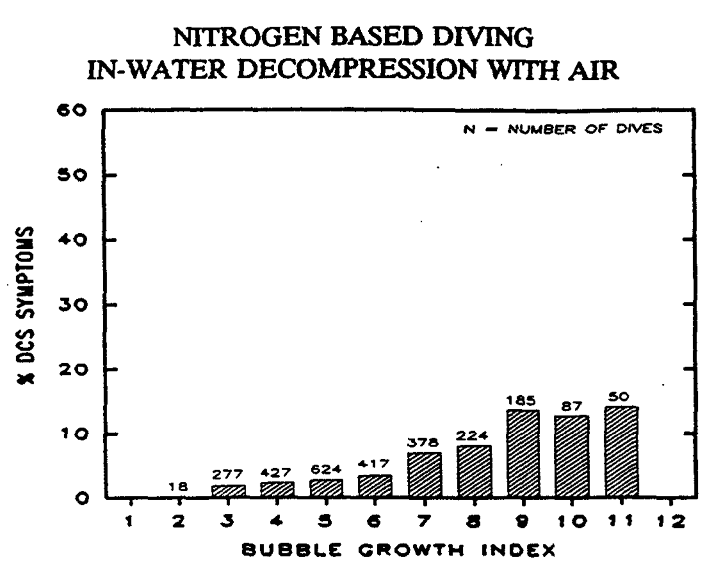

Figure 2. Bubble Growth Index vs. DCS incidence for combined nitrogen-based decompression data (Lambertsen *et al.*, 1991; Gernhardt 1991).

The results of the statistical analysis showed that the bubble dynamics model provided a statistically significant prediction of the occurrence of DCS ($p < .05$) and an adequate fit of the DCS incidence data ($p > .05$).

Prospective Validation of the Bubble Dynamics Model

In 1992, animal studies using a pig model were performed to compare the gas phase generated with the Bubble Dynamics Tables (generated by the Institute for Environmental Medicine (IFEM)) to equivalent USN Sur-D-O_2 Tables. The results indicated significantly less gas phase in the IFEM tables (Brubakk, 1993).

The first human trials of decompression tables based on the Bubble Dynamics model were performed at the National Hyperbaric Center in Aberdeen, Scotland, sponsored and directed by the British Department of Energy (Robertson and Simpson, 1997). A summary of these trials is shown below in Table 3.

Table 3. National Hyperbaric Center Laboratory Trials.

Profile (FSW/min)	n	DCS	Symptoms
110/40	10	1	Shoulder pain, spontaneous resolution
100/50	16	1	Itching
80/70	12	0	
120/40	30	0	
150/40	6	5	Rash
150/60	3	1	Rash/Visual
Total	77	8	*7 / 8-Skin Rash

These trials were compromised by procedural anomalies that were not representative of operational circumstances. Limitations in the depressurization rates of the wet pot required the diver subjects to exit the wet pot at depth, remove their hot water suits and perform the ascent and water stop portions of the dive profile in a cold air environment.

The majority of the symptoms reported (> 87%) included skin rash. Since skin rash is not a common symptom for these types of profiles, it is likely that the sudden change in thermal environment (from hot water to cold air) during the stressful ascent and water stop phases resulted in skin circulation changes that interfered with nitrogen elimination. Because of these procedural anomalies, an additional set of laboratory trials was performed at the Sub-Sea International Hyperbaric Center in New Orleans. The results of these trials are shown below in Table 4.

Table 4. Subsea International Laboratory Trials.

Profile FSW/min	n	DCS	V.G.E. * (Grade 3, 4)
90/80	6	0	0
120/40	6	0	1 – Grade 4
130/40	3	0	0
150/40	9	0	3 = Grade 3
Total	24	0	4 (16%)

These results, 24 dives with zero DCS incidents, were more in line with the theoretical predictions. Based on the successful laboratory trials in New Orleans, operational sea trials were conducted. The sea trials involved accurate time-depth recorders and post-dive Doppler measurements. The results are summarized below:

- 74 working dives with exposures up to 140 fsw for 90 minutes
- 0% DCS
- 6.7% Grade III and IV VGE

The tables were then released for operational use. Summaries of the operational results are shown below in Table 5.

Table 5. Summary of Operational Results.

Phase	Decompression Procedure	Offshore Dives	DCS Incidents	DCS %
III	"No Decompression"	20,000	0	0%
III 1993-5	Air SUR-D O_2* with N_2-O_2*	4,000** 500*	9	.2%
IV	Air SUR-D-O_2 Multi-Depth	2,500**	1	.04%

The initial operational implementation of the tables (Phase III) resulted in over 20,000 no-decompression dives with zero DCS incidents, and 4500 decompression dives with nine cases of DCS (.2%). The majority of the DCS incidents were on dives with bottom times beyond the recommended operational limits. The final operational table system, which incorporated in-water decompression, surface decompression on oxygen and multi-level diving (Phase IV) were then implemented with slightly reduced bottom times, still within the "Z" to extreme exposure range of equivalent USN tables. The integrated Phase IV tables also included multi-depth diving with the capability to perform forward or reverse dive profiles. These tables resulted in one DCS incident in 2,500 dives.

Analysis of Reverse Dive Profiles with the Bubble Dynamics Model

The purpose of the previous discussion and data was to establish the long history and validation of the Bubble Dynamics Model. It is important to state that the following are theoretical predictions of the model, which was validated primarily on conventional forward dive profiles. No model can provide a true description of the complicated physical, physiological, statistical and biochemical processes involved in DCS.

Figure 3 illustrates the decompression stresses occurring on forward and reverse dive profiles for dives to 100 fsw and 60 fsw. The graph plots Bubble Growth Index (BGI) against time. The IFEM tables based on the bubble dynamics model controlled decompression stresses to a BGI level of three. For this comparison, there are no differences in decompression stresses between forward and reverse dive profiles.

Figure 4 illustrates no significant differences in decompression stresses for forward or reverse dive profiles for these exposures with a 2-hour surface interval, compared to a one-hour surface interval.

Figure 5 illustrates the decompression stresses associated with forward and reverse dive profiles with dives to the USN no-decompression limits at 100 fsw and 60 fsw, with a 2-hour surface interval. There are small differences in the decompression stresses. However, these differences are related to differences in the no-decompression limits at 100 fsw and 60 fsw, and not to the dive profile sequence.

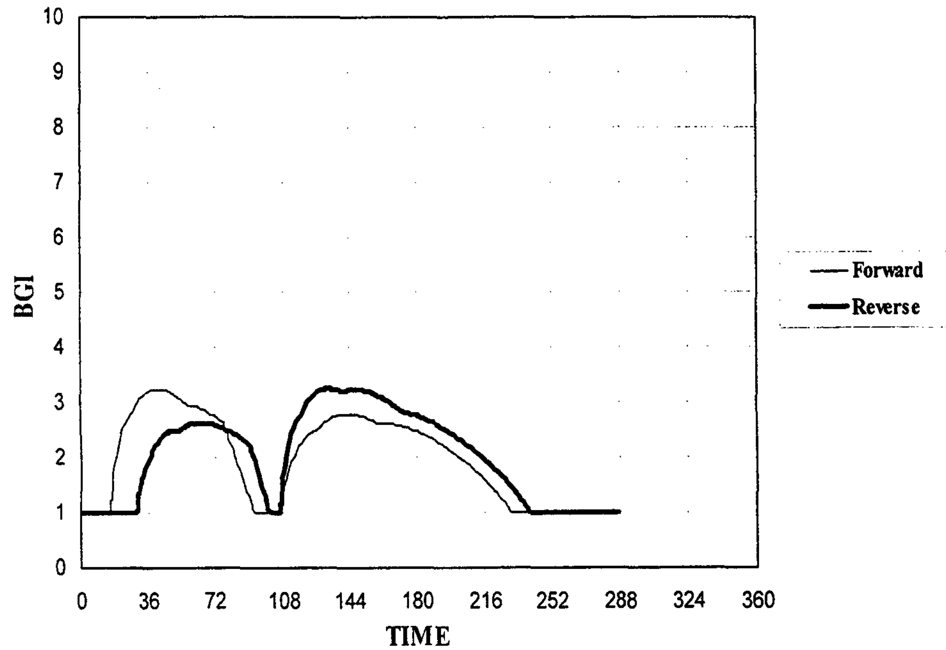

Figure 3. 100 fsw/15 min, 1-hr surface interval, 60 fsw/30min (forward and reverse).

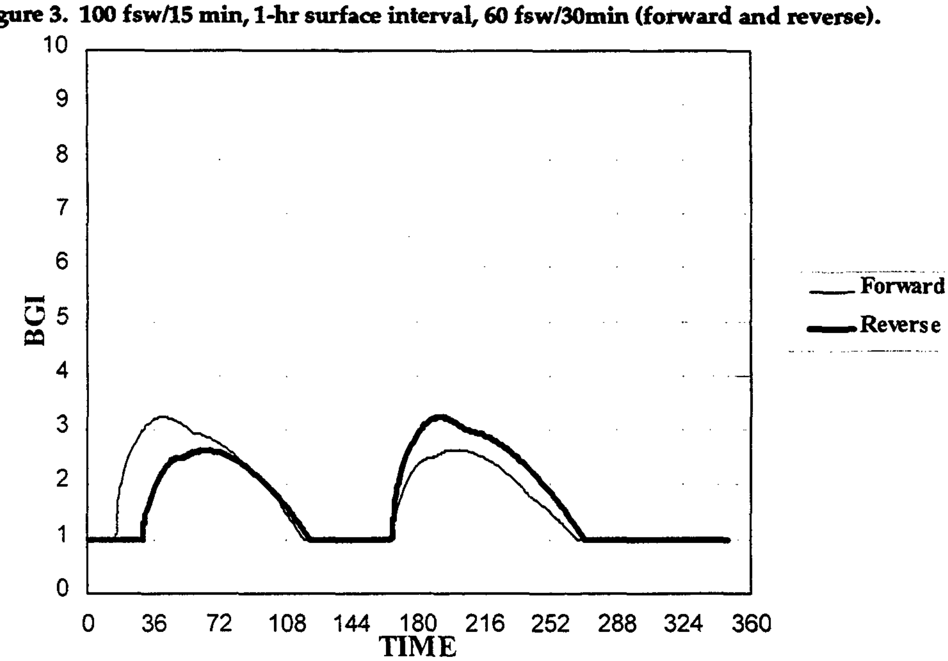

Figure 4. 100 fsw/15min, 2-hr surface interval, 60 fsw/30 min (forward and reverse).

Figure 6 illustrates the effects of increased bottom time at 100 fsw on the reverse dive profile described in Figure 5. Conventional dissolved gas supersaturation models limit the bottom time at 100 fsw to 3 minutes at the USN no-decompression limits. The Bubble Dynamics Model predicts that gas phase separation and growth occurs during the surface interval following the 60 fsw/60 minute dive. The gas phase is not completely resolved at the end of the surface interval or even after the 3-minute bottom time at 100 fsw. The model predicts that the gas phase would resolve after 10 minutes at 100 fsw. Although additional tissue nitrogen loading occurs during the 10-minute bottom time, the subsequent decompression stress upon surfacing is no more than that associated with the 3-minute bottom time. This illustrates the trade-off between gas phase resolution and increased tissue nitrogen loading. Once the gas phase is resolved, then additional bottom time and tissue nitrogen loading would result in higher decompression stresses as illustrated in Figure 6 with the 20 and 40-minute bottom times. In some special cases, the trade-off between gas phase resolution and nitrogen elimination can result in beneficial effects of shorter surface intervals, as reported by Wong (1996) in Australian pearl divers.

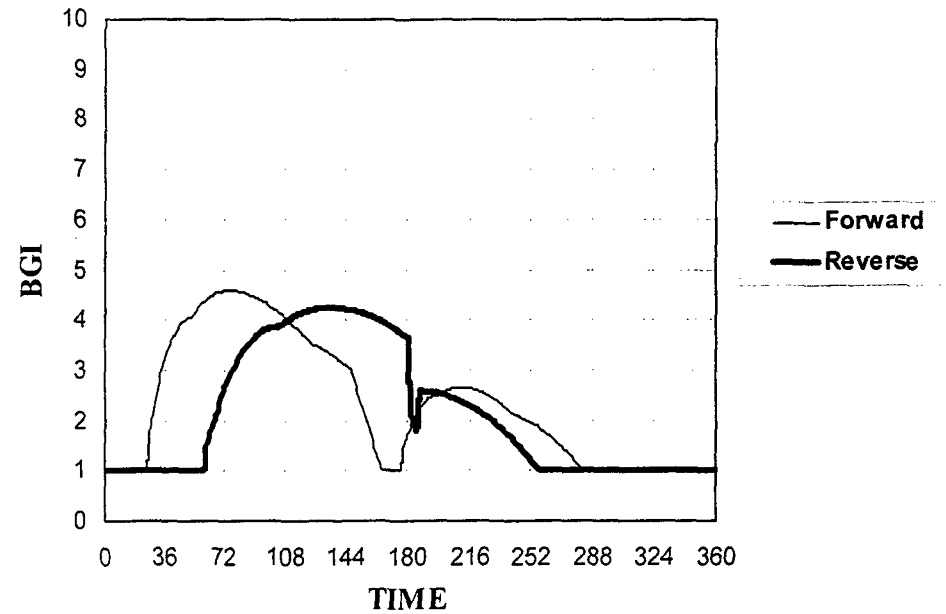

Figure 5. 100 fsw/25 min, 2-hr surface interval, 60 fsw/30min (forward and reverse).

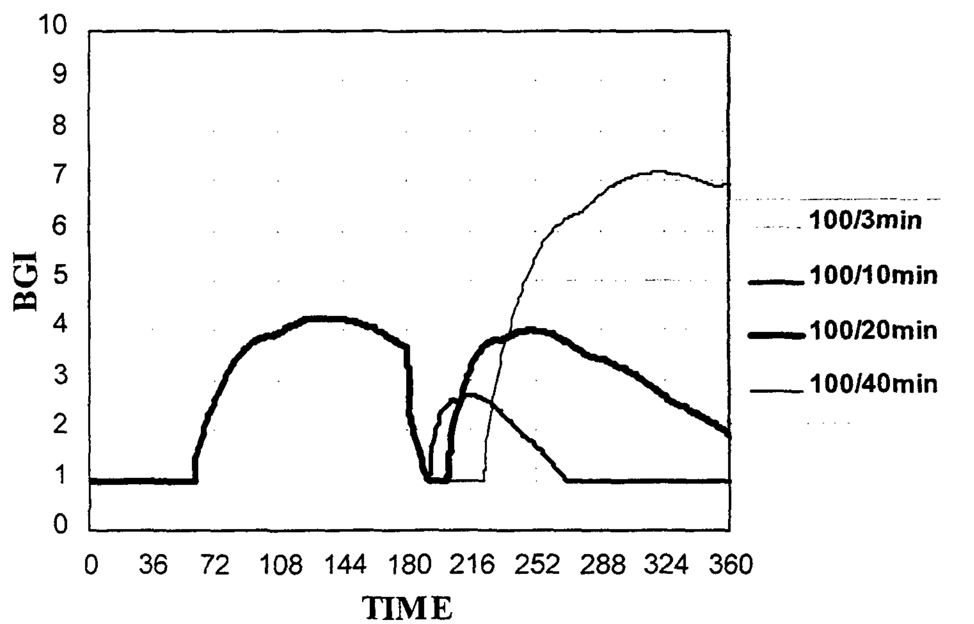

Figure 6. 60 fsw/60min, 2-hour surface interval, 100 fsw for 3, 10, 20 and 40-min bottom times.

Special Topics

In commercial construction diving, a technique called "Hang-Off" was developed to provide additional bottom time on dives that required rigging reconfigurations. The procedure allows the diver to leave the bottom, stop the bottom time and hang-off at 30 fsw (provided there are no decompression stops deeper than 30 fsw). The diver can then return to the bottom depth and resume the bottom time count. This procedure can be repeated several times. The theoretical decompression stresses associated with this form of reverse dive profile are illustrated in Figure 7. Although not used extensively, there have been no reports of DCS associated with this procedure in commercial diving operations (Ocean Systems, Oceaneering, Subsea International).

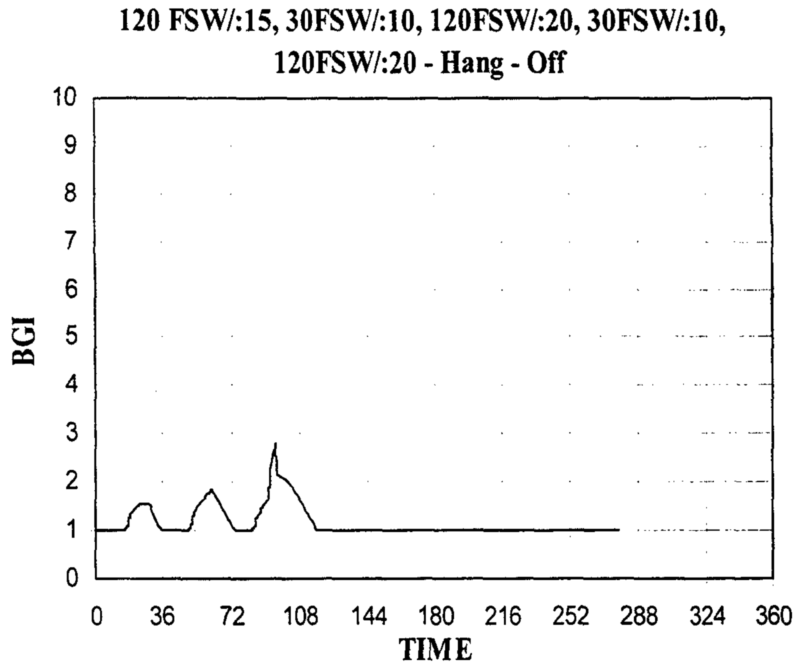

Figure 7. Commercial Division Hang-off procedure.

Influence of Exercise on Decompression Stress

A detailed discussion of the effects of exercise on inert gas uptake and elimination is beyond the scope of this paper. However, it has been well established that exercise during oxygen prebreathing prior to altitude decompression significantly reduces the risk of DCS (Webb *et al.*, 1996; Vann *et al.*, 1989).

There are also studies to indicate that exercise during decompression, at low levels of supersaturation, reduces the decompression stress as detected by VGE (Jankowski *et al.*, 1997).

Multi-depth diving is a common practice in both sport and commercial diving. The most common approach is to work at progressively shallower depths on the same dive. Figure 8 illustrates the theoretical bubble growth associated with a multi-depth dive, with progressively shallower versus deeper depths.

There is an obvious decompression advantage in working at progressively shallow depths. If exercise increases nitrogen uptake and elimination, the advantages of exercise would be beneficial when working at progressively shallower depths and detrimental when working at progressively deeper depths.

Multi-depth, Multi-gas Dive Profiles

Theoretically, the advantages of multi-depth, forward and reverse dive profiles can be enhanced by switching inert gases. A common technique used in some commercial diving operations during 1970-1980 was to perform a shallow air dive prior to switching to a HeO_2 breathing gas for a deep dive. Figure 9 illustrates the decompression stresses occurring in a 240 fsw/40 minute bottom time dive, preceded by a 30 and 60 min air dive at 30 fsw.

The theoretical predictions and limited field operational experience do not suggest DCS problems with these dives. However, it is important to point out that there is no hard scientific data to support the efficacy of this type of diving.

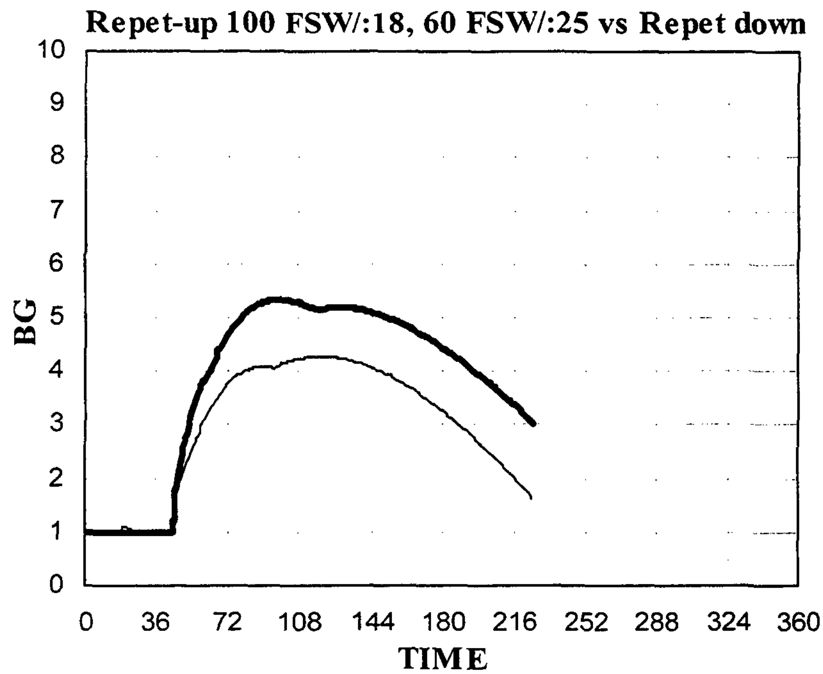

Figure 8. Multi-depth dives, forward vs. reverse profiles.

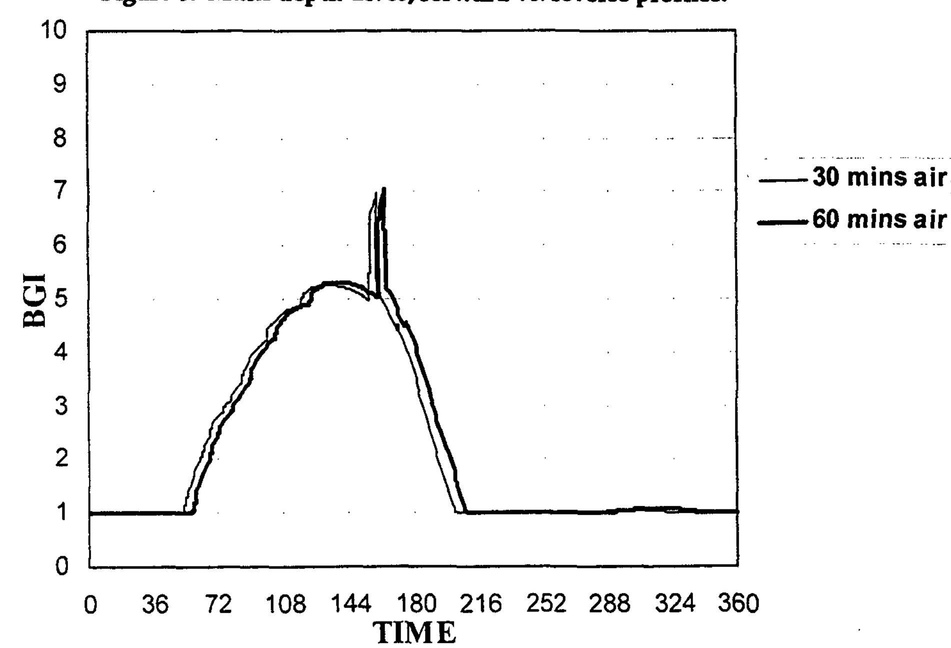

Figure 9. Multi-depth, multi-gas dive – 240 fsw/40 min – 16% HeO_2 preceded by air dives to 30 fsw (30 and 60 min).

Decompression tables have been developed (Gernhardt, 1985) to exploit the decompression advantages associated with multi-depth, multi-gas, reverse and forward dive profiles. These tables have not been used in operations and are suggested only as a possibility for additional research and development.

The approach of these tables is to first perform an air dive at a depth shallower than the final decompression stop of a subsequent gas dive. The diver is then switched to an HeO_2 mixture and works at the deepest level, followed by a shallower working depth on the same mixed gas. The diver is then switched back to air and performs work at two additional, progressively shallower working levels, followed by in-water decompression stops and surface decompression on oxygen. A typical profile is shown below in Table 6.

Table 6. Typical Multi-depth, Multi-gas Reverse Dive Profiles.

Depth (FSW)	Time (Minutes)	GAS
30	60-120	Air
240	40	He O_2 (10%)
180	40	He O_2
120	40	Air
610	80	Air

This type of diving would, theoretically, offer a very efficient work index (defined as bottom time/decompression time). At applicable depths, the work index associated with this type of diving approaches the efficiency of saturation dives as shown below in Table 7.

Table 7. Comparison of Decompression Efficiencies (Work Index).

Dive Type	Depth Range (FSW)	Work Index
SUR-D-O_2 (Single Depth)	70 - 170	.5 - .65
Repet Up	40 - 190	.8 – 1.0
Multi-Depth SUR-D-O_2	30 - 190	1.75 – 2.0
HeO_2 SUR-D-O_2	200 - 300	.4
Multi-Depth Multi-Gas	30 - 300	3.0 – 3.5
Saturation	300 FSW	3 – 10 (10 – 30 Days)

Conclusions and Recommendations

The theoretical predictions of the Bubble Dynamics model suggest that there are no fundamental differences in the decompression stresses associated with "no-decompression" forward and reverse dive profiles. It is not clear that the same is true of dives that require decompression stops. Although there are theoretical advantages associated with some applications of multi-gas reverse dive profiles, they have not been scientifically proven at this time. It is recommended that additional studies and data collection be performed to better characterize the risk of reverse dive profiles under a wider range of diving exposures.

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III. Physiology/Modeling Session Discussion.
Charles E. Lehner, Moderator

J. Lewis: Paul, I am wondering how many exposures occurred where there was no incidence of decompression sickness? Did they go into the overall model in some way?

P. Weathersby: Oh, absolutely.

J. Lewis: Then how do you deal with the idea if there is a threshold like Ron Nishi was talking about below which there is no expectation? It seems to me if you get any kind of a reasonable curve on something that has got a lot of zeros and you do a curve fit of everything, you are going to overestimate things that are near the threshold and below?

P. Weathersby: Well, my first answer is I don't believe in thresholds. If you dive, you have some finite chance of decompression sickness, regardless of the modesty of the dive. And the mathematical models that are used tend to allow that as a possibility and see if parameters reject it. What you do about non-decompression sickness outcome cases is defined by the principle of maximum likelihood that we use for estimating the parameters and the whole thing. You make a prediction of a hit, and in fact in this case we predict that the hit has to occur during the time when we know it did occur. So it ups the ante on your ability to predict. But the same calculation also carries the prediction that it shouldn't have occurred. So on a given profile, it may say I predict a 3 percent chance that this will have a hit and a 97 percent chance that it will not. Then, depending upon the outcome, you do the appropriate mathematical combination of the probability of that event maximized over the entire data set. Ninety percent of the outcomes in the calibration data set are uneventful.

J. Lewis: Is there anywhere in the modeling some explicit analytical feature of a curve for this? For example, if I plotted something?

P. Weathersby: Yes, that has its function.

J. Lewis: So that has been predetermined?

P. Weathersby: Yes.

J. Lewis: Do you know the sensitivity and the choice of that function?

P. Weathersby: We have published a number of those and over a fair range the sensitivity to the shape of the form of the function you wish to use is not particularly sensitive.

R. Nishi: Back to John's comment, I didn't want to give the impression that that threshold I talked about was a threshold of no DCS versus DCS. It is a low risk dive versus a high risk dive. So it is possible to be below that threshold I have mentioned and still have DCS.

B. Wienke: Paul, I have a question about your risk function. Were you using tissue tension minus ambient pressure divided by ambient pressure or something like that? Suppose you were to redo those profiles and use a risk function that was based on the deltas between the dives in those profiles? It would be interesting to see what your data would say on something like that.

P. Weathersby: Wayne Gerth is going to present later in this workshop the result of how the probabilistic models make pure predictions on hypothetical profiles, if that is what you are asking.

B. Wienke: I was just wondering if you were to apply that analysis to the data set here, what your incidence rate table would look like if you regrouped the profiles and just looked at some measure of the separation between dives in those profiles.

P. Weathersby: I haven't bothered to do so. The total number of reverse profiles is sufficiently small. I don't imagine there is any important power from the test.

W. Gerth: I will elaborate for Bruce Wienke about the forms of the risk functions. The three risk functions that underlie the three models, the results of which Paul presented there, USN93, the Duke BVM3, and then the JAP98-2 models - those risk functions are all very different. The important thing is that all of them provide correlations of a given data set that are roughly the same. Each of those different risk functions, those different structures, is really irrelevant what they are. They are providing a generalization of the same data, and that is reflected in the fact that, as Paul pointed out, the predictions on those profiles are all about the same for the three models. And that holds across the whole data set, which is extremely heterogeneous and diverse. Now the BVM-3 model, just to close, is a model that is very much different than the LE-1 or the USN93 and the JAP, and it has all these bubble dynamics things that you are talking about. In fact, it implements the Van Liew-Nostala bubble growth model in there. And the bubbles, unlike in the LE model, are able to grow by diffusion limitation or not. But it is the data that tells that model how to behave.

B. Wienke: I agree. I was wondering if there was just another way to portray the correlations against the data.

W. Gerth: The only governing factors are covariates that play into the outcome, DCS yes or no, in these models are the pressure, respired gas, and time profiles. Any other factors you might want to find there, are not part of the model structure.

V. Flook. Mike, in fairness to my current landlords, I have to say that the National Hyperbaric Center had nothing to do with the design of those profiles or the design of the trials. They only provided the knob twiddlers. I think it might be nice, Mike, if you were to relabel that table with the true culprits at the top, UK Health and Safety Executive.

M. Gernhardt: Will do.

V. Flook: And I can also carry on and say that we have successfully carried out trials of Sur-D decompressions earlier this year under my control, and they were able to operate the chambers and give you a properly constructed dive. So come back again and you will get it done better.

G. Beyerstein: I would just like to underscore what Mike said. We have about 4,000 decompression dives, Sur-D-O_2, not counting NoD's. These are actual dives that were in the chamber and involved chamber decompression on Sur-D-O_2, and a significant proportion of those are in water. They had water stops plus chamber decompression on the last phase of the tables that were introduced. Out of those 4,000 dives, many of which were equivalent to the U.S. Navy triple-Z's or quadruple-Z's for the operational planning limit. Because as you know in the commercial field, we always dive as long as we can. If it is shorter, it is only because the work was finished or the weather came up. But we had one suspected bend, a visual disturbance that cleared on the way to the chamber. We treated him anyway. So I think it is a really good testimony of the effectiveness of that model. And when we ever get a chance to find somebody to correlate all of these dives, we have about 300 or so of that set involved multi-level diving where we dived in one dive both descent and ascent at several levels, up and down, which is a feature of those tables. So it would be interesting to see and compare if we can set up a data base where we can actually get some operational data that might be useful to you people to analyze what effect there is as we talked about doing, shallow first or deep first.

T. Mutzbauer: I think this is the right audience to ask a question about something that I found in the literature when I prepared for this workshop. I found a lot about the subject in the lung filter and micro-bubbles measuring less than 20 micrometers are only partially trapped. The diameter of the lung capillaries is 3 to 15 micrometers, and micro-bubbles smaller than 3 micrometers are never trapped. We have heard a lot about these bubble sizes and the measurements and I have discussed this problem previously with Alf Brubakk, who told me that there has been some suggestion in the past about this issue. If you have a 20 micrometer bubble at 0 feet or 0 meters and you go down to 20 meters, this size is only 13.9 micrometers. So this might fit and is not trapped in the lung filter. Perhaps one of the speakers of the last session could comment on this with respect to possible damages to tissues after a repetitive dive or even a reverse profile.

M. Gernhardt: I will just make a brief comment on that. I am aware of the publications on that topic. The fact that we very successfully do Sur-D-O_2 dives, where you generate some gas phase in the water on the way to the chamber and then recompress in the chamber would be evidence that says that that is not a big factor. If it was a real big factor, I think you would see a real high incidence of DCS in Sur-D-O_2 diving that we don't see.

R. Vann: A comment for Till. There is a study done by Brian Smith in the 1970's with animals that showed if you used just the right surface interval so that the bubbles were peaked or began to peak at your compression on the second dive, then those bubbles could pass through the pulmonary filter and become arterialized. And there were some other studies by Hallenbeck in which they would use repetitive dives to preferentially generate spinal cord decompression sickness. This is animal stuff. It doesn't necessarily apply to humans. But at least the mechanisms do suggest that what you say could be correct.

A. Brubakk: I don't think that the size of the bubble actually matters that much. I think the most likely mechanism for breakthrough of gas through the lung vasculature is simply that you have a multi-gas coming into the lungs from the venous system and there is a balance between what you can excrete through the lungs and what is actually in the system. If there is an excess of gas in that vascular system, eventually that will break through to the arterial side. It is a matter of how much gas you have on the venous side, not a single bubble or one of 3 microns or whatever. It would probably get absorbed and get rid of. But if you have a lot of gas, in a lot of the studies that I am aware of, the data seems to point that that is the mechanism and much of the other data is simply spheres of other material, not something that is in dynamic equilibrium with the environment. So I think it is a matter of how much gas you have on the venous side. If you can limit that, then you limit the risk of actually having bubbles going through.

J. Lewis: Mike presented a slide that said, and I presume well-documented, 20,000 examples of no-decompression dives for which there were no incidences. Is that fair, Mike? I would really like to know what the predictions of the probabilistic model based on the Navy data are for those 20,000. I would like to know what the pDCS is that is predicted. It is only a fair question when these models are presented on a limited data base for which they are calibrated. It is just not fair to ignore other data bases with which to test them. In fact, I think the same thing with respect to these cases of NoD dives with no cases of incidence, 20,000 is a huge number. And also the same bubble models, not the probabilistic model, that we run against these repetitive deep dives which are problems, both of those cases are well documented, and it is important that these models be tested against those as well as the ones upon which they have been calibrated.

M. Gernhardt: Those are good points. Let me just add a little bit more information on these 20,000 dives. The no-decompression limits are driven out of the bubble dynamics model, and I won't read them all off to you, but they are basically less bottom time in the shallow depths and actually more bottom time in the deeper depths. The other thing to point out is these are not laboratory dives. These are field dives - well documented with dive sheets. But it does not mean that the divers went down and laid on the bottom for the full duration. So I think you've got to factor that into your analysis. I think you can walk away thinking these are low stress dives, for sure. But there is a limit to how far you can go without the time depth report.

P. Weathersby: I think I speak for Wayne Gerth and other people with probabilistic models. We are certainly willing to apply them in a predictive sense if anyone brings us 10,000 specific profiles with every detail of the dive in there. So far, no one has been able to hand such a package to us.

D. Yount: I thought I would make an off-the-wall comment. Alf was saying that it is really the volume of gas that matters and not the size of the gas bubbles, and that might be true because there is a phenomenon called micro-bubble fission, and when the large bubbles come together, instead of coalescing as we might think, they break apart. They fission. Brian Hills has observed this. It occurs when you have an environment with a critical monocell concentration and you have a large number of surfactant molecules around, as you certainly would have in the lung. So you might enter the lung with a 50 micron bubble, but you might find when you get a bunch of them crowded together that you have a lot of 20 micron bubbles.

A. Brubakk: I want to make a comment on what Mike Gernhardt said about the difference between the experiments that were done at the National Hyperbaric Center and the particular way he described it of in-water trials. There probably is another way of looking at that. And the way to look at it probably is at the outset the effect of the particular type of diving that we are using was not part of the original model. I mean, it is no part of that model as far as I understand that actually describes those particular circumstances. What it actually tells us is perhaps a more general rule that came as more or less of a surprise. Namely, that if you have a particular model developed and calibrated for one set of data, you cannot automatically use it for a different situation. There is no direct way of correlating that. So maybe that should give us some caution about when you calibrate the model with one set of data, how valid is that for a situation that might be different, for instance a different type of diving. And that experiment seemed to indicate that it actually is not so.

M. Gernhardt: I think in general that is true, particularly when you use data to calibrate your models and then try to extrapolate them. I think that in this particular case, there are some pretty compelling physiological differences in switching from a hot water suit to a cold air environment on the bottom, closing the hatch and so forth. So I don't know that this is a good example to support that point. And I would also say that the parameterization of the bubble model, although not rigorously statistical, was taken from reported values in the literature and operational records from one kind of diving. The Sur-D-O_2 tables that we actually developed were a completely different projection that had us doing bubble control with no water stops or deeper water stops. They really were an extrapolation from the data that they were calibrated on. So I agree with your point in general, but I don't think that this specific example illustrates it well.

A. Brubakk: The point is of course that the predictions from the animal experiments was that the bubble growth model would actually perform much better than the U.S. Navy procedures, and that is exactly what that experiment showed. Actually, there were more problems with your model, and we didn't know exactly how to correlate between what you got from the animals in absolute terms like I said. But for the comparison between the two different profiles, we got exactly the same results from the experimental work as for the animal work. So it actually worked out.

K. Huggins: If you've got the bubbles forming after the first dive, even though you may crush them on the second dive, are you not doing physiological damage and what are the ramifications of that in the models themselves for the outcome of the second dive - because you are looking at the effect of the bubble growth on both the first and the second dive?

V. Flook: I was asked by HSE about two years ago now to look specifically at the trials that had been carried out at NHC on Mike's profiles, and I did look at them using the facility that my model has to have different skin temperatures in different parts of the body. I think I was able to demonstrate quite well that the outcome of those trials would have been completely different, if the procedure had been carried out correctly and the divers hadn't stayed in that hot suit. But that was only my theoretical model for what it is worth. To answer Karl Huggins' question, to some extent this was the point I wanted to make with my last slide that, if you get a lot of bubbles after the first dive, it is just as bad as if you get them all after the second. Bubbles are bad and it doesn't matter when they come. And it is possible in my model to build in any physiological damage and any pathological damage if somebody could measure it and give me some numbers.

A. Brubakk: We actually have looked a bit at the endothelial damage caused by bubbles. What we found in our limited experience is that at least in animals, even a short exposure to high bubble grades will damage the endothelium. There are measurable changes in the pulmonary artery endothelium. What that means in terms of pathophysiology, in terms of real damage to the organism, I do not know. The cells probably get regenerated. But it is no doubt that both these exposures, regardless of which way you do them, will produce changes in endothelium, at least experimentally.

C. Lehner: Specifically, Alf, what kind of endothelial damage?

A. Brubakk: Specifically you can see that the endothelial layer gets destroyed, and it is actually a large part of it that simply disappears. You can see the underlying muscular layers. We also tested the response of the vessels to endothelial-dependent substances to measure the degree, and there was less activity shown. So that is quite well documented. It was published in the UBR a short while ago.

ESTIMATED DCS RISKS OF REVERSE DIVE PROFILES

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Safety, efficiency and operational considerations motivate the advisability of diving "reverse" profiles, or profiles in which one or more repetitive dives are made to depths deeper than those of their antecedent dives. From the standpoint of safety and risk of decompression sickness (DCS), such profiles can arguably be dived to within any level of acceptable DCS risk if the dive bottom times and intervening surface intervals are appropriately scheduled. Thus, the safety of such diving practices rests largely on the method(s) used to schedule the dives. In the absence of primary empirical information, probabilistic models of DCS occurrence can be used to assess both the "safety" of schedules prescribed by any given method and the suitability of that method for application to particular types of diving. Probabilistic models, including the Duke implementation of the USN93 Air/N_2O_2 algorithm and the Duke BVM(3) gas and bubble dynamics model, were used to estimate the probabilities of DCS for hypothetical repetitive air dive profiles, including reverse profiles, provided by representatives of dive computer manufacturers in response to a questionnaire. Each profile consisted of two dives, with dive depths and intervening surface intervals specified in the questionnaire. Responders provided the no-decompression limit bottom times for the dives computed using algorithms that operate in a variety of commercially available dive computers. Estimated DCS risks of all profiles completed by the various algorithms were generally lower than the mean estimated DCS risk of the USN Standard Air no-decompression limits. In particular, the algorithms tested schedule no-decompression reverse dive profiles that incur estimated DCS risks similar to those they allow for "regular" no-decompression dives.

Introduction

Safety, efficiency and operational considerations motivate the advisability of diving reverse profiles, or profiles in which one or more dives are made to depths deeper than those of their antecedent dives. From the standpoint of safety and risk of decompression sickness (DCS), such profiles can arguably be dived to within any level of acceptable DCS risk, if the dive bottom times and intervening surface intervals are appropriately scheduled. Thus, the safety of such diving practice rests largely on the method(s) used to schedule the dives. In the absence of primary empirical information, probabilistic models of DCS occurrence can be used to assess both the "safety" of schedules prescribed by any given method and the suitability of that method for application to particular types of diving.

A probabilistic model of DCS occurrence is a formal mathematical and logical expression of a hypothetical relationship between selected properties of a dive profile and the probability that an individual will remain DCS-free throughout that profile. Rigorous statistical methods are then used to quantitatively adjust, or calibrate, the model to provide its best possible correlation of observed decompression outcomes in a large and heterogeneous collection of well-described dives. The methods include tools to formally assess the ability of a model to describe its calibration data, or any other data, and compare that ability among different models. A successful model is judged to provide a descriptive generalization of its calibration data suitable for making interpolations within, and extrapolations from, that data. Such models thus provide a "ruler" by which untested profiles can be evaluated against available high quality data.

Probabilistic models were used in present work to estimate the probabilities of DCS for hypothetical no-stop repetitive air dive profiles, including reverse dive profiles, provided by developers of decompression algorithms for commercially available dive computers. Profiles for similar dives prescribed by the U.S. Navy Standard Air Tables, the DCIEM Sport Diving Tables, and the PADI/DSAT Recreational Dive Planner were also analyzed. Finally, selected repetitive air dive profiles completed using the U.S. Navy Standard Air Tables were analyzed in which one of two dives in each profile exceeded the no-stop limit and required decompression stops. Results were used to ascertain whether the various methods for scheduling repetitive dives produced schedules with DCS risks in "reverse" profiles different from those allowed in "regular" profiles.

Profiles Analyzed

Most of the profiles analyzed in this work were obtained in response to informal questionnaires prepared by coordinators of the Reverse Dive Profiles Workshop and circulated to developers of decompression algorithms for dive computer manufacturers. The questionnaires presented dive profile templates that the developers were asked to complete using algorithms that operate in their commercially available dive computers. The profile templates are given in Tables I and II. Each profile consisted of two dives with specified dive depths and intervening surface intervals. Responders completed each Series I profile in Table I by providing the no-stop (=no-decompression) limit bottom times for both dives. Series II profiles in Table II required completion of similar information for some profiles, and included others that only required completion of the no-stop limit for the second dive after a first dive to specified depth and bottom time.

A total of 417 completed profiles were returned by the respondents listed in the Acknowledgments, as some elected to provide additional information for dives not included in the questionnaire.

Table I. Series I dive profile templates.

	1st DIVE		SURFACE INTERVAL	2nd DIVE	
	Depth (fsw)	Bottom Time (min)	(min)	Depth (fsw)	Bottom Time (min)
1a)	40	NDL ?	30	100	NDL ?
1b)	100	NDL ?	30	40	NDL ?
2a)	40	NDL ?	60	100	NDL ?
2b)	100	NDL ?	60	40	NDL ?
3a)	40	NDL ?	120	100	NDL ?
3b)	100	NDL ?	120	40	NDL ?

Table II. Series II dive profile templates.

	1st DIVE		SURFACE INTERVAL	2nd DIVE	
	Depth (fsw)	Bottom Time (min)	(min)	Depth (fsw)	Bottom Time (min)
1a)	100	15	60	60	NDL ?
1b)	60	30	60	100	NDL ?
1c)	100	NDL ?	60	60	NDL ?
1d)	60	NDL ?	60	100	NDL ?
2a)	100	15	120	60	NDL ?
2b)	60	30	120	100	NDL ?
2c)	100	NDL ?	120	60	NDL ?
2d)	60	NDL ?	120	100	NDL ?
3a)	100	15	240	60	NDL ?
3b)	60	30	240	100	NDL ?
3c)	100	NDL ?	240	60	NDL ?
3d)	60	NDL ?	240	100	NDL ?

Models

All profiles were analyzed using two probabilistic models of DCS incidence and time of occurrence: the USN93 Air/N_2-O_2 Algorithm (Parker *et al.*, 1992; Survanshi *et al.*, 1997; Thalmann *et al.*, 1997) and the Duke BVM(3) gas and bubble dynamics model (Gerth and Vann, 1996; 1997). The USN93 Air/N_2-O_2 algorithm was used as independently implemented at Duke University from published reports (Gerth and Vann, 1996; 1997), and is herein designated as USN93D. Both models use hazard/risk functions of varying complexity and have been calibrated using high quality data from 3322 air and N_2-O_2 man-dives, including a limited number of reverse dive profiles (Weathersby and Gerth, this volume).

Results

Completed profiles and respective model-estimated DCS probabilities are given in Tables A.1 – A.10 appended to this paper. It is useful to consider the magnitudes of these probabilities in comparison to the estimated DCS probabilities for familiar dives. Model-estimated DCS probabilities for single dives to the no-stop limits of the U.S. Navy Standard Air Tables are given in Table III. The probabilities estimated by the two models for each dive are similar and vary with dive depth. Shallow dives to their no-stop limits incur higher DCS probabilities than deep dives to their no-stop limits. The mean DCS probability for all the dives according to either model slightly exceeds 2.0%.

Table III. Estimated DCS probabilities for the no-stop limits in the USN Standard Air Tables.

Depth (fsw)	No-Stop Limit (min)	P_{DCS}, % (95% CL) BVM(3)		USN93D	
35	310	4.7	(4.0 - 5.4)	5.5	(4.5 - 6.7)
40	200	3.4	(2.9 - 3.9)	4.0	(3.2 - 5.0)
50	100	2.0	(1.6 - 2.6)	2.5	(2.0 - 3.3)
60	60	1.7	(1.2 - 2.3)	2.1	(1.6 - 2.8)
70	50	2.1	(1.5 - 2.7)	2.4	(1.8 - 3.1)
80	40	2.2	(1.6 - 2.9)	2.4	(1.8 - 3.1)
90	30	2.2	(1.6 - 3.0)	2.1	(1.6 - 2.8)
100	25	2.3	(1.6 - 3.1)	2.1	(1.5 - 2.8)
110	20	2.2	(1.6 - 3.1)	1.9	(1.4 - 2.6)
120	15	2.0	(1.3 - 2.9)	1.7	(1.1 - 2.3)
130	10	1.7	(1.0 - 2.7)	1.3	(0.8 - 2.1)
140	10	1.9	(1.2 - 3.0)	1.5	(0.9 - 2.2)
150	5	1.4	(0.7 - 2.6)	1.1	(0.6 - 1.9)
160	5	1.5	(0.8 - 2.8)	1.2	(0.6 - 2.0)
170	5	1.7	(0.8 - 3.1)	1.2	(0.7 - 2.1)
180	5	1.8	(0.9 - 3.3)	1.3	(0.7 - 2.2)
190	5	2.0	(1.0 - 3.5)	1.3	(0.8 - 2.2)
	Mean =	2.2		2.1	

Total bottom times and model-estimated DCS probabilities for individual dive pairs in "forward" mode (deepest dive first) and "reverse" mode (shallow dive first) were collected for the various algorithms and decompression tables from Tables A.1 - A.10 and illustrated in Figures A.1 – A.9, also appended to this paper. Total bottom times for dive pairs with both dives to their prescribed no-stop limits tended to be higher with the pairs configured in reverse mode than when configured in forward mode, regardless of the methods used to compute the limits (Figures A.1 –A.6). In contrast, total bottom times for pairs in which the first dives have bottom times lower than their respective no-stop limits tended to be higher with the dives configured in forward mode (Figures A.7 – A.9).

DCS probabilities estimated by the two models for a given profile usually agreed to within the 95% binomial confidence limits on the estimates. Estimated probabilities for all the no-stop, single repetitive dive profiles examined tended to fall in the 1.0 – 3.0% range, making them comparable to the DCS risks estimated for dives to the USN Standard Air no-stop limits.

With three exceptions, DCS probabilities obtained using either model for each "forward" - "reverse" profile pair examined were equal to within the 95% confidence limits on the estimates. DCS risks estimated by both models for schedules prescribed by the Suunto Vyper algorithm for the Series I 1a-b and 2a-b profile pairs were significantly higher for the dives in the reverse configuration (Figures A.1 and A.2). Similarly, DCS risks estimated by the USN93D model for schedules prescribed by the Suunto Vyper algorithm for the series I 3a-b pair were also significantly higher for the dives in reverse configuration (Figure A.3). The magnitude of the probabilities in these exceptional cases, however, remained within the range of the probabilities for profiles prescribed by the other methods. Overall, then, the various methods for scheduling these profiles allow DCS risks in "reverse" profiles indistinguishably different from the risks allowed in the respective "forward" profiles.

Decompression Diving

It must be emphasized that the above analyses included only no-stop dives in profiles with only a single repetitive dive. It is readily illustrated that results for such profiles cannot be generalized into the domain of dives that require decompression stops. Using the U.S. Navy Standard Air Tables, repetitive air dive profiles were completed in which one of two dives in each profile exceeded the no-stop limit and required decompression stops. Two dive pairs were examined: a) 40fsw/150 min and b) 120fsw/30 min. Two series of profiles were generated for each dive pair by holding the bottom times on the two dives constant while decreasing the surface interval between the dives. The dives were configured in "forward" mode in one series, and in "reverse" mode in the other. In principle, the tables should accommodate such conditions by adding and prolonging decompression stops. Profiles were analyzed using the USN93 probabilistic model to yield results illustrated in Figures 1 and 2.

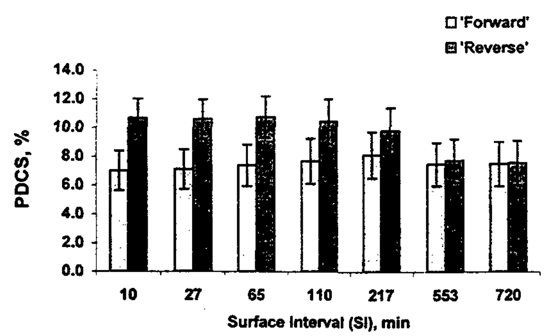

Figure 1. USN93-estimated DCS risks for 120fsw/40min (decompression) and 40fsw/150 min dives paired in "forward" and "reverse" modes with indicated intervening surface interval times.

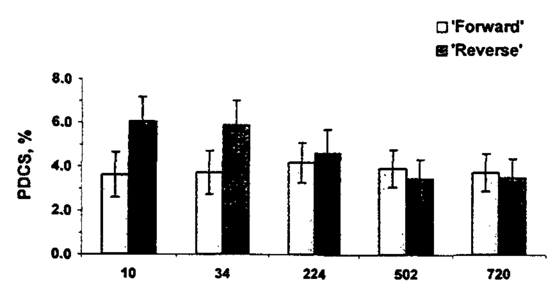

Figure 2. USN93-estimated DCS risks for 100fsw/30 min (decompression) and 40fsw/150 min dives paired in "forward" and "reverse" modes with indicated intervening surface interval times.

In both series, the "reverse" profiles have DCS probabilities that become higher than those of their "forward" counterparts as the surface interval is decreased. The differences become significant for each profile pair at the shortest surface intervals, as the 95% confidence intervals on the estimates fail to overlap. Such significant differences would be expected to be observable in an actual experimental trial of either series. These results clearly indicate that the Standard Air Tables may be inadequate to the task of scheduling reverse profiles that include dives requiring increasing amounts of decompression time. They may also provide some insights into the origin of the current bias against reverse dive profiles.

Early operational experience with these tables in accord with these model estimates would have discouraged such diving.

Conclusions

Estimated DCS risks of all profiles completed by the various algorithms were generally near or below the mean estimated DCS risk of the USN Standard Air no-stop limits. The algorithms tested prescribe schedules for no-stop reverse dive profiles that incur estimated DCS risks similar to those they allow for "forward" no-stop dives. Results cannot be generalized to decompression diving or profiles with multiple repetitive dives.

Acknowledgments

We are grateful to the following individuals who completed and forwarded most of the dive profiles analyzed in this work: Stefano Giovanni (Mares), Karl Huggins (Orca), John Lewis (Oceanic), Jarmo Luukkanen (Suunto), Ron Nishi (DCIEM), Ernst Voellm (Dynatron), and Eric Yester (Mares).

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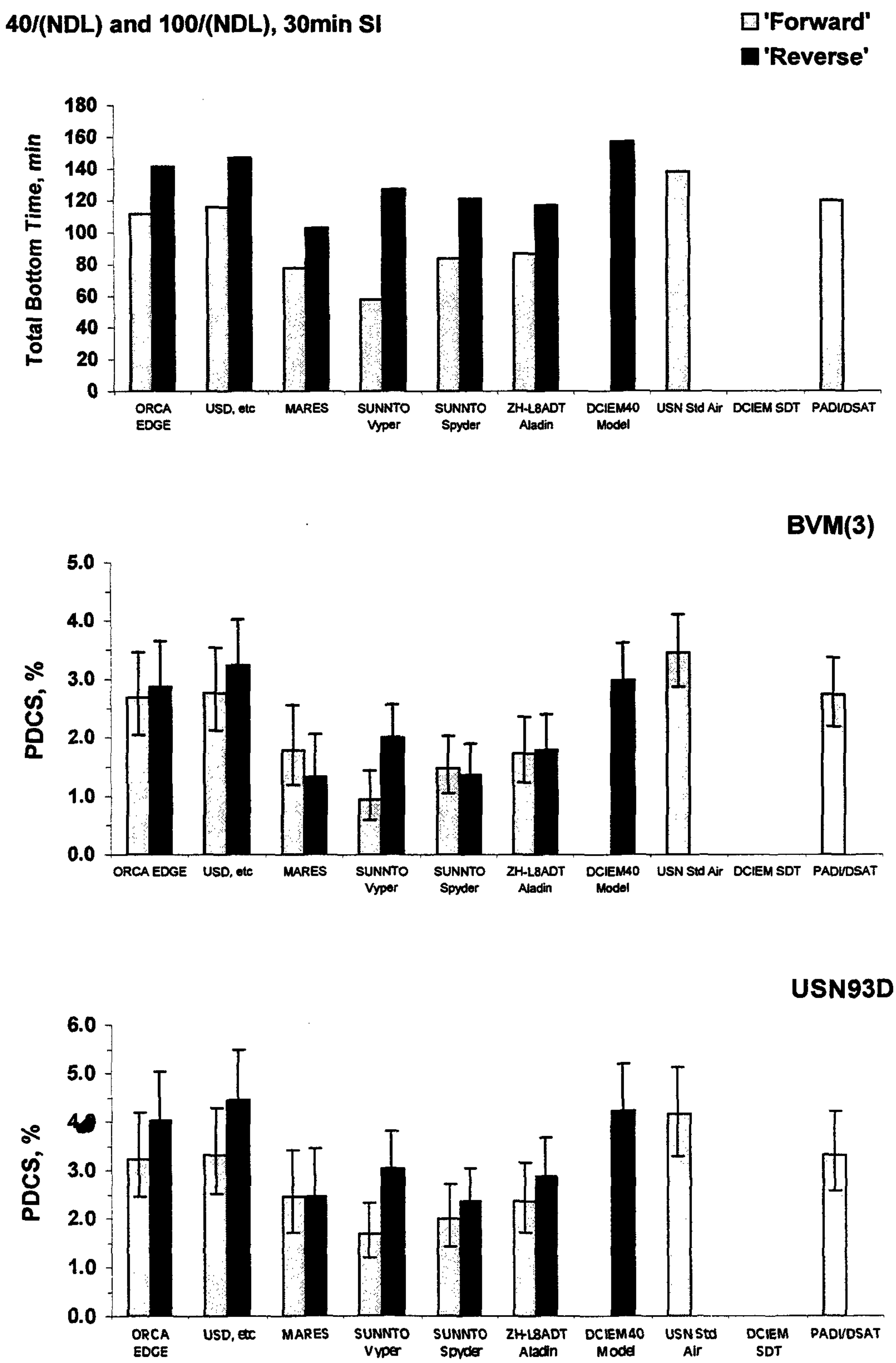
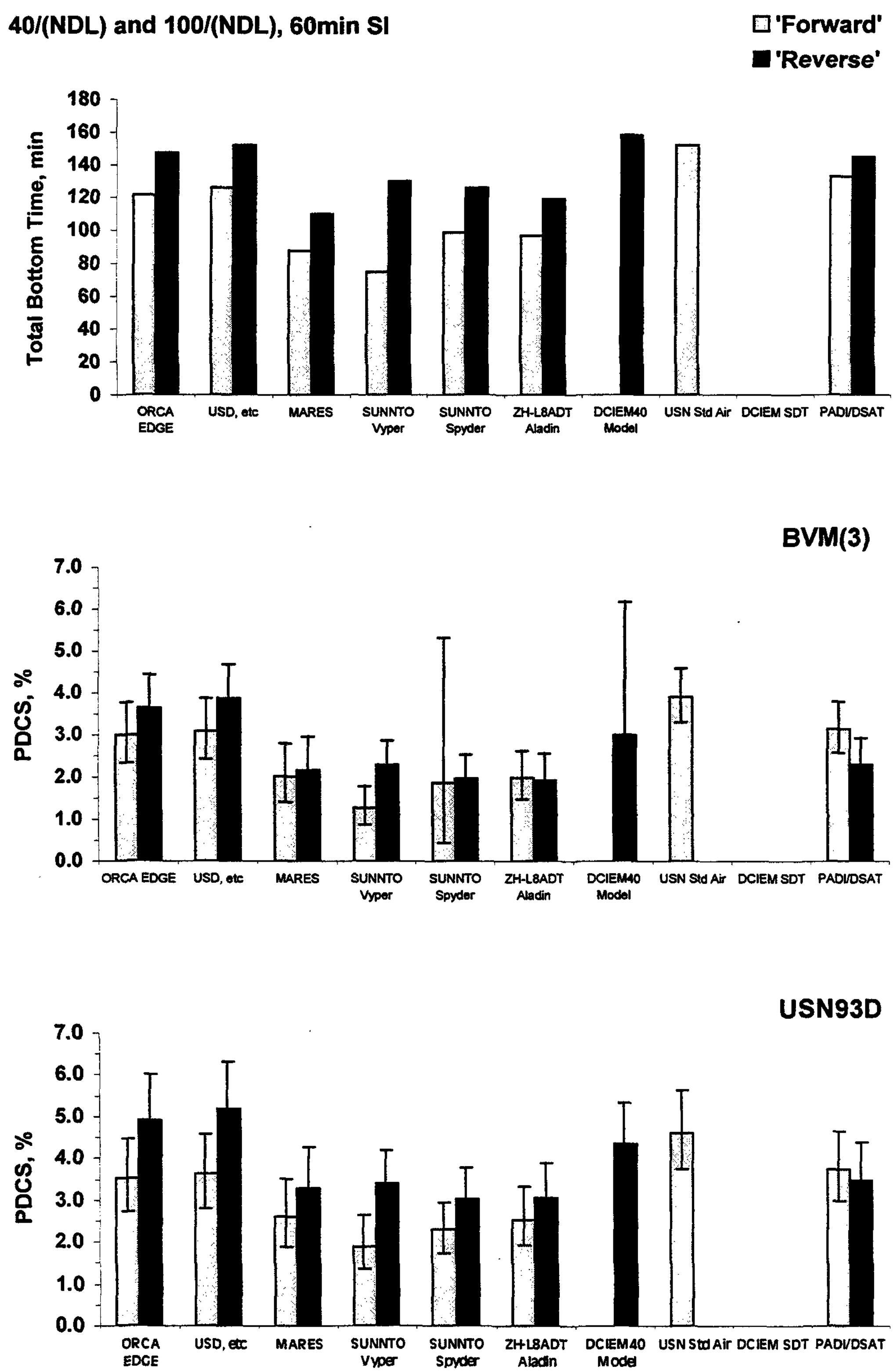


40/(NDL) and 100/(NDL), 30min SI
'Forward'
'Reverse'
Total Bottom Time, min
180
160
140
120
100
80
60
40
20
0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
5.0
4.0
3.0
2.0
1.0
0.0
USN93D
6.0

Figure A.1.



40/(NDL) and 100/(NDL), 60min SI
'Forward'
'Reverse'
Total Bottom Time, min
180
160
140
120
100
80
60
40
20
0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
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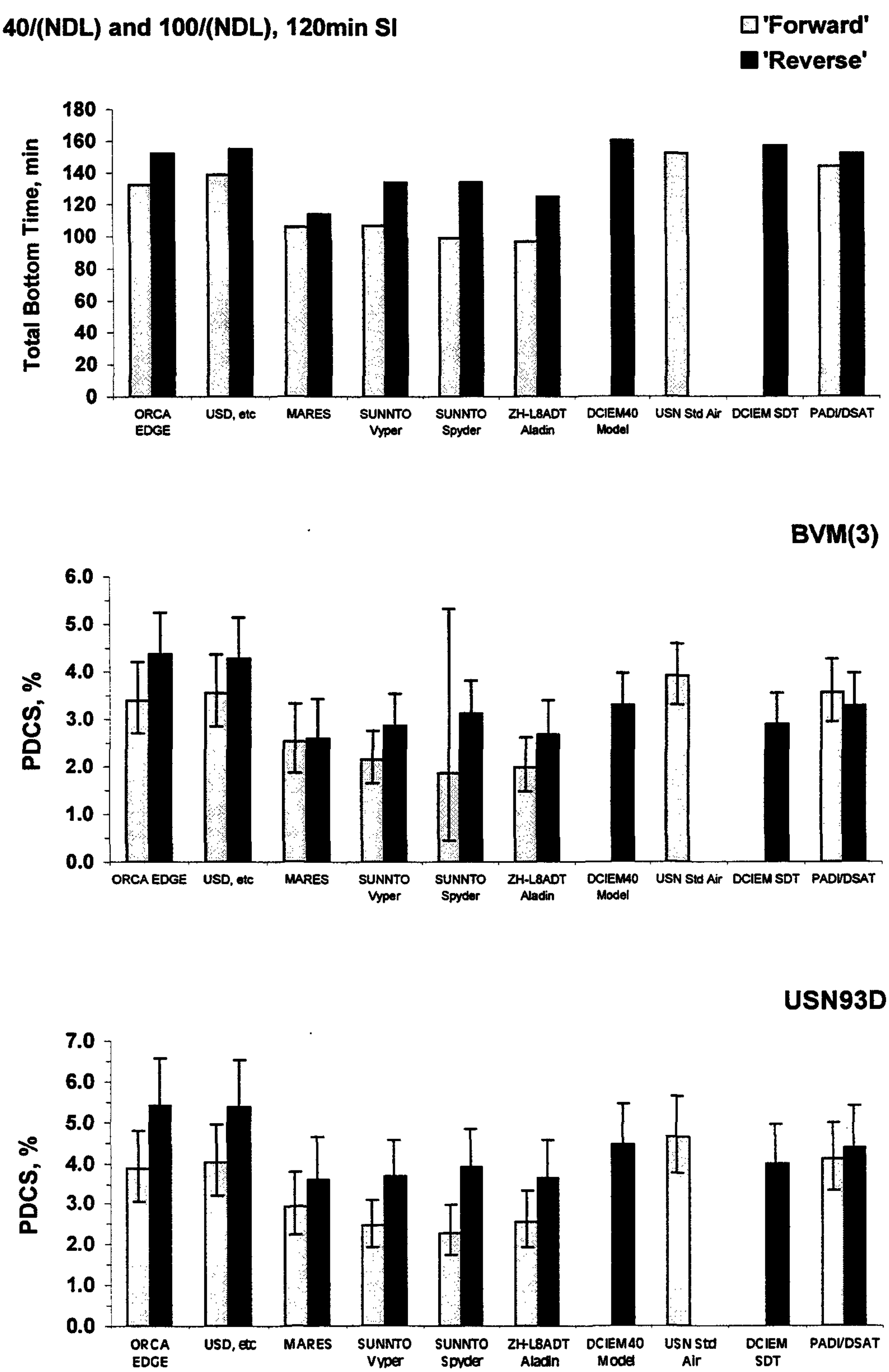
6.0
5.0
4.0
3.0
2.0
1.0
0.0
USN93D

Figure A.2.


40/(NDL) and 100/(NDL), 120min SI
'Forward'
'Reverse'
Total Bottom Time, min
180
160
140
120
100
80
60
40
20
0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
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5.0
4.0
3.0
2.0
1.0
0.0
USN93D
7.0

Figure A.3.

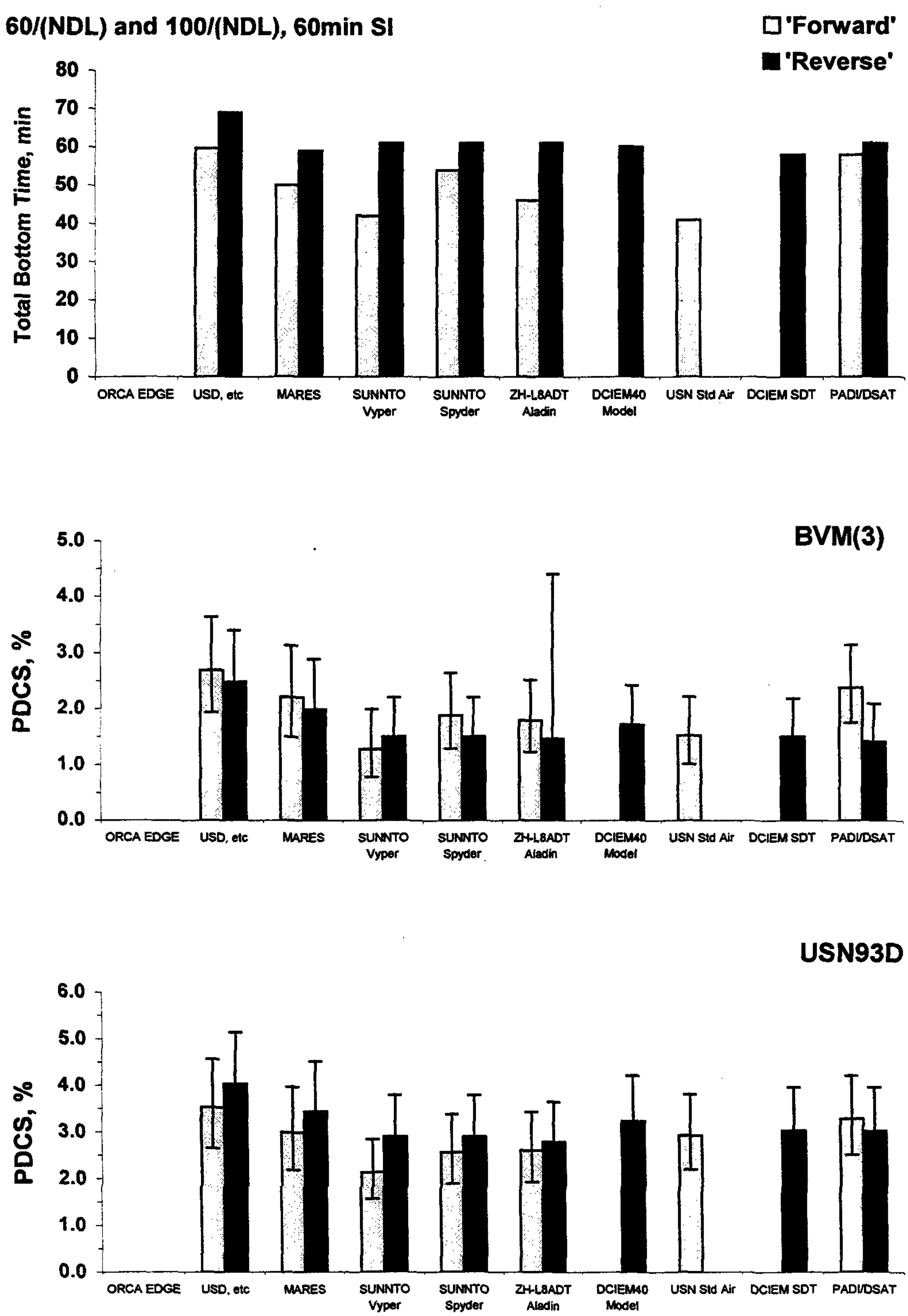
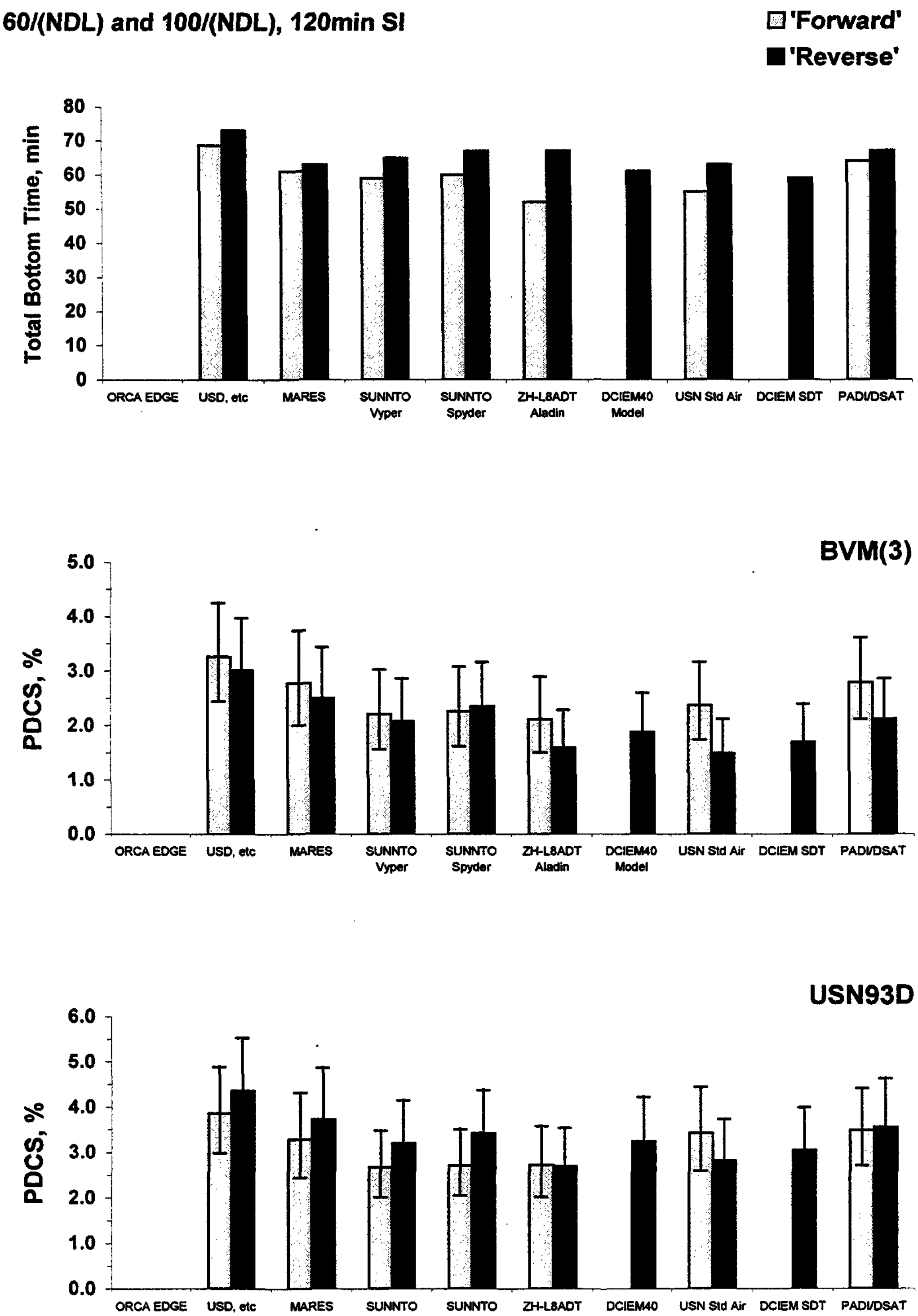

60/(NDL) and 100/(NDL), 60min SI
'Forward'
'Reverse'
Total Bottom Time, min
0
10
20
30
40
50
60
70
80
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
USN93D
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
6.0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT

Figure A.4.



60/(NDL) and 100/(NDL), 120min SI
'Forward'
'Reverse'
Total Bottom Time, min
0
10
20
30
40
50
60
70
80
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
USN93D
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure A.5.

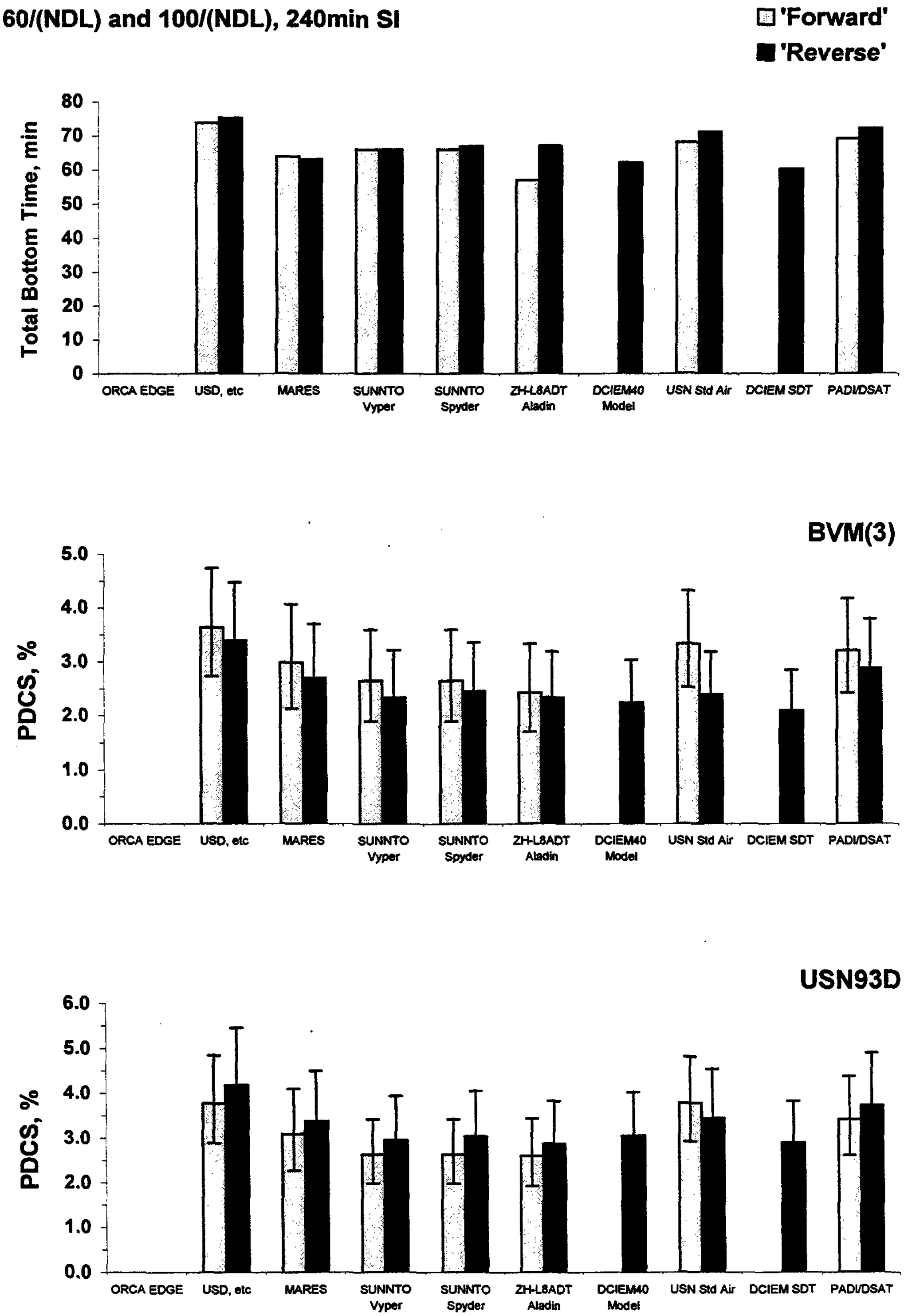
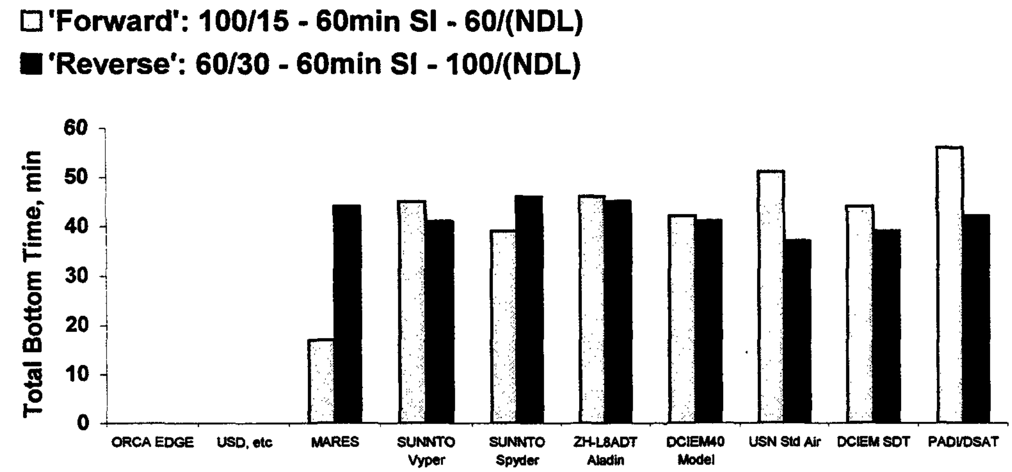

60/(NDL) and 100/(NDL), 240min SI
'Forward'
'Reverse'
Total Bottom Time, min
0
10
20
30
40
50
60
70
80
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
USN93D
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
6.0

Figure A.6.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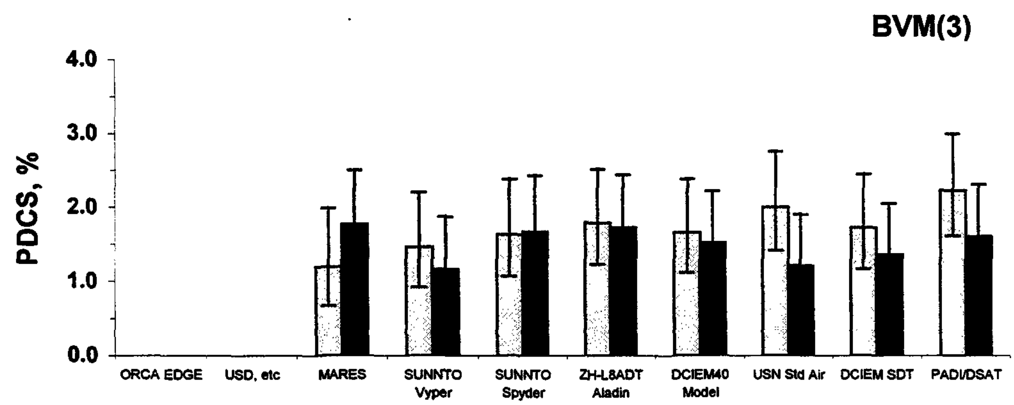
'Reverse': 60/30 - 60min SI - 100/(NDL)
Total Bottom Time, min
0
10
20
30
40
50
60
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT


BVM(3)
PDCS, %
0.0
1.0
2.0
3.0
4.0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT

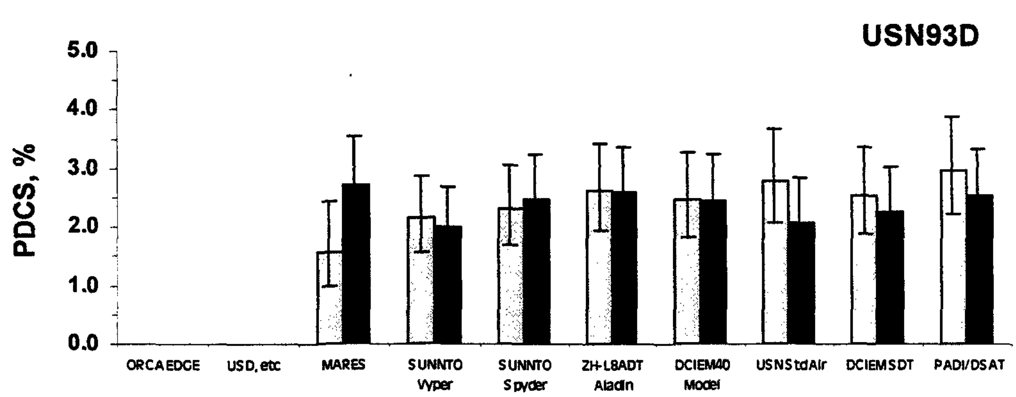

USN93D
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT

Figure A.7.

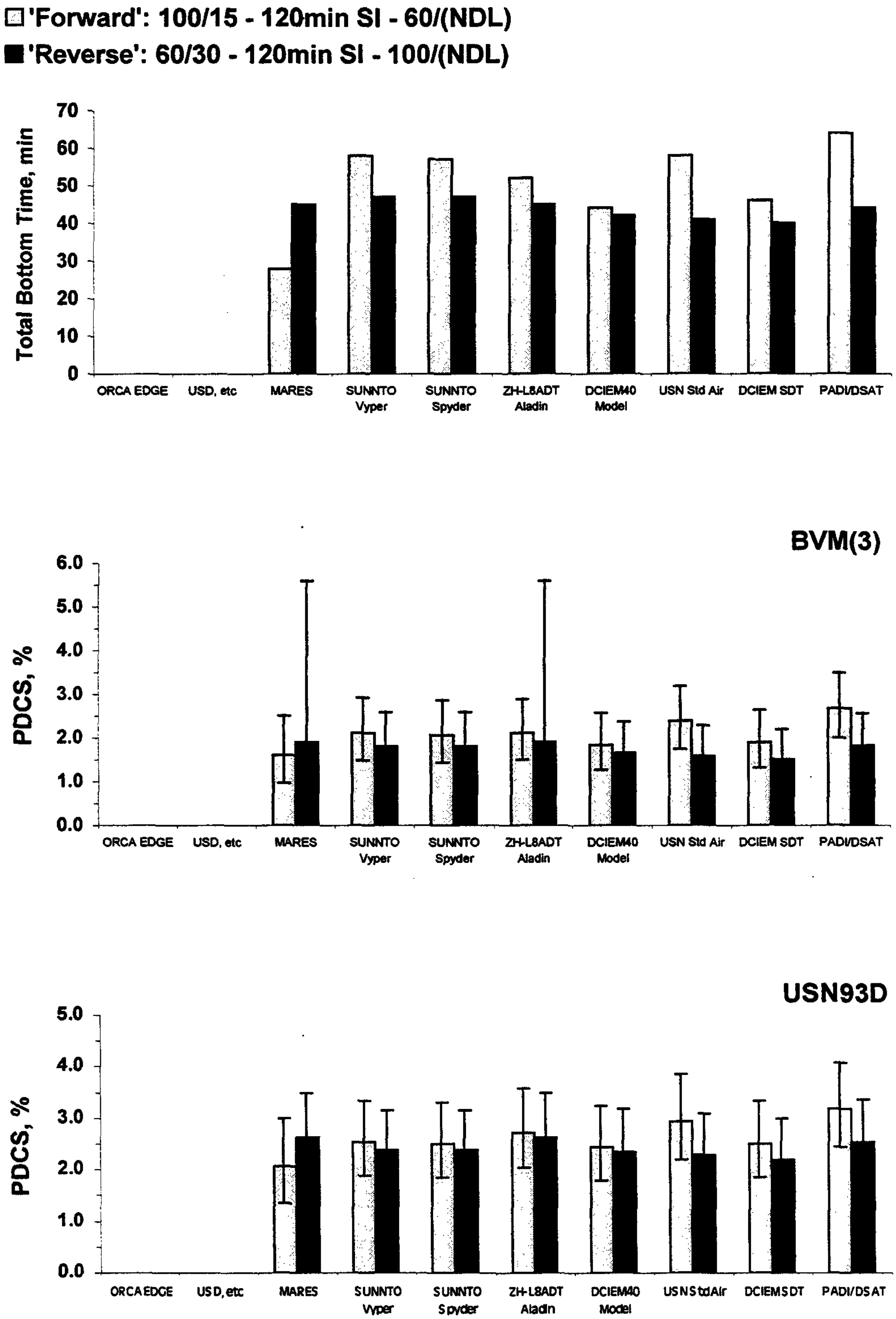
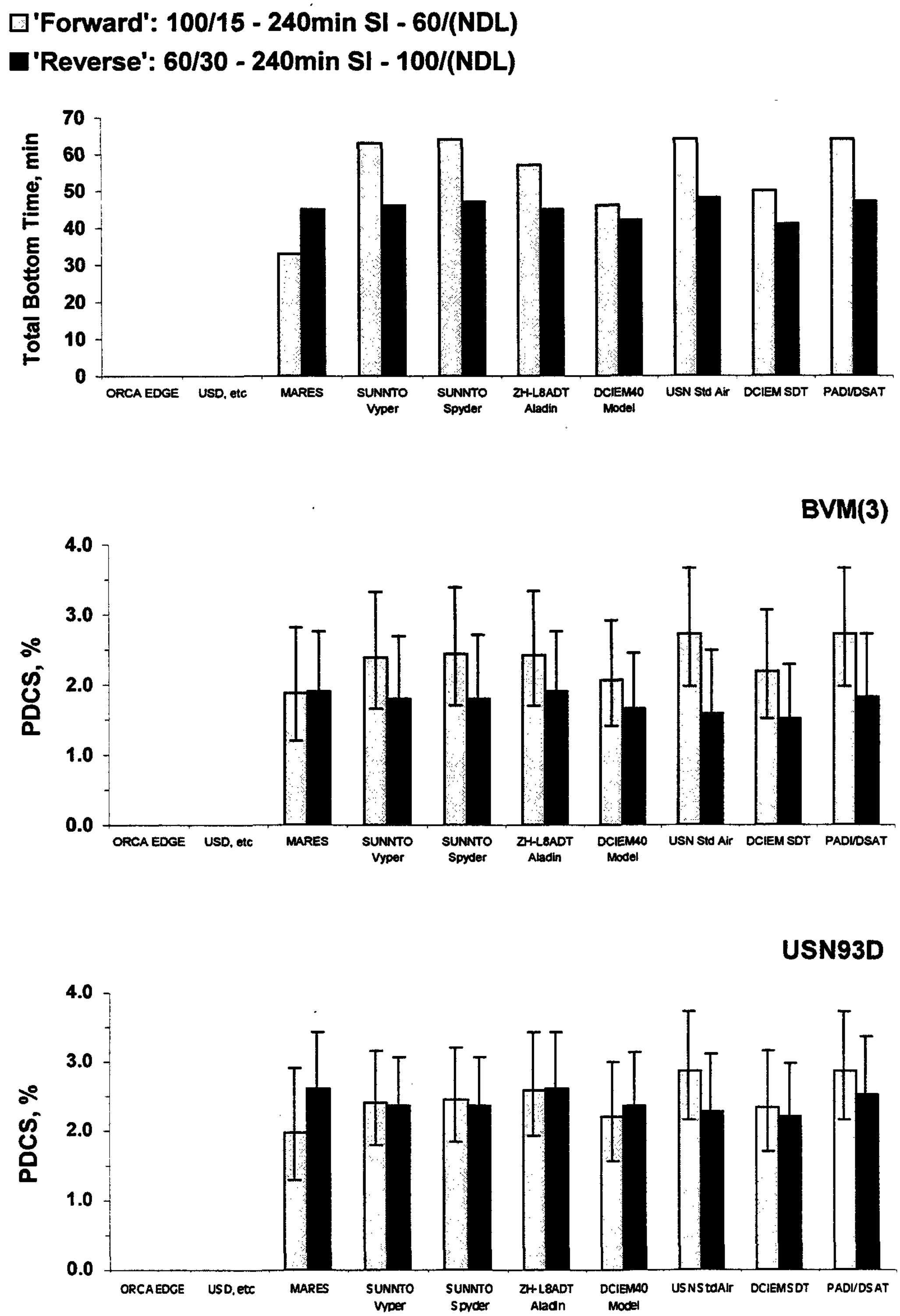

'Forward': 100/15 - 120min SI - 60/(NDL)
'Reverse': 60/30 - 120min SI - 100/(NDL)
Total Bottom Time, min
0
10
20
30
40
50
60
70
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0
6.0
USN93D
PDCS, %
0.0
1.0
2.0
3.0
4.0
5.0

Figure A.8.



'Forward': 100/15 - 240min SI - 60/(NDL)
'Reverse': 60/30 - 240min SI - 100/(NDL)
Total Bottom Time, min
0
10
20
30
40
50
60
70
ORCA EDGE
USD, etc
MARES
SUNNTO Vyper
SUNNTO Spyder
ZH-L8ADT Aladin
DCIEM40 Model
USN Std Air
DCIEM SDT
PADI/DSAT
BVM(3)
PDCS, %
0.0
1.0
2.0
3.0
4.0
USN93D

Figure A.9.

Table A.1. ORCA EDGE.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	133.0	30	100	8.4	141.4	2.9	(2.2 - 3.7)	4.0	(3.2 - 5.0)
		60	100	14.3	147.3	3.6	(3.0 - 4.5)	4.9	(4.0 - 6.0)
		120	*100*	*19.3*	*152.3*	*4.4*	*(3.6 - 5.2)*	*5.4*	*(4.4 - 6.6)*
100	19.4	30	40	92.4	111.8	2.7	(2.0 - 3.5)	3.2	(2.4 - 4.2)
		60	40	102.0	121.4	3.0	(2.3 - 3.8)	3.5	(2.7 - 4.5)
		120	40	113	132.4	3.4	(2.7 - 4.2)	3.9	(3.1 - 4.8)

Table A.2. Aeris, Dacor Quantum Loop, Genesis, Oceanic, Pelagic, USD Maris.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	137	30	100	10	147	3.2	(2.6 - 4.0)	4.4	(3.6 - 5.5)
		60	100	15	152	3.9	(3.2 - 4.7)	5.2	(4.2 - 6.3)
		120	100	18	155	4.3	(3.5 - 5.1)	5.4	(4.3 - 6.5)
60	56	30	100	9	65	2.2	(1.5 - 3.1)	3.6	(2.7 - 4.7)
		60	100	13	69	2.5	(1.8 - 3.4)	4.0	(3 1 - 5.1)
		120	100	17	73	3.0	(2.2 - 4.0)	4.4	(3.4 - 5.5)
		180	100	18	74	3.5	(2.7 - 4.5)	4.8	(3.9 - 6.0)
		240	100	19.2	75.2	3.4	(2.5 - 4.5)	4.2	(3.1 - 5.5)
		300	100	19.5	75.5	3.4	(2.5 - 4.6)	4.0	(2.9 - 5.3)
100	19	30	40	97	116	2.8	(2.1 - 3.5)	3.3	(2.5 - 4.3)
		60	40	107	126	3.1	(2.4 - 3.9)	3.6	(2.8 - 4.6)
		120	40	120	139	3.6	(2.9 - 4.4)	4.0	(3.2 - 5.0)
100	19.7	0	60	15	34.7				
		30	60	32	51.7	2.4	(1.6 - 3.3)	3.2	(2.4 - 4.3)
		60	60	40	59.7	2.7	(1.9 - 3.6)	3.5	(2.7 - 4.6)
		120	60	49	68.7	3.3	(2.4 - 4.3)	3.9	(3.0 - 4.9)
		180	60	52	71.7	3.5	(2.6 - 4.5)	3.9	(3.0 - 4.9)
		240	60	54	73.7	3.6	(2.7 - 4.7)	3.8	(2.9 - 4.8)
		300	60	55	74.7	3.7	(2.7 - 4.8)	3.7	(2.8 - 4.7)

Table A.3. MARES.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)		
40	99 (NDL)	30	100	4	103	1.3	(.8 - 2.1)	2.4	(1.7 - 3.4)	1a
		60	100	11	110	2.2	(1.5 - 3.0)	3.3	(2.5 - 4.3)	2a
		120	100	15	114	2.6	(1.9 - 3.4)	3.6	(2.7 - 4.6)	3a
60	30	60	100	14	44	1.8	(1.2 - 2.5)	2.7	(2.0 - 3.5)	II-1b
		120	100	15	45	1.9	(.4 - 5.6)	2.6	(1.9 - 3.5)	II-2b
		240	100	15	45	2.0	(1.4 - 2.9)	2.2	(1.6 - 3.0)	II-3b
60	48 (NDL)	60	100	11	59	2.0	(1.3 - 2.9)	3.4	(2.6 - 4.5)	II-1d
		120	100	15	63	2.5	(1.8 - 3.4)	3.7	(2.8 - 4.9)	II-2d
		240	100	15	63	2.7	(1.9 - 3.7)	3.4	(2.5 - 4.5)	II-3d
100	16 (NDL)	30	40	62	78	1.8	(1.2 - 2.6)	2.5	(1.7 - 3.4)	1b
		60	40	72	88	2.0	(1.4 - 2.8)	2.6	(1.9 - 3.5)	2b
		120	40	90	106	2.5	(1.9 - 3.3)	2.9	(2.3 - 3.8)	3b
100	15	60	60	2	17	1.2	(.7 - 2.0)	1.6	(1.0 - 2.4)	II-1a
		120	60	13	28	1.6	(1.0 - 2.5)	2.1	(1.4 - 3.0)	II-2a
		240	60	18	33	1.9	(1.2 - 2.8)	2.0	(1.3 - 2.9)	II-3a
100	16 (NDL)	60	60	34	50	2.2	(1.5 - 3.1)	3.0	(2.2 - 4.0)	II-1c
		120	60	45	61	2.8	(2.0 - 3.7)	3.3	(2.4 - 4.3)	II-2c
		240	60	48	64	3.0	(2.1 - 4.1)	3.1	(2.3 - 4.1)	II-3c

Table A.4. SUUNTO Vyper. Ascent rate 30 fsw/min; All dives include a 15 fsw/3 min stop.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)		
40	119 (NDL)	30	100	8	127	2.0	(1.5-2.6)	3.0	(2.4-3.8)	1a
		60	100	11	130	2.3	(1.8-2.9)	3.4	(2.7-4.2)	2a
		120	100	15	134	2.9	(2.3-3.5)	3.7	(2.9-4.6)	3a
60	30	60	100	11	41	1.2	(.7-1.9)	2.0	(1.5-2.7)	II-1b
		120	100	17	47	1.8	(1.2-2.6)	2.4	(1.7-3.2)	II-2b
		240	100	16	46	1.8	(1.2-2.7)	1.9	(1.3-2.6)	II-3b
60	50 (NDL)	60	100	11	61	1.5	(1.0-2.2)	2.9	(2.2-3.8)	II-1d
		120	100	15	65	2.1	(1.5-2.9)	3.2	(2.4-4.2)	II-2d
		240	100	16	66	2.3	(1.6-3.2)	2.9	(2.1-3.9)	II-3d
100	16 (NDL)	30	40	42	58	0.9	(.6-1.4)	1.7	(1.2-2.3)	1b
		60	40	59	75	1.3	(.9-1.8)	1.9	(1.3-2.6)	2b
		120	40	91	107	2.2	(1.7-2.8)	2.5	(1.9-3.1)	3b
100	15	60	60	30	45	1.5	(.9-2.2)	2.2	(1.6-2.9)	II-1a
		120	60	43	58	2.1	(1.5-2.9)	2.5	(1.9-3.3)	II-2a
		240	60	48	63	2.4	(1.7-3.3)	2.4	(1.8-3.2)	II-3a
100	17 (NDL)	60	60	25	42	1.3	(.8-2.0)	2.1	(1.6-2.8)	II-1c
		120	60	42	59	2.2	(1.6-3.0)	2.7	(2.0-3.5)	II-2c
		240	60	48	65	2.6	(1.9-3.5)	2.6	(1.9-3.4)	II-3c

Table A.5. SUUNTO Spyder. Ascent rate 30 fsw/min; All dives include a 15 fsw/3 min stop.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)		
40	117 (NDL)	30	100	4	121	1.4	(1.0-1.9)	2.4	(1.8-3.0)	1a
		60	100	9	126	2.0	(1.5-2.5)	3.0	(2.4-3.8)	2a
		120	100	17	134	3.1	(2.5-3.8)	3.9	(3.1-4.8)	3a
60	30	60	100	16	46	1.7	(1.1-2.4)	2.5	(1.8-3.2)	II-1b
		120	100	17	47	1.8	(1.2-2.6)	2.4	(1.7-3.2)	II-2b
		240	100	17	47	1.9	(1.2-2.8)	1.9	(1.4-2.6)	II-3b
60	50 (NDL)	60	100	11	61	1.5	(1.0-2.2)	2.9	(2.2-3.8)	II-1d
		120	100	17	67	2.3	(1.7-3.2)	3.4	(2.6-4.4)	II-2d
		240	100	17	67	2.5	(1.7-3.4)	3.0	(2.2-4.0)	II-3d
100	16	30	40	68	84	1.5	(1.1-2.0)	2.0	(1.4-2.7)	1b
		60	40	83	99	1.9	(.4-5.3)	2.3	(1.7-3.0)	2b
		120	40	96	112	2.3	(1.8-2.9)	2.6	(2.0-3.2)	3b
100	15	60	60	34	39	1.6	(1.1-2.4)	2.3	(1.7-3.1)	II-1a
		120	60	42	57	2.1	(1.4-2.9)	2.5	(1.8-3.3)	II-2a
		240	60	49	64	2.4	(1.7-3.4)	2.4	(1.8-3.2)	II-3a
100	17 (NDL)	60	60	37	54	1.9	(1.3-2.6)	2.6	(1.9-3.4)	II-1c
		120	60	43	60	2.3	(1.6-3.1)	2.7	(2.1-3.5)	II-2c
		240	60	49	66	2.6	(1.9-3.6)	2.6	(2.0-3.4)	II-3c

Table A.6. ZH-L8ADT; Aladdin (Water temp. 28°C, Workload 75 W).

1st DIVE		SURFACE INTERVAL	2nd DIVE		Total Bottom Time	Estimated P_{DCS}, % (95% CL)				
Depth (fsw)	Bottom Time NDL (min)	(min)	Depth (fsw)	Bottom Time NDL (min)	(min)	BVM(3)		USN93(D)		
40	111 (NDL)	30	100	6	117	1.8	(1.3 - 2.4)	2.9	(2.2 - 3.7)	1a
		60	100	8	119	1.9	(1.4 - 2.6)	3.1	(2.4 - 3.9)	2a
		120	100	14	125	2.7	(2.1 - 3.4)	3.6	(2.8 - 4.6)	3a
60	30	60	100	15 DSR[a]	45	1.7	(1.2 - 2.4)	2.6	(1.9 - 3.4)	II-1b
		120	100	15 (<NDL)	45 (<NDL)	1.9	(.4 - 5.6)	2.6	(1.9 - 3.5)	II-2b
		240	100	15 (<NDL)	45 (<NDL)	2.0	(1.4 - 2.9)	2.2	(1.6 - 3.0)	II-3b
60	42 (NDL)	60	100	9	61	1.5	(.3 - 4.4)	2.8	(2.1 - 3.7)	II-1d
		120	100	9	67	1.6	(1.1 - 2.3)	2.7	(2.0 - 3.5)	II-2d
		240	100	15	67	2.3	(1.7 - 3.2)	2.9	(2.1 - 3.8)	II-3d
100	15 (NDL)	30	40	72	87	1.7	(1.2 - 2.4)	2.4	(1.7 - 3.2)	1b
		60	40	82	97	2.0	(1.5 - 2.6)	2.6	(1.9 - 3.3)	2b
		120	40	93	108	2.4	(1.9 - 3.1)	2.9	(2.3 - 3.6)	3b
100	15 (NDL)	60	60	31	46	1.8	(1.2 - 2.5)	2.6	(1.9 - 3.4)	II-1a = II-1c
		120	60	37	52	2.1	(1.5 - 2.9)	2.7	(2.0 - 3.6)	II-2a = II-2c
		240	60	42	57	2.4	(1.7 - 3.3)	2.6	(1.9 - 3.4)	II-3a = II-3c

* DSR ≡ decompression stops required

[a] 10 fsw/4 min

Table A.7. DCIEM40 Model.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	100	10	40	1.2	(.8 - 1.8)	1.7	(1.2 - 2.4)
		60	100	11	41	1.2	(.7 - 1.8)	1.7	(1.2 - 2.4)
		120	100	12	42	1.2	(.8 - 1.8)	1.6	(1.1 - 2.3)
		240	100	13	43	1.3	(.8 - 1.9)	1.5	(1.0 - 2.1)
40	60	30	100	9	69	1.3	(.8 - 1.9)	2.3	(1.7 - 3.0)
		60	100	10	70	1.2	(.8 - 1.8)	2.3	(1.7 - 3.1)
		120	100	11	71	1.4	(.9 - 2.0)	2.3	(1.7 - 3.0)
		240	100	12	72	1.5	(1.0 - 2.2)	2.0	(1.4 - 2.7)
40	90	30	100	8	98	1.6	(1.1 - 2.2)	2.7	(2.0 - 3.5)
		60	100	9	99	1.5	(1.0 - 2.1)	2.7	(2.0 - 3.6)
		120	100	10	100	1.6	(1.1 - 2.2)	2.7	(1.9 - 3.7)
		240	100	11	101	1.6	(1.1 - 2.3)	2.5	(1.7 - 3.5)
40	120	30	100	7	127	2.2	(1.6 - 2.8)	3.3	(2.6 - 4.1)
		60	100	9	129	2.3	(1.8 - 2.9)	3.5	(2.7 - 4.4)
		120	100	10	130	2.4	(1.8 - 3.1)	3.4	(2.6 - 4.3)
		240	100	11	131	2.3	(1.7 - 3.1)	3.0	(2.2 - 4.0)
40	150 (NDL)	30	100	7	157	3.0	(2.4 - 3.6)	4.2	(3.4 - 5.2)
		60	100	8	158	3.0	(1.2 - 6.2)	4.3	(3.5 - 5.3)
		120	100	10	160	3.3	(2.7 - 4.0)	4.4	(3.5 - 5.5)
		240	100	11	161	3.3	(2.7 - 4.1)	3.9	(3.1 - 5.0)

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	130	7	37	1.5	(.9 - 2.2)	1.8	(1.3 - 2.5)
		60	130	7	37	1.3	(.8 - 2.1)	1.7	(1.2 - 2.5)
		120	130	8	38	1.4	(.0 - 13.4)	1.6	(1.1 - 2.4)
		240	130	8	38	1.4	(.3 - 4.6)	1.5	(1.0 - 2.2)
40	60	30	130	6	66	1.5	(.9 - 2.2)	2.4	(1.7 - 3.1)
		60	130	7	67	1.5	(1.0 - 2.2)	2.4	(1.8 - 3.2)
		120	130	7	67	1.5	(1.0 - 2.2)	2.3	(1.7 - 3.1)
		240	130	8	68	1.7	(1.1 - 2.5)	2.0	(1.4 - 2.8)
40	90	30	130	5	95	1.7	(1.1 - 2.4)	2.7	(2.0 - 3.6)
		60	130	6	96	1.7	(1.1 - 2.4)	2.8	(2.1 - 3.8)
		120	130	7	97	1.8	(1.2 - 2.5)	2.8	(2.0 - 3.9)
		240	130	8	98	1.9	(1.3 - 2.7)	2.6	(1.8 - 3.7)
40	120	30	130	5	125	2.4	(.9 - 5.1)	3.4	(2.7 - 4.3)
		60	130	6	126	2.5	(1.9 - 3.2)	3.6	(2.8 - 4.5)
		120	130	7	127	2.6	(2.0 - 3.4)	3.5	(2.7 - 4.4)
		240	130	7	127	2.4	(1.8 - 3.2)	3.1	(2.2 - 4.1)
40	150 (NDL)	30	130	4	154	2.9	(2.3 - 3.6)	4.1	(3.3 - 5.1)
		60	130	6	156	3.3	(2.7 - 4.1)	4.6	(3.7 - 5.6)
		120	130	7	157	3.5	(2.8 - 4.3)	4.6	(3.6 - 5.6)
		240	130	7	157	3.4	(2.7 - 4.2)	3.9	(3.0 - 5.0)

Table A.7. DCIEM40 Model (cont.).

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
60	30	30	100	9	39	1.5	(.9 - 2.2)	2.3	(1.7 - 3.1)
		60	100	11	41	1.5	(1.0 - 2.2)	2.4	(1.8 - 3.2)
		120	100	12	42	1.7	(1.1 - 2.4)	2.4	(1.7 - 3.2)
		240	100	12	42	1.8	(1.2 - 2.6)	2.0	(1.4 - 2.8)
60	40	30	100	8	48	1.5	(1.0 - 2.2)	2.6	(2.0 - 3.5)
		60	100	10	50	1.5	(1.0 - 2.2)	2.8	(2.1 - 3.7)
		120	100	11	51	1.7	(.2 - 6.6)	2.8	(2.1 - 3.6)
		240	100	12	52	2.1	(1.4 - 2.8)	2.5	(1.8 - 3.4)
60	50 (NDL)	30	100	8	58	1.7	(1.1 - 2.4)	3.1	(2.3 - 4.0)
		60	100	10	60	1.7	(1.2 - 2.4)	3.2	(2.4 - 4.2)
		120	100	11	61	1.9	(1.3 - 2.6)	3.2	(2.4 - 4.2)
		240	100	12	62	2.2	(1.6 - 3.0)	3.0	(2.3 - 4.0)

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
100	10	30	40	122	132	2.6	(2.0 - 3.2)	3.1	(2.4 - 4.0)
		60	40	128	138	2.8	(2.2 - 3.4)	3.3	(2.6 - 4.1)
		120	40	130	140	2.8	(2.2 - 3.5)	3.3	(2.6 - 4.0)
		240	40	138	148	2.9	(.1 - 16.7)	3.3	(2.7 - 4.1)
100	15	30	40	112	127	2.7	(2.1 - 3.3)	3.2	(2.5 - 4.1)
		60	40	117	132	2.9	(2.3 - 3.5)	3.4	(2.7 - 4.3)
		120	40	124	139	3.1	(2.5 - 3.8)	3.6	(2.9 - 4.4)
		240	40	132	147	3.3	(2.7 - 4.1)	3.6	(3.0 - 4.4)
100	20	30	40	DSR					
		60	40	DSR					
		120	40	DSR					
		240	40	DSR					
100	25 (NDL)	30	40	DSR					
		60	40	DSR					
		120	40	DSR					
		240	40	DSR					
100	10	30	60	26	36	1.5	(1.0 - 2.3)	2.1	(1.5 - 2.8)
		60	60	29	39	1.6	(1.0 - 2.3)	2.1	(1.5 - 2.9)
		120	60	31	41	1.7	(1.1 - 2.4)	2.0	(1.4 - 2.8)
		240	60	32	42	1.7	(1.1 - 2.5)	1.9	(1.3 - 2.6)
100	15	30	60	23	38	1.6	(1.0 - 2.3)	2.4	(1.7 - 3.1)
		60	60	27	42	1.7	(1.1 - 2.4)	2.5	(1.8 - 3.3)
		120	60	29	44	1.8	(1.3 - 2.6)	2.4	(1.8 - 3.2)
		240	60	31	46	2.1	(1.4 - 2.9)	2.2	(1.6 - 3.0)
130	5 ·	30	40	132	137	2.8	(2.2 - 3.5)	3.2	(2.5 - 4.1)
		60	40	134	139	2.8	(2.2 - 3.6)	3.2	(2.5 - 4.1)
		120	40	136	141	2.9	(2.2 - 3.6)	3.2	(2.5 - 4.1)
		240	40	141	146	2.9	(2.3 - 3.6)	3.3	(2.6 - 4.1)
130	10	30	40	DSR					
		60	40	DSR					
		120	40	DSR					
		240	40	DSR					

* DSR = decompression stops required

Table A.8. U.S. Navy Standard Air Tables.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	100	11	41	1.3	(.8 - 1.9)	1.8	(1.3 - 2.5)
		60	100	11	41	1.2	(.7 - 1.8)	1.7	(1.2 - 2.4)
		120	100	15	45	1.5	(1.0 - 2.1)	1.8	(1.3 - 2.5)
		240	100	22	52	2.1	(1.5 - 2.9)	2.2	(1.6 - 2.9)
40	60	30	100	DSR					
		60	100	3	63	0.7	(.4 - 1.2)	1.6	(1.2 - 2.3)
		120	100	11	71	1.4	(.9 - 2.0)	2.3	(1.7 - 3.0)
		240	100	15	75	1.8	(1.2 - 2.5)	2.2	(1.6 - 2.9)
40	90	30	100	DSR					
		60	100	DSR					
		120	100	3	93	1.0	(.7 - 1.5)	2.0	(1.4 - 2.9)
		240	100	15	105	2.1	(1.4 - 2.8)	2.8	(2.0 - 3.9)
40	120	30	100	DSR					
		60	100	DSR					
		120	100	DSR					
		240	100	11	131	2.3	(1.7 - 3.1)	3.0	(2.2 - 4.0)
40	150	30	100	DSR					
		60	100	DSR					
		120	100	DSR					
		240	100	11	161	3.3	(2.7 - 4.1)	3.9	(3.1 - 5.0)
40	200 (NDL)	30	100	DSR					
		60	100	DSR					
		120	100	DSR					
		240	100	DSR					

* DSR ≡ decompression stops required

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
60	30	30	100	3	33	0.9	(.5 - 1.5)	1.7	(1.2 - 2.4)
		60	100	7	37	1.2	(.7 - 1.9)	2.1	(1.5 - 2.8)
		120	100	11	41	1.6	(1.1 - 2.3)	2.3	(1.6 - 3.1)
		240	100	18	48	2.3	(1.6 - 3.2)	2.4	(1.8 - 3.3)
60	40	30	100	DSR					
		60	100	3	43	1.0	(.6 - 1.6)	2.1	(1.5 - 2.8)
		120	100	11	51	1.7	(.2 - 6.6)	2.8	(2.1 - 3.6)
		240	100	15	55	2.3	(1.6 - 3.1)	2.7	(2.0 - 3.7)
60	50	30	100	DSR					
		60	100	DSR					
		120	100	7	57	1.6	(1.0 - 2.2)	2.9	(2.1 - 3.8)
		240	100	15	65	2.5	(1.8 - 3.4)	3.3	(2.4 - 4.3)
60	60 (NDL)	30	100	DSR					
		60	100	DSR					
		120	100	3	63	1.5	(1.0 - 2.1)	2.8	(2.1 - 3.7)
		240	100	11	71	2.4	(1.8 - 3.2)	3.4	(2.5 - 4.5)

* DSR ≡ decompression stops required

Table A.8. U.S. Navy Standard Air Tables (cont.).

1st DIVE		SURFACE INTERVAL	2nd DIVE		Total Bottom Time	Estimated P_{DCS}, % (95% CL)			
Depth (fsw)	Bottom Time NDL (min)	(min)	Depth (fsw)	Bottom Time NDL (min)	(min)	BVM(3)		USN93(D)	
100	10	30	40	163	173	3.7	(3.1 - 4.3)	4.3	(3.5 - 5.3)
		60	40	163	173	3.7	(3.1 - 4.4)	4.3	(3.5 - 5.3)
		120	40	175	185	4.0	(3.4 - 4.7)	4.7	(3.8 - 5.6)
		240	40	193	203	4.4	(2.4 - 7.2)	5.1	(4.2 - 6.1)
100	15	30	40	151	166	3.7	(3.1 - 4.4)	4.4	(3.5 - 5.4)
		60	40	163	178	4.1	(3.5 - 4.8)	4.8	(3.9 - 5.8)
		120	40	175	190	4.5	(3.9 - 5.2)	5.2	(4.3 - 6.2)
		240	40	183	198	4.7	(4.0 - 5.5)	5.3	(4.4 - 6.3)
100	20	30	40	139	159	3.8	(3.2 - 4.5)	4.5	(3.6 - 5.5)
		60	40	151	171	4.2	(3.6 - 4.9)	4.9	(4.0 - 5.9)
		120	40	163	183	4.6	(4.0 - 5.4)	5.3	(4.4 - 6.3)
		240	40	183	203	5.2	(4.5 - 6.1)	5.9	(5.0 - 6.9)
100	25 (NDL)	30	40	113	138	3.5	(2.9 - 4.1)	4.2	(3.3 - 5.1)
		60	40	127	152	3.9	(3.3 - 4.6)	4.6	(3.8 - 5.6)
		120	40	151	176	4.7	(4.0 - 5.5)	5.5	(4.6 - 6.5)
		240	40	175	200	5.5	(4.8 - 6.4)	6.2	(5.3 - 7.3)
100	10	30	60	36	46	1.8	(1.2 - 2.6)	2.4	(1.8 - 3.2)
		60	60	36	46	1.8	(1.2 - 2.5)	2.4	(1.7 - 3.2)
		120	60	43	53	2.0	(.1 - 9.8)	2.5	(1.8 - 3.3)
		240	60	49	59	2.2	(1.6 - 3.1)	2.5	(1.9 - 3.3)
100	15	30	60	30	45	1.8	(1.2 - 2.6)	2.6	(1.9 - 3.4)
		60	60	36	51	2.0	(1.4 - 2.8)	2.8	(2.1 - 3.7)
		120	60	43	58	2.4	(1.7 - 3.2)	2.9	(2.2 - 3.8)
		240	60	49	64	2.7	(2.0 - 3.7)	2.9	(2.1 - 3.7)
100	20	30	60	24	44	1.8	(1.2 - 2.5)	2.8	(2.1 - 3.7)
		60	60	30	50	2.0	(1.4 - 2.7)	3.0	(2.2 - 3.9)
		120	60	36	56	2.4	(.3 - 8.8)	3.2	(2.4 - 4.1)
		240	60	49	69	3.2	(2.4 - 4.2)	3.4	(2.6 - 4.4)
100	25 (NDL)	30	60	8	33	1.3	(.8 - 2.0)	2.6	(2.0 - 3.5)
		60	60	16	41	1.5	(1.0 - 2.2)	2.9	(2.2 - 3.8)
		120	60	30	55	2.4	(1.7 - 3.2)	3.4	(2.6 - 4.4)
		240	60	43	68	3.3	(2.5 - 4.3)	3.8	(2.9 - 4.8)

Table A.9. DCIEM Sport Diving Tables.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	100	10	40	1.2	(.8 - 1.8)	1.7	(1.2 - 2.4)
		60	100	11	41	1.2	(.7 - 1.8)	1.7	(1.2 - 2.4)
		120	100	11	41	1.1	(.7 - 1.7)	1.5	(1.0 - 2.2)
		240	100	13	43	1.3	(.8 - 1.9)	1.5	(1.0 - 2.1)
40	60	30	100	9	69	1.3	(.8 - 1.9)	2.3	(1.7 - 3.0)
		60	100	9	69	1.2	(.7 - 1.7)	2.2	(1.6 - 3.0)
		120	100	10	70	1.3	(.9 - 1.9)	2.2	(1.6 - 2.9)
		240	100	11	71	1.4	(.9 - 2.1)	1.9	(1.4 - 2.6)
40	90	30	100	7	97	1.5	(1.0 - 2.1)	2.6	(1.9 - 3.4)
		60	100	8	98	1.4	(.9 - 2.0)	2.6	(1.9 - 3.5)
		120	100	9	99	1.4	(1.0 - 2.0)	2.6	(1.9 - 3.6)
		240	100	10	100	1.6	(1.1 - 2.2)	2.4	(1.7 - 3.4)
40	120	30	100	DSR					
		60	100	7	127	2.0	(1.5 - 2.7)	3.2	(2.5 - 4.0)
		120	100	8	128	2.2	(1.6 - 2.8)	3.1	(2.4 - 4.0)
		240	100	9	129	2.1	(1.6 - 2.8)	2.9	(2.1 - 3.9)
40	150 (NDL)	30	100	DSR					
		60	100	DSR					
		120	100	7	157	2.9	(2.3 - 3.6)	4.0	(3.1 - 5.0)
		240	100	9	159	3.1	(2.4 - 3.8)	3.7	(2.9 - 4.8)

* DSR ≡ decompression stops required

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	130	6	36	1.3	(.8 - 2.0)	1.7	(1.2 - 2.4)
		60	130	6	36	1.2	(.7 - 1.9)	1.6	(1.1 - 2.3)
		120	130	6	36	1.2	(.7 - 1.9)	1.5	(.9 - 2.2)
		240	130	7	37	1.3	(.8 - 2.0)	1.4	(.9 - 2.1)
40	60	30	130	5	65	1.3	(.8 - 2.0)	2.2	(1.6 - 3.0)
		60	130	5	65	1.2	(.8 - 1.9)	2.2	(1.6 - 2.9)
		120	130	6	66	1.4	(.9 - 2.1)	2.2	(1.6 - 2.9)
		240	130	6	66	1.5	(.9 - 2.2)	1.9	(1.3 - 2.6)
40	90	30	130	4	94	1.5	(1.0 - 2.2)	2.5	(1.8 - 3.4)
		60	130	4	94	1.3	(.8 - 2.0)	2.5	(1.8 - 3.4)
		120	130	5	95	1.5	(1.0 - 2.2)	2.6	(1.8 - 3.5)
		240	130	6	96	1.7	(1.1 - 2.4)	2.4	(1.7 - 3.4)
40	120	30	130	DSR					
		60	130	4	124	2.0	(1.5 - 2.7)	3.1	(2.4 - 4.0)
		120	130	5	125	2.3	(1.7 - 3.0)	3.1	(2.4 - 4.0)
		240	130	5	125	2.2	(1.6 - 2.9)	2.8	(2.0 - 3.8)
40	150 (NDL)	30	130	DSR					
		60	130	DSR					
		120	130	4	154	2.9	(2.3 - 3.6)	3.9	(3.0 - 4.9)
		240	130	5	155	3.1	(2.4 - 3.8)	3.6	(2.8 - 4.7)

* DSR ≡ decompression stops required

Table A.9. DCIEM Sport Diving Tables (cont.).

1st DIVE		SURFACE INTERVAL	2nd DIVE		Total Bottom Time	Estimated P_{DCS}, % (95% CL)			
Depth (fsw)	Bottom Time NDL (min)	(min)	Depth (fsw)	Bottom Time NDL (min)	(min)	BVM(3)		USN93(D)	
60	30	30	100	9	39	1.5	(.9 - 2.2)	2.3	(1.7 - 3.1)
		60	100	9	39	1.4	(.9 - 2.0)	2.3	(1.6 - 3.0)
		120	100	10	40	1.5	(1.0 - 2.2)	2.2	(1.6 - 3.0)
		240	100	11	41	1.7	(1.1 - 2.5)	1.9	(1.3 - 2.7)
60	40	30	100	8	48	1.5	(1.0 - 2.2)	2.6	(2.0 - 3.5)
		60	100	9	49	1.4	(.9 - 2.1)	2.7	(2.0 - 3.5)
		120	100	10	50	1.6	(1.1 - 2.3)	2.7	(2.0 - 3.5)
		240	100	11	51	2.0	(1.4 - 2.7)	2.4	(1.8 - 3.3)
60	50 (NDL)	30	100	8	58	1.7	(1.1 - 2.4)	3.1	(2.3 - 4.0)
		60	100	8	58	1.5	(1.0 - 2.2)	3.0	(2.3 - 4.0)
		120	100	9	59	1.7	(1.2 - 2.4)	3.1	(2.3 - 4.0)
		240	100	10	60	2.1	(1.5 - 2.8)	2.9	(2.1 - 3.8)

1st DIVE		SURFACE INTERVAL	2nd DIVE		Total Bottom Time	Estimated P_{DCS}, % (95% CL)			
Depth (fsw)	Bottom Time NDL (min)	(min)	Depth (fsw)	Bottom Time NDL (min)	(min)	BVM(3)		USN93(D)	
100	10	30	40	115	125	2.4	(1.9 - 3.0)	2.9	(2.2 - 3.7)
		60	40	125	135	2.7	(2.1 - 3.3)	3.2	(2.5 - 4.0)
		120	40	125	135	2.7	(2.1 - 3.3)	3.1	(2.5 - 3.9)
		240	40	136	146	2.9	(2.3 - 3.5)	3.3	(2.6 - 4.1)
100	15	30	40	100	115	2.4	(1.9 - 3.0)	2.9	(2.2 - 3.8)
		60	40	107	122	2.6	(2.1 - 3.2)	3.1	(2.4 - 3.9)
		120	40	115	130	2.9	(2.3 - 3.6)	3.3	(2.7 - 4.1)
		240	40	125	140	3.1	(2.5 - 3.9)	3.4	(2.8 - 4.2)
100	20	30	40	DSR					
		60	40	DSR					
		120	40	DSR					
		240	40	DSR					
100	25 (NDL)	30	40	DSR					
		60	40	DSR					
		120	40	DSR					
		240	40	DSR					
100	10	30	60	31	41	1.7	(1.1 - 2.4)	2.3	(1.6 - 3.0)
		60	60	35	45	1.8	(1.2 - 2.5)	2.3	(1.7 - 3.1)
		120	60	35	45	1.8	(1.2 - 2.5)	2.2	(1.5 - 3.0)
		240	60	40	50	1.9	(1.3 - 2.8)	2.2	(1.6 - 2.9)
100	15	30	60	27	42	1.7	(1.1 - 2.4)	2.5	(1.8 - 3.3)
		60	60	29	44	1.7	(1.2 - 2.4)	2.5	(1.9 - 3.4)
		120	60	31	46	1.9	(1.3 - 2.6)	2.5	(1.8 - 3.3)
		240	60	35	50	2.2	(1.5 - 3.1)	2.3	(1.7 - 3.2)
130	5	30	40	125	130	2.6	(2.0 - 3.4)	3.0	(2.3 - 3.9)
		60	40	136	141	2.9	(2.3 - 3.6)	3.3	(2.6 - 4.2)
		120	40	136	141	2.9	(2.2 - 3.6)	3.2	(2.5 - 4.1)
		240	40	136	141	2.8	(2.1 - 3.5)	3.1	(2.4 - 4.0)
130	10	30	40	DSR					
		60	40	DSR					
		120	40	DSR					
		240	40	DSR					

* DSR ≡ decompression stops required

Table A.10. PADI/DSAT Tables.

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	100	12	42	1.4	(.9-2.0)	1.9	(1.4-2.5)
		60	100	14	44	1.4	(1.0-2.1)	1.9	(1.4-2.6)
		120	100	17	57	1.6	(1.1-2.3)	2.0	(1.4-2.7)
		240	100	17	57	1.6	(1.1-2.3)	1.8	(1.2-2.4)
40	60	30	100	6	66	1.0	(.6-1.6)	2.0	(1.5-2.7)
		60	100	11	71	1.3	(.9-1.9)	2.4	(1.8-3.2)
		120	100	14	74	1.6	(1.1-2.3)	2.5	(1.9-3.3)
		240	100	17	77	1.9	(1.3-2.8)	2.3	(1.7-3.1)
40	90	30	100	2	92	0.7	(.4-1.2)	1.9	(1.3-2.7)
		60	100	8	98	1.4	(.9-2.0)	2.6	(1.9-3.5)
		120	100	14	104	2.0	(1.5-2.7)	3.1	(2.4-4.1)
		240	100	17	107	2.3	(1.7-3.1)	3.0	(2.1-4.1)
40	120	30	100	DSR					
		60	100	6	126	1.9	(1.4-2.5)	3.0	(2.3-3.9)
		120	100	12	132	2.7	(2.1-3.4)	3.6	(2.8-4.6)
		240	100	17	137	3.1	(2.4-4.0)	3.7	(2.8-4.7)
40	140 (NDL)	30	100	DSR					
		60	100	5	145	2.3	(1.8-2.9)	3.5	(2.7-4.4)
		120	100	12	152	3.3	(2.7-4.0)	4.4	(3.5-5.4)
		240	100	17	157	3.8	(3.1-4.7)	4.4	(3.4-5.5)

* DSR ≡ decompression stops required

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
40	30	30	130	4	34	1.0	(.6-1.7)	1.5	(1.0-2.1)
		60	130	5	35	1.1	(.6-1.8)	1.5	(1.0-2.2)
		120	130	7	37	1.3	(.8-2.0)	1.5	(1.0-2.3)
		240	130	7	37	1.3	(.8-2.0)	1.4	(.9-2.1)
40	60	30	130	DSR					
		60	130	3	63	0.9	(.5-1.6)	1.9	(1.3-2.5)
		120	130	5	65	1.3	(.8-2.0)	2.1	(1.5-2.8)
		240	130	7	67	1.6	(.5-4.2)	2.0	(1.4-2.7)
40	90	30	130	DSR					
		60	130	DSR					
		120	130	5	95	1.5	(1.0-2.2)	2.6	(1.8-3.5)
		240	130	7	97	1.8	(1.2-2.6)	2.5	(1.7-3.6)
40	120	30	130	DSR					
		60	130	DSR					
		120	130	4	124	2.1	(1.5-2.8)	2.9	(2.2-3.8)
		240	130	7	127	2.4	(1.8-3.2)	3.1	(2.2-4.1)
40	140 (NDL)	30	130	DSR					
		60	130	DSR					
		120	130	7	147	3.2	(2.6-4.0)	4.2	(3.3-5.2)
		240	130	7	147	3.1	(2.4-3.9)	3.6	(2.7-4.6)

* DSR ≡ decompression stops required

Table A.10. PADI/DSAT Tables (cont.).

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
60	30	30	100	8	38	1.4	(.9 - 2.1)	2.2	(1.6 - 3.0)
		60	100	12	42	1.6	(1.1 - 2.3)	2.5	(1.9 - 3.3)
		120	100	14	44	1.8	(1.3 - 2.6)	2.5	(1.9 - 3.4)
		240	100	17	47	2.2	(1.5 - 3.1)	2.4	(1.7 - 3.2)
60	40	30	100	4	44	1.1	(.7 - 1.8)	2.2	(1.6 - 3.0)
		60	100	9	49	1.4	(.9 - 2.1)	2.7	(2.0 - 3.5)
		120	100	14	54	2.0	(1.4 - 2.7)	3.1	(2.3 - 4.0)
		240	100	17	57	2.5	(1.8 - 3.4)	2.9	(2.1 - 3.9)
60	50	30	100	2	52	0.8	(.5 - 1.4)	2.3	(1.7 - 3.1)
		60	100	7	57	1.4	(.9 - 2.1)	2.9	(2.2 - 3.8)
		120	100	14	64	2.2	(1.6 - 3.0)	3.5	(2.7 - 4.6)
		240	100	17	67	2.7	(2.0 - 3.6)	3.5	(2.6 - 4.6)
60	55 (NDL)	30	100	DSR					
		60	100	6	61	1.4	(.9- 2.1)	3.0	(2.3 - 4.0)
		120	100	12	67	2.1	(1.5- 2.9)	3.6	(2.7 - 4.6)
		240	100	17	72	2.9	(2.1- 3.8)	3.7	(2.8 - 4.9)

* DSR ≡ decompression stops required

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
100	10	30	40	118	128	2.5	(.0 - 17.8)	3.0	(2.3 - 3.8)
		60	40	124	134	2.6	(1.0 - 5.8)	3.2	(2.5 - 4.0)
		120	40	131	141	2.8	(2.3 - 3.5)	3.3	(2.6 - 4.1)
		240	40	131	141	2.7	(2.1 - 3.4)	3.1	(2.5 - 3.9)
100	15	30	40	109	124	2.6	(2.1 - 3.2)	3.2	(2.4 - 4.0)
		60	40	118	133	2.9	(2.3 - 3.5)	3.4	(2.7 - 4.3)
		120	40	131	146	3.3	(2.7 - 4.0)	3.8	(3.1 - 4.6)
		240	40	131	146	3.3	(2.6 - 4.1)	3.6	(2.9 - 4.4)
100	20 (NDL)	30	40	100	120	2.7	(2.2 - 3.4)	3.3	(2.6 - 4.2)
		60	40	113	133	3.1	(2.6 - 3.8)	3.7	(3.0 - 4.6)
		120	40	124	144	3.6	(2.9 - 4.3)	4.1	(3.3 - 5.0)
		240	40	131	151	3.8	(3.2 - 4.6)	4.2	(3.5 - 5.0)

* DSR ≡ decompression stops required

Table A.10. PADI/DSAT Tables (cont.).

1st DIVE Depth (fsw)	1st DIVE Bottom Time NDL (min)	SURFACE INTERVAL (min)	2nd DIVE Depth (fsw)	2nd DIVE Bottom Time NDL (min)	Total Bottom Time (min)	Estimated P_{DCS}, % (95% CL) BVM(3)		USN93(D)	
100	10	30	60	41	51	2.0	(1.4 - 2.8)	3.8	(3.0 - 4.7)
		60	60	44	54	2.1	(1.5 - 2.8)	4.2	(3.4 - 5.2)
		120	60	49	59	2.3	(1.6 - 3.1)	4.6	(3.8 - 5.6)
		240	60	49	59	2.2	(1.6 - 3.1)	4.8	(4.0 - 5.7)
100	15	30	60	36	51	2.0	(1.4 - 2.8)	2.6	(1.9 - 3.5)
		60	60	41	56	2.2	(1.6 - 3.0)	2.7	(2.0 - 3.5)
		120	60	49	64	2.7	(2.0 - 3.5)	2.7	(2.0 - 3.5)
		240	60	49	64	2.7	(2.0 - 3.7)	2.5	(1.9 - 3.3)
100	20 (NDL)	30	60	30	50	2.0	(1.4 - 2.8)	2.8	(2.1 - 3.7)
		60	60	38	58	2.4	(1.8 - 3.1)	3.0	(2.2 - 3.9)
		120	60	44	64	2.8	(2.1 - 3.6)	3.2	(2.4 - 4.1)
		240	60	49	69	3.2	(2.4 - 4.2)	2.9	(2.1 - 3.7)
130	5	30	40	124	129	2.6	(2.0- 3.3)	3.0	(2.3 - 3.9)
		60	40	131	136	2.8	(2.2- 3.5)	3.2	(2.4 - 4.0)
		120	40	131	136	2.7	(2.1- 3.5)	3.1	(2.4 - 3.9)
		240	40	131	136	2.6	(2.0- 3.4)	3.0	(2.3 - 3.8)
130	10	30	40	115	125	2.9	(2.3- 3.7)	3.3	(2.5 - 4.2)
		60	40	124	134	3.2	(2.6- 4.0)	3.6	(2.8 - 4.5)
		120	40	131	141	3.4	(2.8- 4.2)	3.8	(3.0 - 4.7)
		240	40	131	141	3.4	(2.7- 4.3)	3.6	(2.9 - 4.4)

IV. Dive Computer Session Discussion. Michael A. Lang, Moderator.

T. Neuman: Wayne, one of the questions that I had about the reverse dive profiles, of course limited by the constraints of what you were asked to do, was on the second set of dives. You went into the decompression mode and said the reverse dive might be more troublesome than in the first set of dives where you weren't in the decompression mode. There was also a difference between the depths as well, such that in the first set of dives, the delta P that Bruce Wienke or the Y that John Lewis were talking about was about 40 feet, whereas in the second set of dives, the delta P or the Y were 70 to 80 feet. Do you think that may have been the critical difference rather than the decompression? Because that is really a critical point as far as our diving practices are concerned.

W. Gerth: Again, that sort of delta P isn't part of what enters into the methodology that was used to generate the USN57 tables or the standard air tables. So my answer would be, in explicit terms, no. Neither is that sort of thing, as I said earlier, a factor in the models that are used to estimate the risk. No, I don't think that is a problem. It has to do simply with the arrangement of pressure and gas and time.

A. Brubakk: On the Y axis of your slides, you are operating with a pDCS in the order of 6 to 10 percent for these dives. Isn't that an extraordinarily high number for the risk of decompression sickness and not anywhere what we expect or accept?

W. Gerth: Those were the U.S. Navy table risks. That is what the model says the risks are under that model.

A. Brubakk: Can you extrapolate from that to the type of real risks that we have?

W. Gerth: I can't speak to the operational use of those particular profiles that manifest those risks that you are speaking about, whether they have been explicitly tested. However, there are a good number of profiles, within the calibration data, that are repetitive dives that do have risks that high as observed. But the confidence limits on the observations in those cases are still pretty wide because the n's in those bends are pretty low. I think the take-home message of those slides should be simply that the relative risk for forward and reverse dive profiles under a given evaluation that is tagged to data indicates that the reverse cases may be handled by those algorithms in adverse ways compared to the way the forward mode dives are.

R. Moon: If it is correct that the U.S. Navy air tables as currently published do not handle reverse profiles as safely as forward profiles, would you speculate, or do you have any information on the way the current dive computers would handle the same profiles?

W. Gerth: No, I won't handle the second question. I can't speculate. Because I don't have profiles from the dive computers to analyze. If they were to be forwarded to me, I would be happy to do the same thing for those. With regard to the U.S. Navy tables, I want to emphasize that this difference between forward and reverse has to do with when we exercise the profiles into the decompression range. They were included, when they allowed you to do the NoD dives, in the other figures and therefore were included under my general conclusion that they are also fine. The U.S. Navy standard air tables prescribe forward and reverse dives that are within the NoD limit and that are only single repets just fine. The risks of those dives done in reverse order are no more than those done forward. Therefore, if you are happy with the forward results, I am saying you should be happy with them reverse, as long as they are NoD.

R. Moon: It is possible that the current dogma that reverse dive profiles are bad came from an operational appreciation of the fact that the U.S. Navy tables were not working as well when used in the reverse dive profile mode. Perhaps it was like a clinical observation that somehow never got put in the literature.

W. Gerth: That, in fact, is what Ed Thalmann believes might be at least partly the origin for what has become an admonition of doing reverse dive profiles. This is a suggestion that maybe the Navy operators during the early years of using the tables just observed. Namely, that with reverse dive profiles we are having a little more trouble than with those in the forward mode. Possibly then, just in accord with that observation, said under the table, we are not going to do those any more. I agree this is in accord with that observation.

E. Baker: We didn't have as many sources as you did; we just looked at one, the Bühlmann ZH86 air diving tables. One of the conclusions that I drew personally from our analysis of the forward and reverse dive series was that reverse profiles are not inherently more risky than forward profiles, but that the use of the conventional tables or algorithms applied to those profiles could be inherently more risky. The basis of that was the fact that your gas loadings were traveling so far into the radial distribution of nuclei to form bubbles. You can get away with that once on a first dive that correlates with the validation trials or the titrations of divers, as David would say. But when you try to do that twice in a repetitive dive, that is where you run into problems. In fact, we analyzed an actual DCS incident that just happened back in August where a diver in Europe did a short 7-minute dive to 35 meters, came up and then did another dive to 42 meters for six minutes and ended up with pretty severe spinal symptoms.

W. Gerth: Did you have anybody else do that dive DCS-free?

E. Baker: No. We just looked at that one. All we were looking at there was just how far into the radial distribution the diver went, and it was in the 0.5 or 0.6 micron range. The idea there being that he formed bubbles on the first dive that may have impacted the second, formed bubbles again and had problems. It did show good correlation with Bühlmann's association of the various compartments with symptoms.

W. Gerth: The only point about that I want to make is that I certainly would not want to go and prescribe procedures for the fleet, and that includes recreational divers and so forth, on the basis of an N of one. The binomial uncertainty on that observation is anywhere from zero plus an infinite amount to 1. So it really doesn't tell you much. You haven't explained anything by observing an N of 1. You might have done the next 50 dives on that profile without a problem. That sort of tendency for us to get wrapped up around a limited amount of data is proscribed rigorously in the kind of probabilistic approach that we take. We are forced to take all of it at once.

Dive Computer Panel Discussion
Michael A. Lang, Moderator

M. Lang: We have invited John Lewis, Ernst Voellm, Sergio Angelini, Jarmo Luukkanen, Ron Nishi, Karl Huggins and Steve Miller to this Dive Computer Panel Discussion. Mike Cochran sends his apologies for not being able to attend. We envisioned this session as an interactive panel discussion with representatives who can speak to the dive computers programs on the market, and specifically how they handle reverse dive profiles. Karl Huggins will speak for the ORCA Industries' algorithm. The ORCA units are no longer in production, but there is a significant number still in use today.

K. Huggins: The Orca model is a pure Haldanean model. It calculates reverse dive profiles in the same manner that it calculates forward dive profiles. Determination of allowable no-decompression times for repetitive dives is based on the level of nitrogen that remains in the twelve compartments of the model following the initial dive and the subsequent surface interval. The time it will take each compartment to reach its allowable surfacing pressure (Mo value) is calculated taking into account the residual nitrogen remaining in the compartments. The shortest of these twelve "no-decompression" times is then displayed. There are no adjustments made to the model if a repetitive dive is deeper than a previous dive.

The responses of the Orca model to the proposed profiles are presented on the following three pages in a graphical form simulating the Orca EDGE dive computer display (Figures 1, 2 and 3). The half-times of the compartments in the Orca model range from 5-minutes (compartment on the far left) to 480-minutes (compartment on the far right). The open bars represent the Mo value for the compartment, the lightly shaded bars reflect the "nitrogen" build-up in the compartments, and the solid black bar represents the controlling compartment for the dive (or the one that reaches its Mo value first). For ease of calculation, instantaneous descents and ascents were assumed.

The first six slides show the response to the 100 fsw and 40 fsw no-decompression limit series. As would be expected, the no-decompression limit for the second dive increases as the surface interval between the dives increases. In the deep-to-shallow series, the loading of the model following the 40 fsw dive is equivalent no matter what the surface interval was. For each surface interval, the end loading of the model is greater in the shallow-to-deep dives versus the deep-to-shallow dives. Additionally, in the reverse profile series the overall loading of the model at the end of the 100 fsw dive increases as the surface interval increases. The second group of six slides shows the response to the 100 fsw / 15 min and 60 fsw / 30 min dive series. Given a fixed dive time, the results are what would be expected. The model loading at the end of the second dives decreases

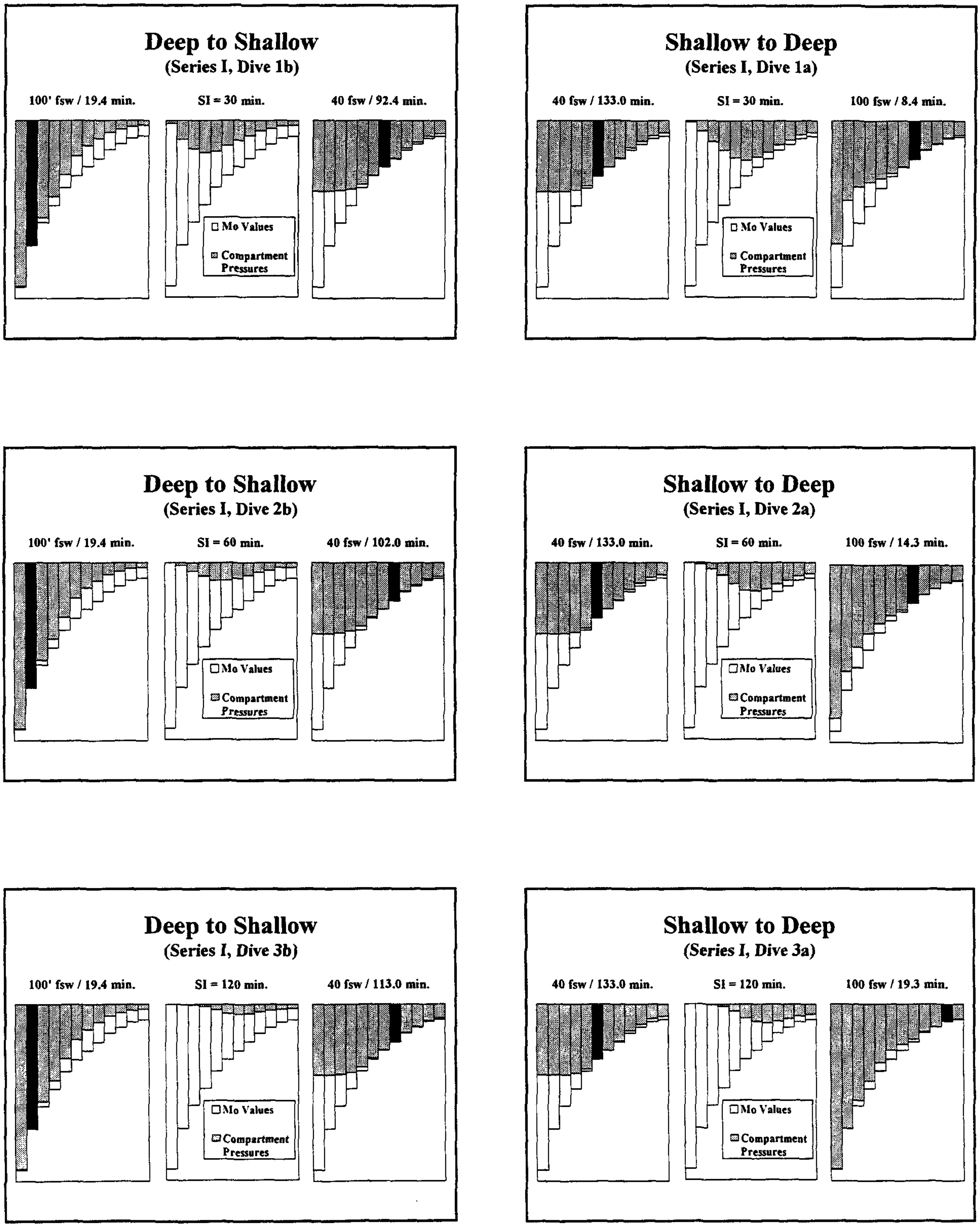


Figure 1. Orca EDGE graphical display (100 fsw and 40 fsw, forward and reverse profiles).

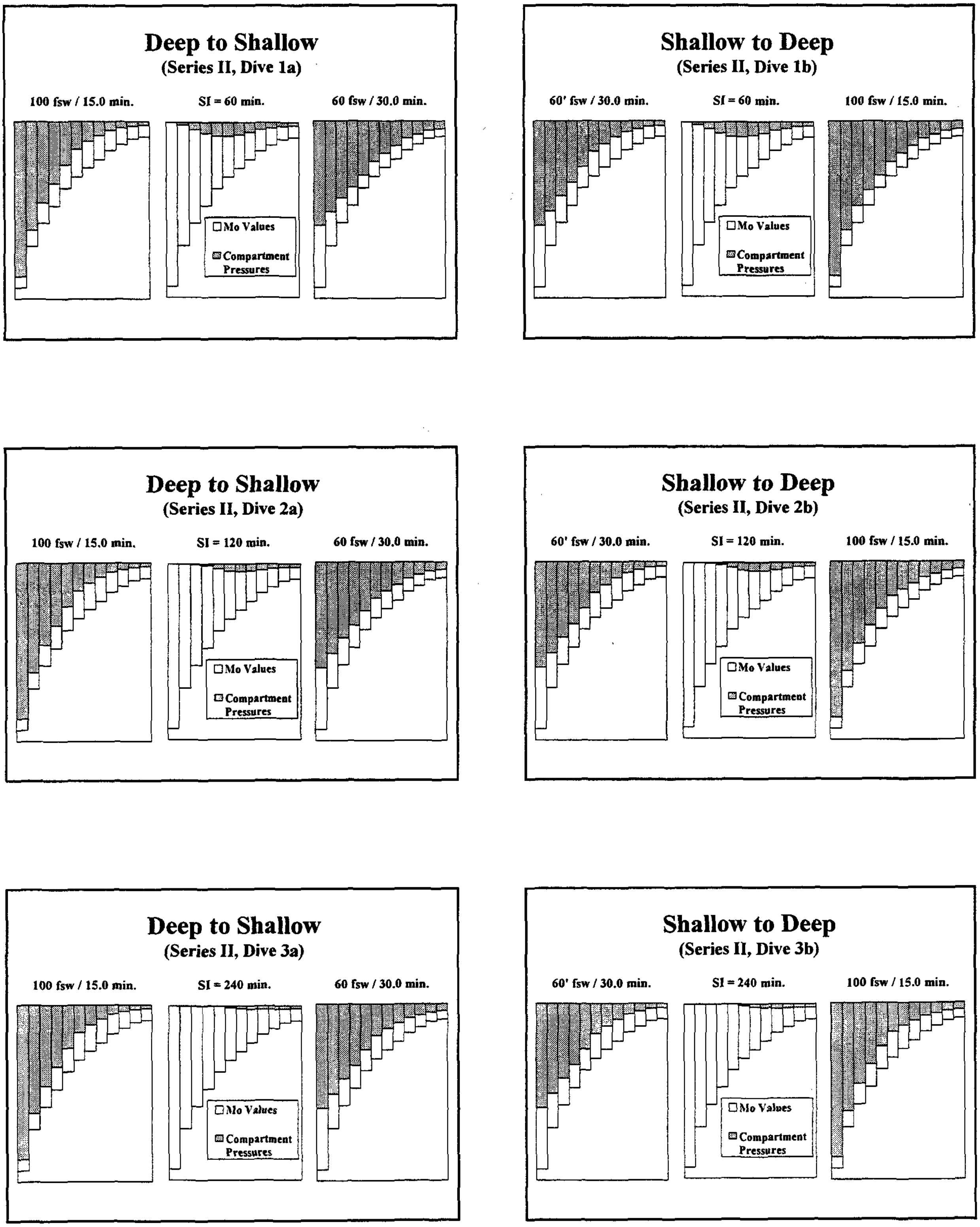


Figure 2. Orca EDGE graphical display (100 fsw and 60 fsw, forward and reverse profiles).

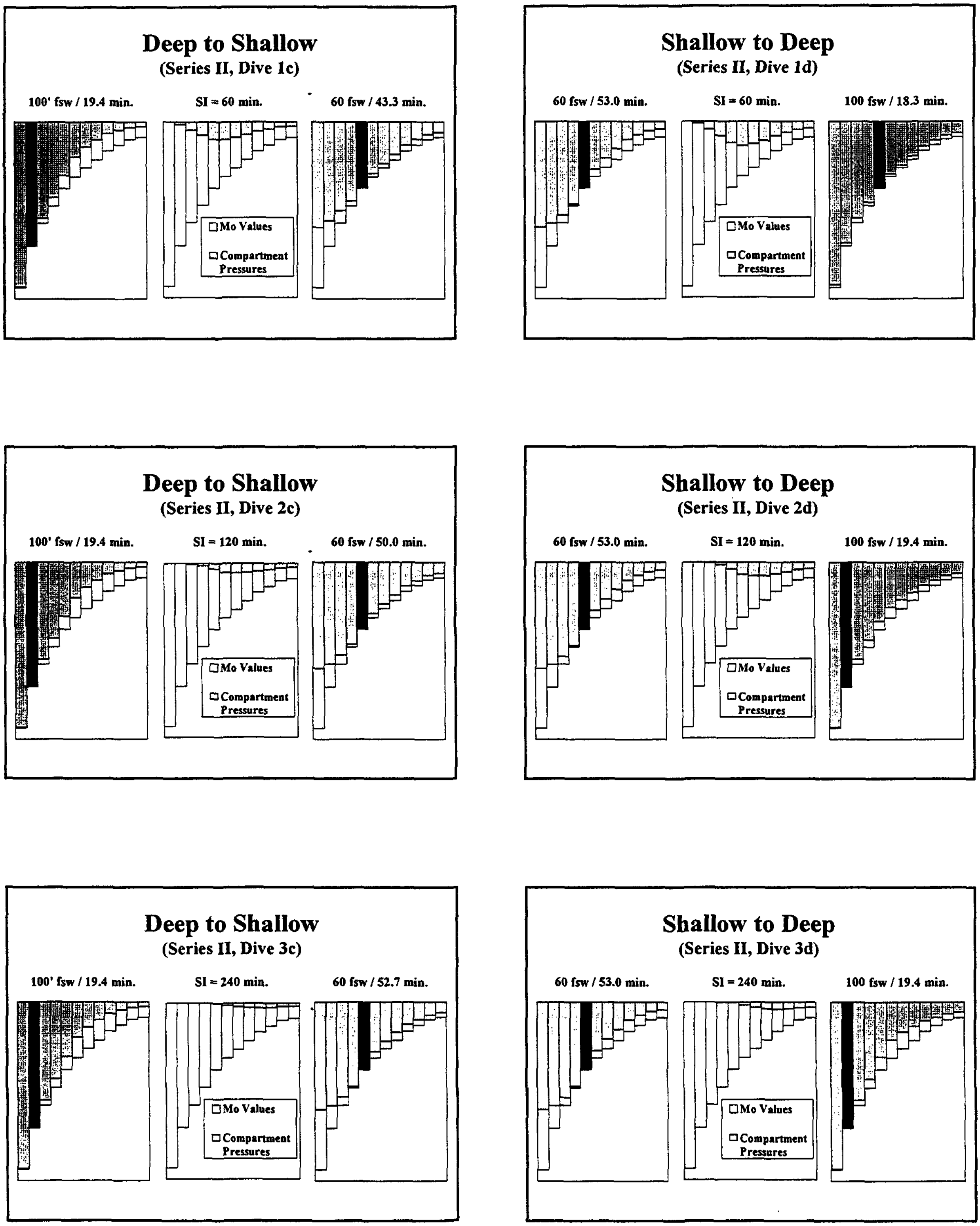


Figure 3. Orca EDGE graphical display (100 fsw and 60 fsw) cont'd.

slightly as the surface interval increases. Once again, the loading at the end of the shallow-to-deep series is greater than at the end of the deep-to-shallow series. The final six slides show the response to the 100 fsw and 60 fsw no-decompression limit series. They show a slight increase in the loading at the end of the deep-to-shallow series as the surface interval increases. As expected, the loading at the end of the shallow-to-deep series is greater than at the end of the deep-to-shallow dives. However, instead of model loading increasing as the surface interval increases (as seen in the 40 fsw no-decompression limit series) the end loading decreases in the shallow-to-deep series as the surface interval increases.

This analysis shows that the overall loading of the Edge model is greater following a shallow-to-deep dive series versus a deep-to-shallow series. Some reverse dive profiles (to the no-decompression limits) will result in close to maximum model loading after short surface intervals while others show increased loading as the surface interval increases. If this additional loading represents an increased risk for decompression sickness, then this would be a reason to avoid reverse dive profiles. However, if the risk of decompression sickness is negligible as long as the model is within its limits, then there is no reason to prohibit reverse dive profiles. The penalty for this additional model loading from a reverse dive profile is a greater amount of residual nitrogen in the compartments that needs to be taken into account in computing subsequent dives.

There is not enough data to conclude if the level of risk is indeed increased significantly in reverse dive profiles. In response to this lack of data, and recommendations from previous AAUS workshops, Orca addressed the reverse dive profile issue in their publication "Dive Computers & Diving Safety" (ORCA Division of EIT, Inc., 1992): "Do not make repetitive dives below 80 feet unless your surface interval is greater than one hour... Repetitive diving should be approached cautiously. Safety data is scarce for deep repetitive dives. When making repetitive dives, make your first dive of the day the deepest dive, and then make each subsequent dive shallower than the one preceding it."

J. Lewis: I represent PELAGIC, which manufactures the dive computers that are distributed by Oceanic, Genesis, historically U.S. Divers, and others. There is nothing explicit in the algorithm that deals with reverse dive profiles as they are described here. However, because of the inherent nature of multi-level diving, you will see that for short surface intervals, it favors a conventional profile going deeper first in terms of the percentage of no decompression time for a given surface interval. I am sure it is not unique. I believe the dive computers will all behave in that same way. Beyond about a 60-minute surface interval, it makes virtually no difference at all. You get the same fraction of the no decompression time on the second dive, whether it is reverse or conventional. There is one important exception that I would try to emphasize. That is we do make an exception for repetitively deep profiles. These have been demonstrated to be problematic by Ed Thalmann as well as by Leitch and Barnard and others. So we do treat those separately. If you dive repetitively deeply, you will be penalized.

E. Voellm: I am with Dynatron of Switzerland. We are doing the tissue options for the Aladdin dive computers that are marketed by Scubapro. We are using an adaptive human model. This is a Haldanean model with variable perfusion rates. This means that 7 of 8 tissues or 7 of 8 compartments have a variable tissue halftime and variable supersaturation tolerance according to exertion, temperature and bubbles. For that, we use also a bubble formation model that works the same way. We assume that if the bubbles are in the tissue, the perfusion rate in this area will be changed. This means that the wash-out of nitrogen is reduced and the supersaturation tolerances are also reduced. Therefore, we do not handle special cases and there are no special penalties. Everything comes out automatically. The data you have seen before are calculated this way.

S. Angelini: I represent the Technical Division of Scubapro. There are several things in the model that do add some conservatism to the dive that Ernst didn't mention. For example, the yo-yo profiles, going up and down frequently, that is something similar to maybe what John said about performing many repetitive deep dives. There are factors that do restrict the no-decompression limits or extend the decompression times.

M. Lang: Does Dynatron also manufacture the Uwatec units?

S. Angelini: Yes, those are the ones on the market.

J. Luukkanen: I am with Suunto, Finland. We have been producing dive computers since the late 1980's. The first model was the SME. After that, we produced the Solution and Eon line of dive computers and then the Spider. The newest model is the Suunto Vyper. The original algorithms in our dive computers were developed by Ari Nikkola based on the Haldanean model. In the first of our dive computers, we had operational assessment sufficient to make the computers more conservative when that was required. Now in the Suunto Vyper, we used the RGBM implementation developed by Bruce Wienke in cooperation with our engineers. RGBM factors fine-tune to M-values. That way, you could monitor decompression status with the personal assessments. One of the RGBM factors also takes care of the reverse dive profiles. These two dive series didn't show how we penalized for reverse profiles, because we penalize for the third dive after the deep dive. So if you first make a shallow dive and after that a deep dive, we penalize the third dive if the surface interval is short. But, if it is long enough, we don't penalize anything.

R. Nishi: I talked about the DCIEM model earlier. I am representing a company called Bonica, which most of you probably never heard of before. They have a dive computer that is not even on the market yet. It is based on the DCIEM model and I think the beta testers are getting their dive computers sometime in the next three weeks. The DCIEM model is actually a fairly conservative model for the repetitive dive. It is based on a serial arrangement of so-called tissue compartments. It is not Haldanean. The original model that I showed earlier this morning on the slide was developed for repetitive diving, random depth dives and so on. We modified it a bit for the present DCIEM air diving tables. The manufacturer, Bonica, informs me that the computer will follow the DCIEM algorithm for the repetitive dive. They are going by the general idea that you shouldn't be doing reverse dive profiles and the computer will give you a warning. It won't prevent you from doing a reverse dive profile, except that it will probably just get annoying to hear this beeping sound while you are doing the reverse dive. I don't know how long the alarm stays on. That is about all the information that I have right now. How reliable it is, I don't know. I should say that I have no financial connection to that. As a Canadian civil servant, it would be a conflict of interest.

S. Miller: I am with the Marketing Department of Mares, filling in for the engineers who should be here. Mares is a newcomer in the dive computer business. We have been manufacturing two of our own models for only about a year and a half now. If there are any very technical questions, I will have to write them down and get back to you.

R. Hamilton: Jarmo, you said you penalize the diver for a reverse dive. Can you be more specific? Is this penalty just due to the gas loading itself or is it an added penalty because of the order?

J. Luukkanen: It is an added penalty based on the RGBM factors. Maybe Bruce Wienke can provide a more specific answer.

B. Wienke: Within the framework of the way Suunto wanted to compute, to fit the RGBM, we had to do an extensive analysis of RGBM phase profiles and then try to do some parameter fitting to get them into a semi-Haldane framework. In terms of what Jarmo described, there are three factors that enter into the algorithm that is in the Vyper. These are depth dependent and also time dependent. There is a factor that, in the case of reverse dive profiles, reduces M-values based on the delta P of successive dives. It also decays in time on the order of one to three hours. There is also a repetitive reduction factor that again affects the M-value consistent with phase dynamics that says after deep dives, the bubble continues to grow as tissue loadings drop. There is a factor there that is also folded into the calculation. It is mostly time dependent, although it has some depth dependence to it based on how deep the previous dive was. And, then there is a multi-day factor. These are the modifications that are in the Vyper. I believe that Wayne, in one of his viewgraphs, showed, at the 95 percent level for deep or reverse dive profiles, a separation by 30-minute intervals. As time went on, if you watched the Vyper, they started to overlap, which meant in time the effect was fading away.

J. Lewis. Bruce, how do you deal with multi-level dives? Do you pick the maximum depth for this penalty?

B. Wienke: On the multi-level applications, we are always taking the deepest point of the dive and weighting it by time. So we have a time-weighted average to come up with an effective depth over the first dive that is used and a delta P for the second dive.

J. Lewis: I don't understand what effective depth means.

B. Wienke: I mean if you are doing multi-level depths over the first dive, you can weight the depth by the time and then just divide by the total time. That is the effective depth of the dive.

J. Lewis: It only plays if you come in with a 60-foot differential?

B. Wienke: No. It plays as a function of effective depths from the previous dive and the present value of your dive. Once that starts to drop below the average depth of the first dive, then these factors come into play. Operationally, it doesn't show a big effect until the changes or the deltas for the dives start to get to be around 40, 50, 60 feet. I think you saw that on the reverse dive profiles for the 160ft case that it really doesn't come into play. So there are three factors that come out of a phase dynamical fit to try to fit it into a Haldane framework so that the whole thing is self-consistent, but it is not fully one or the other. It is sort of in-between.

M. Lang: Is this reverse dive profile issue almost a moot point? From Karl's slides, take the following example: Dive to 100ft maximum first dive depth, ascend shallow in a multi-level format and spend most of the dive at 40ft, take a surface interval and off-gas a little bit. Now dive the repet to a maximum depth of 60ft. I would make the observation that the first dive really was a 40ft dive because the nitrogen loading of the 100ft depth, controlled by the fast compartments, is gone. What controls the dive at the 40ft depth are the intermediate compartments. The resultant profile, it seems, is a 40ft dive (with maximum depth of 100ft) followed by a 60ft dive, for a delta P of 20ft. Is that right?

K. Huggins: That would be pretty close on the ORCA EDGE model, basically pure Haldanean.

E. Baker: Ernst, you mentioned that you use a bubble model in the ZHLA adaptive algorithm, where you described a bubble model that increased the normal physiological right to left shunt, and gave us an example calculation for that. I still haven't figured out exactly what that is doing. Could describe that, is it published information?

E. Voellm: In principle it is proprietary, but I can tell you some things. In principle, we allow bubble formation in several parts. One is in the tissue. This is purely Haldanean. If you exceed the supersaturation tolerances, we allow formation of gas phase. The second point is the formation of venous gas bubbles. These are the bubbles that cause the right to left interpulmonary shunt. With these bubbles, we calculate the shunt. And, from this value, of course, you have the increase of the arterial inspiratory nitrogen pressure. If this shunt exceeds a certain level, we allow a portion of the bubbles to pass the lungs. It is what Alf Brubakk was talking about. Part of the bubbles can pass the lungs and come into the arterial circulation. The third point is that if you exceed a certain ascent rate, we allow the formation of gas in the arterial circulation. For these three places, we allow formation of gas bubbles. This formulation was calibrated using data from literature and also data that we had from different trials. We have also a good connection to DAN Europe, where we take part in the Dive Safety Project evaluation team and can get this data to fine tune the bubble formation model.

E. Baker: So you are getting an increase in arterial nitrogen pressure that is going to delay off-gassing? Is it going to act like a higher inspired pressure?

E. Voellm: One influence is this means you have a delayed off-gassing during the surface interval. The other influence is that bubbles that reach tissues will change their perfusion rates at least locally where they are. The same happens for bubbles that form in the tissues when you have insufficient decompression. And, when you have a change of perfusion at this area, then of course the tissue halftimes and supersaturation will change. The key is the change of tissue halftimes and supersaturation and for any influence of temperature that causes the same thing. It is the influence of effort of the diver and it is the influence of the bubbles. The influence is not on the same tissues - that is clear. But, in principle, it is always the same thing.

E. Baker: So you would have an increase in arterial pressure that would just act like a higher inspired pressure, and then you are going to presumably increase the halftime of that local tissue.

E. Voellm: No, this is a different thing. The increase of the inspiratory nitrogen pressure automatically decreases or increases desaturation time. You don't have to modify anything. This is done automatically because the inspiratory pressure is higher. But if we detect, or if the bubble model tells us, that we have bubbles in one of the tissues, then these tissues will change their tissue halftimes and supersaturation tolerances.

E. Baker: Okay. That is something that is different than what he had in the book. That is something additional?

E. Voellm: In principle, it is mentioned in the fourth edition of the book.

E. Baker: And you still have the maximum of 35 percent cardiac output as the maximum physiological shunt?

E. Voellm: It is what Albert Bühlmann has written in his book. At this high level of a shunt, you will have too low oxygen uptake. You will get hypoxia.

K. Huggins: This question is for Wayne and Bruce. It seems counter-intuitive that you would have on the Vyper results the significant difference, since this is the one that is supposedly giving you some conservatism based on reverse dive profiles. If you didn't have the bubble model in there, would you have expected to see an even greater significant difference between the two profiles? It would seem that you would be reducing the amount of time with the bubble model and therefore having a lower risk.

W. Gerth: It is just the opposite. The answer is directed to what is operating under that algorithm, to which I cannot speak. I think that is what you meant by if you didn't have the bubble thing in there would there be a bigger difference.

K. Huggins: Right. What I am saying is that if the bubble model wasn't in there, that would be running almost a pure Haldanean model, and therefore the second dive would be longer and the risk would be higher and the significance would be greater.

B. Wienke: If we didn't have that in there, then you would see the overlapping of those confidence level bars for the Vyper just as well as you saw them for the other models. So if there was no bubble model there, that would overlap and it would look the same as the other ones.

W. Gerth: I can't resist making a comment about models. I am incredulous at the understanding of decompression sickness etiology that you people have. When we fit models to very large and heterogeneous set of observations from man-dives, we can at best constrain the values of about 12 or 15 parameters. Anymore than that and they are just not statistically warranted by the information that we have. So we are then just flying on dreams. The other thing I want to say about models is that I have several different models, and in those models there are parameters to which I attach what Paul Weathersby calls nouns. I call them solubilities, diffusivities, volumes, blood flows. When I take those models and actually make them reproduce observation, through the calibration (adjusting the parameters so that the model structures reproduce observation as best they possibly can), then I emerge with values that quite disturbingly often don't make sense in the context of the picture I had before I calibrated it. What I at first was calling a solubility and a diffusivity or blood flow comes out with a number that doesn't make sense as a solubility, diffusivity or blood flow. What that means is that my model, as I conceived or constructed it, in our case the risk function, is not complete and correct. But, it does not mean that the product, the calibrated model, does not provide a very good generalization of the data. I wanted to note the distinction between what are we diving, models or real people? What are we going to base prescriptions on for diving? Is it going to be on models and dreams or on real data as manifested in real people?

E. Voellm: I do not completely agree with you because when we developed this model before 1993, we introduced only three main factors. These were the variable tissue halftime, the variable supersaturation tolerance, and the bubble formation model. All of a sudden all the special situations and risk factors that came out of the statistics were explained and handled. It was only a matter of calibrating these influences. But, in principle, what came out was exactly what should come out.

W. Gerth: I wasn't addressing my comment specifically to you, Ernst. To all of us, we have to be careful. Ultimately, as we add parameters to models that represent the influence of different governing factors of covariates, we are going to show that we can make them significant by expanding the nature of the data that we are fitting. But, we do have to be careful all along that we don't overextend the data and actual experience that we have in hand as we build these intellectual machinations for how bends occur. The other thing is there has been a lot of talk about bubbles. One of the conclusions that we have been reaching time and again at trying to make bubble models explains DCS incidence is that bubbles are not always the proximate cause of bends. I think we have almost reached a point where to try to explain DCS incidence only on the basis of bubble dynamics, we have reached the pinnacle of what we are going to get with that. Bubbles oftentimes in turn set in motion a train of events that ensues and continues after the bubbles are gone that can cause DCS. I haven't heard a whole lot of talk about that here, but I don't know that that is relevant within the context of reverse versus forward profiles. I am trying to address in a general way that we can't let ourselves run away theoretically from the data that we have.

K. Huggins: I agree with that from a modeler's perspective who has stepped back because of involvement in the community and learned more and more. You find that the more you find out and learn, the less you actually know about what is going on and you can see how sort of simplistic the initial models were and how they really may or may not apply to the situation. You really don't know what is going on.

V. Flook: I am a little bit worried about the concept of changing tissue halftimes in the presence of bubbles in the belief that the bubbles are going to slow down blood flow. Most of the organs in the body have capillary beds that open and close and open and close, and I think, if there were a serious problem because of the slowing down and reduction of blood flow to tissues, we would see a lot of hypoxic injury. I can appreciate that by doing it that way, you are perhaps taking some account of the effect of bubbles in slowing down the wash-out. But if you really took that to its ultimate and proper conclusion, the halftimes become so prolonged that we certainly would be seeing vast areas of the body with hypoxic injury. I think this is an attempt to be sophisticated based on some very naive knowledge of physiology.

J. Lewis: There is an experimental data base that addresses that nicely. It is the experiments that Ed Thalmann did. Clearly, a purely theoretical model where the halftimes are an invariate both of uptake and relaxation, simply doesn't work. On the other hand, 120 minutes, perhaps the point is well taken, is overly conservative. There is something in-between, but it most assuredly is not purely Haldanean. What we should be dealing with, as Wayne pointed out earlier, are things that simply work and fit the data. The direct connection to the physiology - I am delighted to give up. But it is clear that something is going on that looks, at least from a modeling perspective, as though in order to preclude the problems in terms of relaxation from repetitive dive control, you have to do some modification of either the halftimes or allowable saturation levels. Maybe if that would be more acceptable physiologically to keep the same halftimes and change the allowable supersaturation limits, you could model that just as well. But I don't think the impact in terms of a prediction of a dive computer is going to make a difference.

B. Wienke: I noticed that Cochran Engineering is not here today. Mike Cochran has a version of this RGBM phase model supposedly encoded in the software of the Cochran dive computers. I haven't been in the loop, but he has told me that their engineering department put it in. It will be interesting to see how that all works for them.

R. Vann: Mike Cochran did want to participate in this workshop, but couldn't due to an emergency.

M. Lang: Jon Hardy uses a variety of dive computers and has seen or tested them all. Jon, do you have any observations as a user without necessarily giving away your punch line for tomorrow's presentation?

J. Hardy: I have probably used more of these computers than any other mammal around. It has been eight years now that we have been testing for Rodale's Scuba Diving. We have done hundreds of human tests and those human tests are on these dive computers. Almost all of our tests do involve human subjects. We also have chamber test data. We still use ORCA products as our control model on the liberal left side and the old Scubapro (not Uwatec/Scubapro) on the conservative right side. The new Mares, the Suunto's, and the current Uwatec units are in the middle of the conservative rows. We compile those tables and charts published in Rodale's magazine by performing 13 dive profiles (dive situations), one of which is a reverse dive profile. As has been defined by Bruce and others talking about delta P's, we use a 70-foot differential, from 60ft to 130ft. In fact, as John Lewis explained, they have a depth restriction. If you took only the reverse profile, the Pelagic units would be the most conservative, because we jump 70 feet when we do it, and the ORCA units would be the most liberal. Now the interesting point is that over a total of eight years and 700 to 800 human dives and many hundreds of chamber dives beyond that, we have not bent one of our divers. We have been criticized for allegedly ignoring subclinical bends. Most of our people are chamber operators; they are qualified and know what DCS symptoms are. We have not bent anyone. Yet, we regularly violate the conservative computers. By violate, I mean we come to a need for a decompression stop and don't make the decompression stop, because our control model is the liberal ORCA model that we come up on. Also, because I serve on legal cases, I ask where the hundreds of legal cases are against the manufacturers if these dive computers are allowing something that is unreasonable? In fact, we don't have them. When we do have a legal case about a dive computer, it has to do with a particular function of the computer and is usually not proven during the legal case. I would like to point out is that all these computers are essentially allowing a range of behavior that appears to be acceptable. You might criticize recreational and commercial divers (not oilfield, but general working divers) for not knowing when they are bent, but there is a tremendous amount of diving going on. There is also a tremendous range of behavior that is successfully being done with no apparent harm.

REVERSE DIVES AND *PROJECT DIVE EXPLORATION*

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This report examines two open-water dive studies for evidence suggesting that "reverse" dives are more hazardous than "forward" dives. The following definitions were used: a "reverse" dive is a repetitive dive that is deeper than the previous dive, and a "forward" dive is shallower than the previous dive. Repetitive dives take place in a single day during which there is an 8-12 hr period with no diving.

Surface Interval Oxygen (SIO_2) Dives

The first study tested the safety of multi-day, repetitive, no-stop dives in which oxygen was breathed during the surface intervals to extend the repetitive dive bottom time (Pollock *et al.*, 1992; Stanton *et al.*, 1992; Vann *et al.*, 1992). The tests were conducted at Wakulla Springs, Florida, and involved three dives per day for six consecutive days. The water temperature was 20-22°C, and the divers' mean respiratory minute volume of 18 Lpm (estimated from the open-circuit gas supply pressure) was equivalent to an approximate swimming speed of 0.5 knots (1979 USN Diving Manual).

Dives were to 80 fsw with a mixture of 36% oxygen in nitrogen (hereafter called "36% nitrox") and to 120 fsw with 32% nitrox. Surface intervals between dives were 50, 65, or 130 min. Upon surfacing, the divers breathed air for 5 min and then oxygen for 30 or 35 min followed by air for 15, 25, or 95 min, if there was a repetitive dive. The divers were monitored with Doppler ultrasound instrumentation for precordial and subclavian bubbles. Bubble signals were graded according to the 5-point Spencer system. The depth-time profiles were recorded by Delphi dive computers, on loan from Orca Industries. Ten of the 12 repetitive dives were to the same depth as the previous dive, while two were "reverse" dives in which the previous dive was to 80 fsw while the next dive was to 120 fsw.

Four weeks of diving were planned with eight divers making three dives per day from Monday to Saturday for a total of 576 dives. During the first dive of the initial week, a 25-year old male diver had a seizure after 35 min at 80 fsw. He was rescued and recovered without incident. The oxygen partial pressure during his dive was 1.26 atm. Investigation disclosed a history of seizures and anti-convulsant medications that he had not reported during pre-dive medical exams.

Diving resumed on Monday of the second week, and three of the four planned weeks were completed with 383 individual dives by 5-8 divers per day. There were 27 divers with a mean age of 31 years (range 20-47 years). Five divers were female. Five divers withdrew due to illness, anxiety, or ear infection. Eighty-seven percent of the dives were recorded by computer. Figure 1 is a representative depth-time profile.

A 22-year old female diver developed shoulder pain 20 min after surfacing from a dive to 120 fsw on Tuesday. The pain resolved during recompression on a USN Table 5. Her planned dive profile included a 25 min first dive, a 135 min surface interval, and a 22 min second dive, but she and her dive partners remained at depth for 25 min on the second dive. There were no other incidents of decompression sickness (DCS).

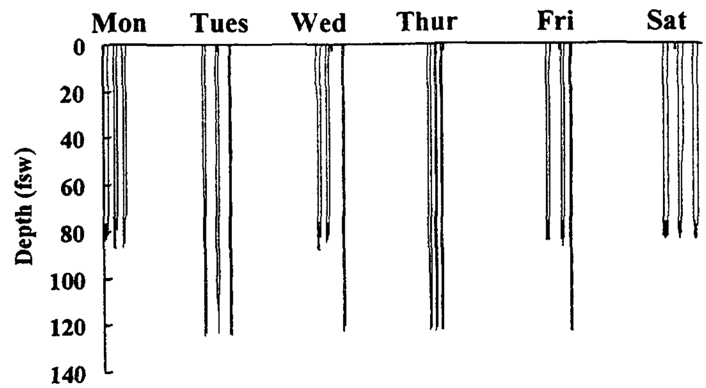

Figure 1. The depth-time profile recorded for one diver during the SIO_2 trials.

Table 1 lists the results of the SIO_2 trials. Precordial bubble signals were detected after 22% of all dives with 4% of the bubbles being Grade 3. The incidence of bubbles was 30% after the 120 fsw dives, and 17% after the 80 fsw dives ($p<0.01$). The combined repetitive dive bottom time for the six days of diving was 352 min. The equivalent time according to the NOAA nitrox tables was 109 min.

Table 1. Description of dives and results (* - one seizure; + - one DCS; # - reverse dive).

Day	Dive	Depth (fsw)	Bottom Time (min)	Surface Interval (min)	Number of Dives	% Doppler Grades 2 & 3	Total Repetitive Dive Time (min) NOAA	Total Repetitive Dive Time (min) SIO_2
Monday	1	80	51	65	21*	19%		
Monday	2	80	37	65	21	5%		
Monday	3	80	37	-	19	6%	16	74
Tuesday	1	120	25	130	18	9%		
Tuesday	2	120	22	130	17+	6%		
Tuesday	3	120	22	-	14	21%	14	44
Wednesday	1	80	51	65	21	30%		
Wednesday	2	80	37	130	21	19%		
Wednesday	3	120	22	-	21#	45%	11	59
Thursday	1	120	25	50	20	5%		
Thursday	2	120	18	50	20	25%		
Thursday	3	120	17	-	20	15%	3	35
Friday	1	80	51	130	20	5%		
Friday	2	80	40	65	19	5%		
Friday	3	120	20	-	18#	28%	17	60
Saturday	1	80	51	130	18	0%		
Saturday	2	80	40	130	18	0%		
Saturday	3	80	40	-	18	6%	48	80

A total of 39 reverse dives to 120 fsw were conducted without reported DCS after dives to 80 fsw. The incidence of Doppler-detected venous gas emboli (VGE) was higher after reverse dives, but this may have reflected their greater depth.

Project Dive Exploration

To estimate DCS risk, one must know the depth-time profiles and outcomes of many dives. The possibility of acquiring such information arose in the late 1980s when the dive computer manufacturers Suunto and Orca introduced relatively inexpensive instruments that could record dive profiles. DAN began working with Suunto and Orca in 1992 and began formal data collection under *Project Dive Exploration* in mid-1997. *Project Dive Exploration* (*PDE*) has collected 13,421 dives in its initial two years of activity (August 1997 to September 1999) as illustrated in Fig. 2. This was possible because of the support of four dive computer manufacturers: Cochran Consulting (Richardson, Texas), Orca Industries (no longer available), Suunto (Finland), and Uwatec (Switzerland). Information about *Project Dive Exploration* is available from the DAN Web Site at www.DiversAlertNetwork.org.

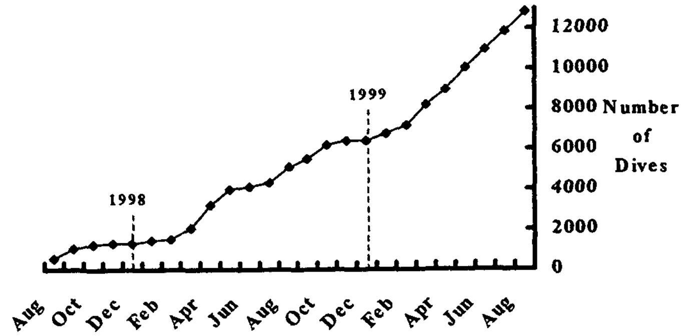

Figure 2. Data collection during *Project Dive Exploration*.

A total of 1,234 divers contributed 1,482 dive series during the two years of data collection. (A dive series is defined as a group of dives preceded by 48 hours without diving and followed by 48 hours without diving or altitude exposure.) The distribution of *PDE* divers across age and gender is shown in Fig. 3. Divers in the 30-39 age range were the most common, and relatively few divers were under 19 or over 50. Females made up 26% of *PDE* volunteers. Most *PDE* dives occurred during dive series lasting one day and six days (Fig. 4). A quarter of the *PDE* series involved two dives and 30-40% involved 11 or more dives (Fig. 5). About 70% of the maximum depths for *PDE* dives were no greater than 90 fsw (Fig. 6). Practically all the *PDE* divers used dive computers to plan their dives.

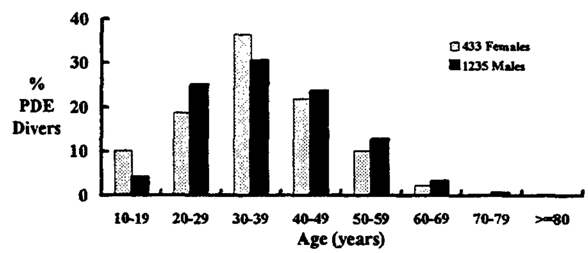

Figure 3. Distribution of age and gender in the *PDE* population.

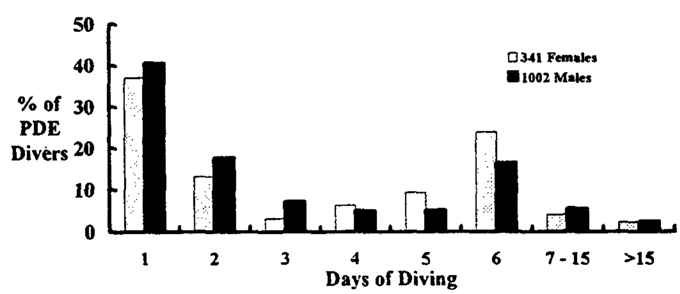

Figure 4. Days diving by *PDE* divers.

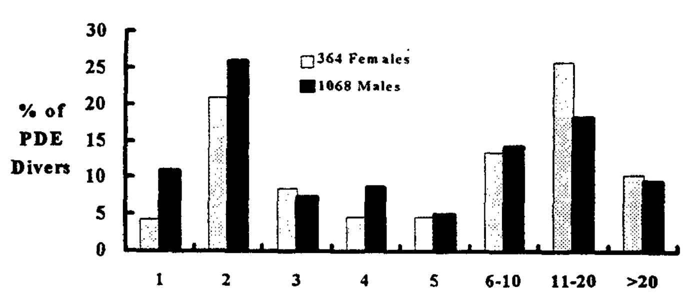

Figure 5. Dives in series by *PDE* divers.

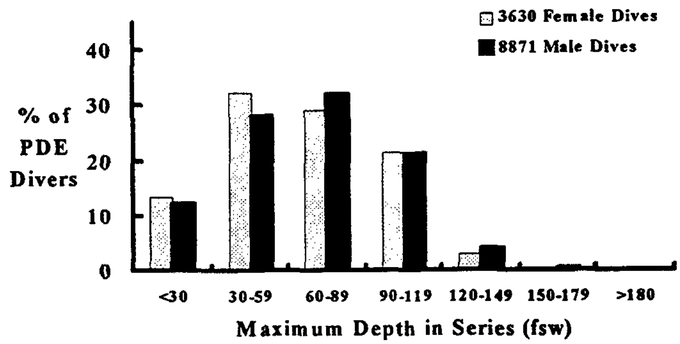

Figure 6. Maximum dive depth by *PDE* divers.

PDE volunteers were questioned at least daily concerning the presence or absence of symptoms after their dives. They were also asked to report the occurrence of all health problems, even if clearly unrelated to the diving exposure. This was to reduce the underreporting of symptoms that might be decompression sickness. When a dive series was finished, a diver was given a form called the 48-Hour Report that was to be completed 48 hrs after the last dive or altitude exposure. The 48-Hour Report asked the diver to deny or confirm the occurrence of symptoms, to report recompression therapy, and to report details concerning altitude exposure. 48-Hour Reports were submitted by 43.5% of *PDE* divers.

Symptom classification was used to distinguish between symptoms due to illness or injury and those that had no identifiable cause but were compatible with DCS. In two years of *PDE* data collection, 76 divers reported symptoms that were classified as indicated below:

a. "Not DCS" (due to illness or injury) - 62 divers
   - Bruises, colds/flu, sunburn, diarrhea, nasal congestion, mechanical injury, inflammation, headache, nausea, hypothermia, ear squeeze, marine animal injury.

b. "Ambiguous" (possible DCS) - 11 divers
   - Diver 1: pain in left shoulder and right wrist.
   - Diver 2: left shoulder pain and tingling in left hand.
   - Diver 3: left shoulder pain and forearm weakness.
   - Diver 4: mild left ankle pain and itching around neck.
   - Diver 5: severe pain in left shoulder; moderate pain and numbness of left elbow.
   - Diver 6: limb pain.
   - Diver 7: mild tingling of left hand and fingers.
   - Diver 8: pain in both elbows.
   - Diver 9: moderate pain in left wrist.
   - Diver 10: skin changes and joint pain.
   - Diver 11: pain in left arm and numbness in elbow.

c. "Recompressed" (diagnosed as DCS by the treating physician) – 4 divers

   - Case 1: pain and neurological symptoms while flying after diving. A 43-year old female diver with 10 years of diving experience made 10 dives in 4 days to depths as deep as 140 fsw (Fig. 7). Dive 6 was reverse to a depth of 123 fsw after a previous dive to 85 fsw. Twenty-six hours after her last dive, she flew home by commercial air. During the flight, she developed right shoulder pain and tingling of her left forearm and hand. She was treated on Table 6 the next day with complete resolution of her symptoms.

   - Case 2: lymphatic symptoms after 20 dives in six days. A 43-year old female diver with extensive experience made 20 dives in 6 days to depths as deep as 110 fsw (Fig. 8). Dive 9 was a reverse dive to a depth of 90 fsw after a previous dive to 75 fsw. Shortly after Dive 20, she developed skin changes and swelling in an unspecified location. Her symptoms were relieved by recompression.

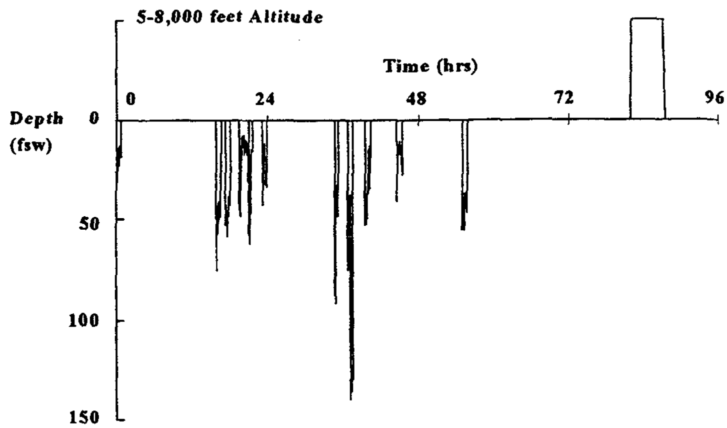

Figure 7. Case 1: pain and neurological symptoms with onset during flying after diving.

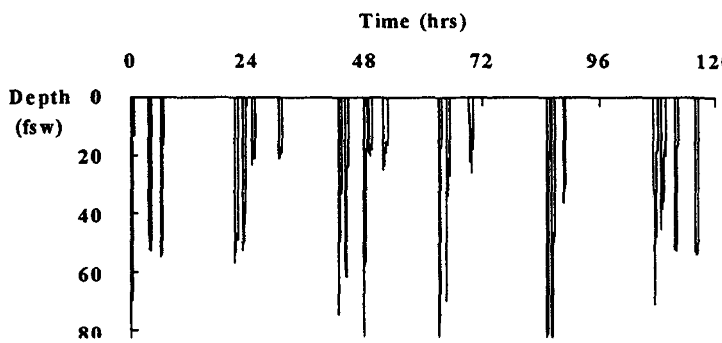

Figure 8. Case 2: lymphatic symptoms after 20 dives in six days with onset after the last dive.

- Case 3: shoulder pain during 20 dives in six days. A 30-year old female diver with three years of diving experience made 20 dives in five days to depths as deep as 110 fsw (Fig. 9). Dive 9 was a reverse dive to 97 fsw after a previous dive to 74 fsw. On Day 5, she made two reverse dives (Dive 16 to 85 fsw after Dive 15 to 64 fsw; Dive 18 to 110 fsw after Dive 17 to 74 fsw) and developed pain in her left shoulder and back but continued diving on Day 6. Three days after her last dive, she was recompressed on a Table 6, resulting in a decrease of pain from Grade 8 to Grade 3 on a scale of 0-10. She was treated the next day for 90 minutes at 45 fsw with 100% oxygen but had no further relief. Her symptoms resolved completely after several days' treatment with NSAIDs.

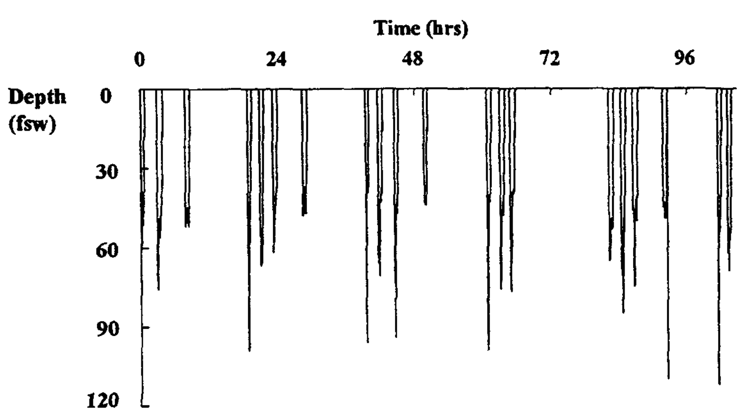

Figure 9. Case 3: shoulder pain during 20 dives in six days.

- Case 4: vestibular symptoms after six trimix dives. A 54-year old male diver with 30 years of diving experience made six trimix dives in six days on the *USS Monitor* (Fig. 10). Only the last two profiles were recorded by dive computer. The last dive was to a depth of 220 fsw. Thirty-eight minutes after the dive, the diver developed vertigo and vomited twice. A neurological examination by a Diving Medical Officer on a nearby Navy vessel revealed no evidence of otic barotrauma, and abnormalities in heel-to-toe and heel-to-shin tests. The diver was recompressed on an extended USN Table 6 with significant improvement but had minor neurological abnormalities post-treatment. These symptoms cleared with two additional treatments over the next two days.

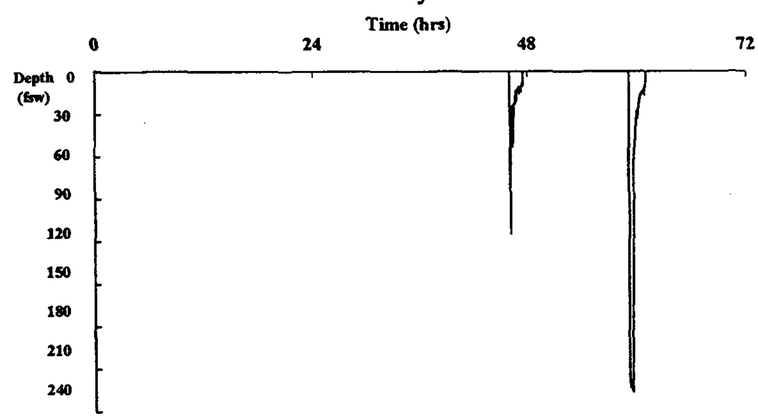

Figure 10. Case 4: vestibular symptoms after six trimix dives.

Table 2 summarizes the diving activity of *PDE* divers by symptom category according to the mean number of dive days, the mean number of dives, the mean dive depth, and the mean maximum dive depth in the series. Divers with ambiguous symptoms had made deeper dives than divers without DCS. Divers who were recompressed had dived a day longer than the other divers, had made more dives, and had a greater maximum depth.

Table 2. Diving activity by symptom categories.

Category	Days Diving	Number of Dives	Depth (fsw)	Maximum Depth (fsw)
1,467 Divers without DCS	3.9	9.1	70	98
11 Divers with Ambiguous Symptoms	3.6	8.5	94	119
4 Recompressed Divers	5.0	14.5	94	149

In Table 3, divers who made reverse dives were characterized in the same fashion as in Table 2. Table 3 divides the *PDE* data into: (a) 1,124 divers who made 6,563 forward dives; (b) 358 divers who made 651 reverse dives out of 6,858 total dives in which the reverse dives were at least 10 fsw deeper than the previous dives; and (c) 195 divers who made 195 reverse dives out of 4,337 total dives in which the reverse dives were at least 40 fsw deeper than the previous dives. The proportion of divers who were recompressed or had ambiguous symptoms was greater for those who had done reverse dives, but these divers had dived 2-3 times as many days, had made over three times as many dives, and had deeper maximum dive depths. The onset of symptoms was chronologically associated with reverse dives for only one recompressed diver (Case 3).

Summary and Conclusions

During open-water trials of surface interval oxygen, there was no DCS in 39 reverse dives to 120 fsw on 32% nitrox after previous dives to 80 fsw on 36% nitrox. During over 13,000 open-water dives in *Project Dive Exploration,* three of four recompressed divers had made reverse dives, but only one had symptoms whose onset was chronologically associated with the reverse dives. Reverse dives also occurred during more intense diving activity than did forward dives.

Table 3. Reverse dives and diving activity.

Category	Days Diving	Number of Dives	Depth (fsw)	Maximum Depth (fsw)	Ambig-uous	Recom-pressed
1,124 Divers with Only Forward Dives	2.7	5.8	71	91	8	1
358 Divers with 10 fsw Deeper Reverse Dives	7.8	19.2	69	120	3	3
195 Divers with 40 fsw Deeper Reverse Dives	9.0	22.2	73	134	3	2

While data on reverse dives are limited and analysis with appropriate statistical controls is needed, the evidence that reverse dives *per se* are more hazardous than forward dives is not strong. On the other hand, reverse dives appear more likely during periods of intense diving which itself may be associated with greater DCS risk.

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REVERSE PROFILES VERSUS "FORWARD" PROFILES: A REVIEW OF DIVERS TREATED AT THE USC CATALINA HYPERBARIC CHAMBER

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There is concern that divers performing reverse dive profiles are placing themselves at greater risk for decompression sickness (DCS). Since the incidence of reverse dive profiles performed by the diving population is unknown, a comparison with the incidence of reverse dive profiles performed by treated divers is not possible. What can be compared is the difficulty in treating DCS between patients who have performed reverse dive profiles and those who performed forward dives. A case record review of the 300+ patients treated for DCS since 1975 was performed. The dive profiles prior to the treatment were examined for occurrence of reverse dive profiles and maximum reverse depth difference (MRDD) between dives. Length of the patient's initial treatment and number of retreatments were collected. "Normal" resolution was defined as a single treatment on the Catalina Consolidated Treatment Tables (CCTT) of 4&9 or less. "Delayed" resolution was defined as a single CCTT treatment longer than a 4&9 or a multiple treatment series. Of the 307 "DCS" treatments reviewed, 214 were following a repetitive dive series, five omitted decompression "treatments" were excluded since no symptoms were present. Reverse dive profiles were performed in 80 of 209 remaining cases (38.3%). There were 34 cases of "Delayed" resolution following reverse dive profiles. In the 129 forward dive profile cases, 49 had delayed resolution. The odds ratio for "Delayed" resolution following reverse dive profiles versus forward profiles is 1.21 (95% C.I. 0.68 – 2.13). Comparing "Delayed" resolution versus the MRDD within the reverse dive profiles produced the following incidences:

MRDD (fsw)	1 – 10	11 – 20	21 – 30	31 – 40	41 – 50	51+
"Delay" Incidence	0.50	0.26	0.33	0.38	0.60	0.62
95% C.I.	0.27-0.73	0.08-0.44	0.02-0.64	0.11-0.65	0.17-1.00	0.36-0.89

These data show no significant difference in the resolution of DCS symptoms resulting from reverse dive profiles versus forward profiles. There appears to be a trend of increasing incidence of "Delayed" resolution as the MRDD increases, however, due to the limited data there are no significant differences between the MRDD groups. Many other variables exist that were not collected or considered in this analysis. Of interest would be maximum depth of series and if the profiles were within the decompression tool (table or computer) utilized, if any. This review hints at the potential for more severe DCS following reverse versus forward profiles and that this potential increases as the MRDD increases. If there is a significant increase in this risk, more data needs to be included in the analysis. DAN and/or other chamber facilities could be enlisted to assistance in obtaining thes data.

Background

In some areas of diving, there is concern that divers performing reverse dive profiles are placing themselves at greater risk for decompression sickness (DCS). Does this additional risk actually exist, does it increase as the maximum reverse depth difference (MRDD) increases, or is this additional risk just perceived, with little or no data to support this conclusion? Most rules for decompression table use recommend deep-to-shallow profiles for maximum efficiency. Could these rules act as a raised flag in cases of DCS within the limits of the tables and be remembered more often than other "within limit" cases, fueling anecdotal reports? Calculations with many models indicate an increased risk with reverse dive profiles. Is this increased risk significant? There are no conclusive data to answer these questions, otherwise there would be no need for this workshop.

Since the incidence of reverse dive profiles performed by the diving population is unknown, as is the incidence and profiles of forward dives, a risk comparison is not feasible. What can be compared is the severity of symptoms and the difficulty in treating DCS between patients who have performed reverse and those who performed forward dives. If reverse dive profiles produce DCS with greater severity than forward profiles, then a general proposal that reverse dive profiles result in a higher DCS risk may be put forth.

This review examines if the treatment records at the USC Catalina Hyperbaric Chamber (CHC) support this type of proposal. The CHC has treated divers for DCS and arterial gas embolism (AGE) for the last 25 years. Over 700 divers have been triaged, with over 500 being treated. There have been 307 cases that fall in the DCS category and 215 treated in the AGE category. The divers treated at the CHC come from many populations including recreational, harvesting, scientific, commercial, and military divers. The primary groups that the treated cases come from are the recreational and harvesting diver communities.

Methods

A case record review of the 307 patients treated for DCS since 1975 was performed. Due to limited time and the use of volunteers, a measure of DCS severity was not obtained. The dive profiles prior to the treatment were reviewed for occurrence of reverse dives and MRDD within and between dives. The protocol used for the patient's initial treatment and number of retreatments was collected.

Difficulty in treating DCS (resolution) was graded either as "Normal" or "Delayed." Resolution of DCS symptoms was defined as "Normal" if the diver required only a single treatment on the Catalina Consolidated Treatment Tables (CCTT) of 4&9 or less. "Delayed" resolution was defined as a single CCTT treatment longer than a 4&9 or a multiple treatment series.

The two hypotheses tested in this paper are:

- "Delayed" DCS symptom resolution is more prevalent following a reverse dive profile series than a "normal" dive series.
- "Delayed" DCS symptom resolution is more prevalent following a deeper profile reversal than a shallower profile reversal.

An odds ratio analysis was performed to determine if there was a greater than even chance of "Delayed" resolution following reverse versus a forward profile. The potential of increased "Delayed" resolution versus MRDD was then evaluated in 10 fsw increments of MRDD up to 50 fsw and in the 51+ fsw group.

Results

There were 307 initial treatments falling in the DCS category. Of these, 10 were removed from the analysis due to the following reasons:

- Test of Pressure (n=6) - symptoms determined not to be DCS.
- Unknown dive profiles (n=4).

The breakdown of the remaining 297 "known dive profile" cases consisted of:

- Single dive profiles (n=83).
- Repetitive dive profiles (n=214).

Reverse dive profiles constituted 28.8% of these cases. Historically, the occurrence of reverse dive profiles leading to a diver being treated at the CHC has not been constant. Looking at the 5 five-year intervals since the CHC opened shows equal incidence (~30%) during the first 10 years (1975-1984), an increase in the 1985-1989 interval to 39%, a drastic drop to 11% in the 1990-1994 years, and an increase to 24% in the last five years (Figure 1).

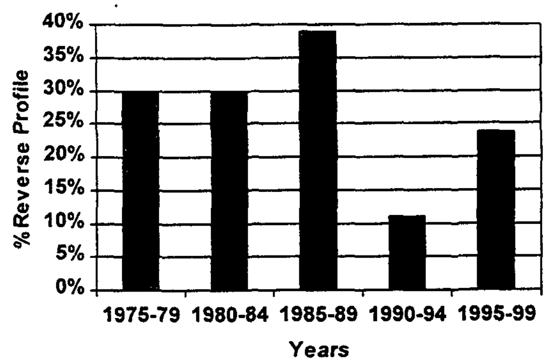

Figure 1. Percent of Reverse Dive Profiles by Years.

Of the 83 single dive profiles, there were seven cases of omitted decompression. Since the diver was showing no symptoms these cases were not included in the analysis.

Of the 76 remaining cases, there were only two that had enough profile data to show reverse profiling had occurred within the single dive. Both of these cases resolved "normally." Of the non-reverse dive profile cases, 29 out of 74 had "Delayed" resolution (39%).

In the 214 repetitive dive profiles, there were five cases of omitted decompression that were excluded.

Of the remaining 209 cases, 80 were following reverse dive profiles that resulted in 34 "Delayed" treatment resolutions and 46 "Normal" resolutions. Of the 129 divers who did not perform reverse dive profiles, the resolution breakdown was 49 "Delayed" and 80 "Normal" (Table 1).

Table 1. Repetitive dive profiles versus resolution type.

		Symptom Resolution	
		"Delayed"	"Normal"
Profile	Reverse	34	46
	Forward	49	80

The percent of "Delayed" resolution in the repetitive non-reverse dive profiles was 38%.

To determine if "Delayed" resolution was more prevalent following reverse dive profiles, the odds ratio (OR) between reverse and forward profile resolution was calculated.

OR = (Odds "Delayed" in Reverse) / (Odds "Delayed" in Forward profiles)
= ((34/46) / (49/80))
= 1.21

The 95% confidence interval for this OR is (0.68 – 2.13).

Within the repetitive reverse dive profiles group, the depth difference between dives ranged from 1 fsw to 80 fsw. To determine if there was an increased occurrence of "Delayed" resolution as the MRDD increased, the cases were grouped into MRDD intervals of 10 fsw up to 50 fsw and a 51+ fsw group (Table 2).

Discussion

These data show no significant difference in the resolution of DCS symptoms resulting from reverse dive profiles versus forward profiles. There appears to be a trend of increasing incidence of "Delayed" resolution as the MRDD increases, however, due to the limited data, there are no significant differences between the MRDD groups.

Table 2. MRDD versus incidence of "Delayed" resolution.

MRDD (fsw)	Cases	Resolution		Incidence of "Delayed"	95% C.I.
		"Normal"	"Delayed"		
1 – 10	18	9	9	0.50	0.27 – 0.73
11 – 20	23	17	6	0.26	0.08 – 0.44
21 – 30	9	6	3	0.33	0.02 – 0.64
31 – 40	12	7	5	0.38	0.11 – 0.65
41 – 50	5	2	3	0.60	0.17 – 1.00
51+	13	5	8	0.62	0.36 – 0.89

The fluctuation in incidence of reverse dive profiles in the treated population over the years was of interest. The increase in the 1985 - 1989 range may reflect the infiltration of dive computers into the diving population in the mid-1980s, which would not penalize divers for conducting reverse dives. The drop in 1990 - 1994 may be the result of stronger admonition against performing reverse dives in scuba instruction.

Another interesting observation was that the incidence of "Delayed" resolution cases from the forward profiles was almost identical in single versus repetitive dives.

Many other variables exist that were not collected or considered in this analysis. Of interest would be maximum depth of series and if the profiles were within the decompression tool (table or computer) utilized, if any.

This review hints at the potential for more severe DCS following reverse versus forward profiles and that this potential may increase as the MRDD increases. If there is an increase in this risk, more data needs to be included in the analysis to obtain a significant degree of certainty. Assistance in obtaining this data could come from DAN and/or other chamber facilities.

TWO CASES OF SEVERE DCS AFTER COMPLETION OF REVERSE DIVE PROFILES

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Two divers suffering severe DCS after having completed reverse dive profiles in the Maldives were treated at the Bandos Island Hyperbaric Treatment Center. Interestingly, dive buddies on almost similar profiles did not present with DCS symptoms. Dive computer algorithms are based on mathematical models, not on an individual's physiology. Considering that DCS is not impossible while using dive computers on conventional repetitive dive profiles, reverse dive profiles might represent an additional risk as more complicated mathematical models would be applicable for these profiles.

Introduction

Each year between 60 and 80 patients have to be treated for decompression illness (DCI) at the Bandos Hyperbaric Treatment Center located on Bandos Island, Republic of Maldives. It has been estimated that in less than 10 percent of these cases arterial gas embolism was the diagnosis (unpubl. data).

Excluding decompression sickness (DCS) cases with rapid ascent, Table 1 shows the numbers of patients with a history of reverse dive profiles. Three subgroups of patients can be described:

- cases of reverse dive profiles contributing directly to DCS;
- cases of reverse dive profiles within a series of dives, where the onset of symptoms was later related to a conventional profile; and,
- cases of reverse dive profiles within a series of dives, where both the reverse profile within the series and a reverse profile before onset of symptoms contributed to DCS.

Table 1: Reverse dive profiles contributing to DCS. Patients with DCS treated at the Bandos Hyperbaric Treatment Center on Bandos Island, Republic of Maldives.

Documented cases with reverse dive profiles contributing directly to DCS
1995 4/~60
1996 3/~58
1997 2/~68

Documented cases with reverse dive profiles within a series of dives not directly related to DCS
1996 3/~58

Documented cases with reverse dive profiles contributing both directly and indirectly
1997 1/~68

There are two case reports with severe DCS after completion of reverse dive profiles.

Case Report No. 1

- 37-year old male Italian diver (150 total logged dives) performed 2 dives as part of a group of 10 divers near Guradoo, South Male Atoll, Republic of Maldives, on the day of his accident.
- Dive Profile: 1st dive at 9:00 hrs. 30 msw/30 mins
  surface interval: 122 mins
  2nd dive: 11:32 hrs. 39.8 meters/28 mins

- The display on the diver's computer required a decompression stop of 7 mins at 3 msw.
- The diver omitted the decompression stop due to being surrounded by a group of reef sharks but did not ascend rapidly.
- Immediately after having surfaced, he realized that a decompression stop would have been necessary and descended again to 3 msw for 2 mins and surfaced again at 12:00 hrs local time.
- On the boat he received oxygen due to the omitted decompression stop.
- Within the next 2 hours, the diver discharged urine twice.
- After 2 hrs, he noticed developing paresthesia in both hands and legs.
- 3 hrs post surfacing, the patient was unable to discharge urine.
- 5.5 hours post surfacing, the diver was admitted to the hyperbaric facility presenting paralysis of both legs and maximum abdominal pain due to the distended urinary bladder.
- The patient was twice treated according to USN TT 6 and three times according to USN TT 5.
- After one hyperbaric oxygen (HBO) follow-up at 2.5 bar, the patient underwent aircraft medevac, pressurized to sea level.
- In Italy he was treated with another 20 HBO treatments and recovered almost totally.
- Adjunctive treatment had included initial methylprednisolone according to NASCIS (as recommended for spinal cord injury) during the first 24 hours and intravenous lidocaine 7mg/kg BW during the first six hyperbaric treatments.

Case Report No. 2

- 38 year old male French diver (more than 1000 total logged dives) performed several dives (Table 2) in the North Male Atoll from a safari boat.
- The surface interval between the two last dives was probably at least 3 hrs.
- Morning dive to 20 msw/68 min required a decompression stop.
- Afternoon dive maximum depth of 40 msw with a total dive time of 40 mins with decompression stops of 6 msw/1min and 3 msw/8mins.
- Diver surfaced at 16:30 hrs local time.
- Immediately after surfacing, diver collapsed due to severe motor impairment of both legs.
- He was semiconscious and vomited several times.
- The dive buddies reported that a rapidly developing ascending paralysis could be observed.
- Upon arrival at the treatment center at 19:00 hrs, the diver had a high level of paralysis and could not move his arms.
- At least 10 dive buddies on the last two profiles were without symptoms.
- One buddy had dived partly similar profiles, exceeding the limits in previous dives as well.
- The injured diver underwent recompression treatment according to an extended USN TT6. After completion of this first hyperbaric oxygen treatment, he could move both arms without help.
- After an interval of 6 hours breathing oxygen under normobaric ambient pressure conditions, another USN TT6 was begun.
- The patient completed two more USN TT6 treatments with intermittent normobaric oxygen breathing intervals before he was repatriated by aircraft, pressurized to sea level.
- Only a moderate improvement of his symptoms could be observed.
- The patient was lost to follow-up.

An interesting observation in both cases reported was the fact that none of the dive buddies developed symptoms. It remains unclear if the reverse dive profile alone or other contributing factors caused the injury since, according to their statements, the dive computers of the dive buddies showed no requirements for decompression stops. This might be true as the same dive computers had not been used. The individual's susceptibility is certainly a factor that is underestimated with respect to the influence to develop symptoms of decompression sickness.

Discussion

According to my own experience with over 300 patients treated for decompression illness at the Bandos Hyperbaric Treatment Center, more than 90 percent involved dehydration as one of the contributing factors. Other factors have to be considered, such as a patent foramen ovale (PFO), which occurs in about 30% of the diving population (Hagen *et al.*, 1984) and has been shown to increase the risk

2.6 times for Type II DCS compared to individuals without a PFO (Bove, 1998). The risk might be further increased in individuals with PFO who perform reverse dive profiles.

Table 2. Dives performed by two experienced European divers in the Maldives. a - afternoon dive, m - morning dive, N - night dive.

	injured diver				buddy diver		
		[m]	[min]			[m]	[min]
1	a	40	40	Deco	a	40	53
2	m	20	68	Deco	m	30	55
3	N	17	45		a	27	36
4	a	21	43		m	28	50
5	m	30	69	Deco	a	33	45
6	a	32	49	Deco	m	16	50
7	m	18	64		a	17	55
8	a	21	50		m	26	53
9	m	29	46		a	30	42
10					m	26	60
11					a	25	54
12						40	40
13						39	35
14						36	41
15						33	51
16						35	45
17						28	54
18						31	46

Irrespective of the dive profile, nitrogen off-gassing after the dive can result in bubble generation. Shrinkage of bubbles and bubbles redissolving during repetitive pressure exposure results in an unknown amount of undersized bubbles escaping the lung filter.

Dive tables applicable to reverse dive profiles do exist, even for dives exceeding the no decompression limits *e.g.*, in the U.S. Navy and the German Navy (U.S. Navy, 1993; Dräger, 8th ed.) An important question is the following: Can a dive computer/table calculate real residual nitrogen times/deco-intervals valid for reverse dive profiles?

The original military dive profiles are derived from "square-wave" profiles. For dives exceeding the no-decompression limits, these are transformed into reproducible multilevel profiles by mandatory decompression stops. During military diving operations, divers perform the decompression stops by using a shot line. "Multilevel" profiles in recreational diving cannot be compared to military diving. Most dives performed in the recreational setting do not require decompression stops, but for those exceeding the limits, it is questionable if the decompression stops comply with the requirements. Furthermore, dive tables and dive computer algorithms do not include many individual factors that may contribute to tissue damage. Dive computers connected to the scuba cylinder might offer more reliable data by including at least an assessment of cardiac output through the air consumption as an individual factor relevant to decompression.

Dives following surface intervals exceeding 12 hours are not considered to be repetitive dives. Mekjavic *et al.* (1998) exposed test subjects to successive dives in series. The surface intervals exceeded 72 hours. Especially if a deeper dive followed a shallower one, increasing bubble counts (post dive) were observed in tear film compared to predive counts. When the surface interval approached 72 hours, the predive tear film bubble count was greater than observed before the first dive in series. Doppler ultrasound, however, failed to detect significant changes compared to predive readings.

It is questionable if 12 hours are a sufficient surface interval between repetitive dives for the prevention of bubble generation causing tissue damage without clinical symptoms. It has previously been shown that some divers develop DCS after apparently safe dives within table or dive computer calculated limits, while others safely complete dives exceeding these limits without any clinical symptoms. This does not guarantee that the latter have no tissue damage. Pathological effects caused by inert gas bubbles might remain clinically inapparent even though tissue damage has occurred (Palmer *et al.*, 1992; Reul *et al.*, 1995)

Considering 72 hours as the minimum surface interval to avoid residual nitrogen time being applied to the repetitive dive, any dive on the next day could be considered repetitive, therefore possibly resulting in a reverse dive profile (Figure 1).

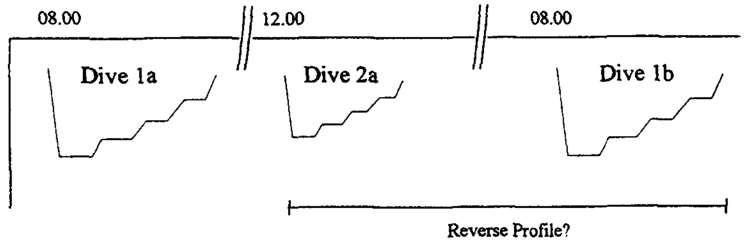

Figure 1. 3 dives performed within approximately 25 hrs. The surface interval between Dive 2a and Dive 1b markedly exceeds 12 hours. Therefore 1b is not considered to be a repetitive dive. Taking the findings of Mekjavic *et al.* (1998) into account, a surface interval exceeding 72 hrs might be adequate to reduce bubble counts below a safe threshold. Dive 1b might also be counted as a reverse repetitive dive, in this case, due to its greater depth than Dive 2a.

Conclusion

As a conclusion, many open questions exist concerning reverse dive profiles and possible risks to divers. Reliability of data provided by dive tables and dive computers are limited mainly by the individual diver and probably by other unknown factors. Limitations probably do not apply to reverse dive profiles only, but to repetitive dives in general. The terms repetitive dive and reverse dive profile should be re-defined with respect to the surface intervals. Although scientific evidence is not available, from the clinical point of view, the need of a prophylaxis for DCS such as hyperbaric oxygen after completion of reverse dive profiles within a 12-hr limit should be discussed.

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SOME OLDE FASHIONED COMPUTATIONS AND CONTEMPORARY THOUGHTS

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Reverse profiles have a bad name. First, let's not make sweeping decisions, in either direction, on very small samples. Properly calculated, a reverse profile within a single dive appears not to be a problem, consistent with experience in recreational, scientific, and commercial dives, and with computer dives. A "straight" dive is certainly more efficient. But more good data here would be welcome. With regard to the kind of repetitive dive in reverse order that is regarded as dangerous, we may be dealing with two kinds of problems. First is the "short, deep dive" problem. Lehner and colleagues noticed this with sheep, as did others, that a short deep dive would be more likely to cause spinal bends. If these are part of a reverse dive profile that causes problems, it has to be seen in that light. Reverse dive profiles need to be considered as repetitive dives first, and then if they are all right there, with the reverse aspect considered. Two (or more) closely-spaced short, deep dives are risky in any case, and probably not much affected by the order. We still do not know much about repetitive diving.

Introduction

This is a complex decompression question. The issue here is whether or not it matters when a second (or subsequent) dive in a repetitive series is deeper than the one preceding. There are anecdotal accounts of serious DCS that develops after an instructor goes down to release the anchor chain after a day of diving instruction. The dive was "within the limits." The only substantive thing to blame was the dive order. The number of examples is very small. This is the extreme example, but this concern has evolved into a general prohibition against the "reverse profile." This has come to apply to any situation when dives are out of "ascending" order, and even applies to subsequent sections of the same dive.

But is this a proper judgement? Look at a similar example. Some saturation-excursion dives resulted in DCS during saturation decompression. Naturally, it must have been due to the excursions. As experience developed, it was found that the saturation profile itself was inadequate. Excursions were blamed because they were the "different" factor. Has this been what has happened with reverse dive profiles?

Here is some opinion on this topic. The typical dive causing this sort of trouble is usually a short, deep dive, "deep" being toward the limit for a recreational dive. Lehner and colleagues called attention to this some time ago, that such dives often led to neurological hits (Lehner *et al.*, 1985). It is also well known that repetitive dives are troublesome. Could that be what we are seeing?

For what it may be worth, commercial and military diving pay no attention whatsoever to the order of profiles.

Methods

For the record, look at some test profiles. These were done with the classical Haldane-Workman-Schreiner Tonawanda IIa Neo-Haldanian perfusion-limited gas loading model, run using DCAP. The ascent constraints were Matrix 11F6 developed for deep air with an excellent track record, informally, for both air and trimix. Although this is a pragmatic and not very sophisticated model, it is all the more important not to believe the numbers; they are not what really happens in the body. The calculations are for 3 pairs of dives, done in both directions. They were performed as a pair in a single calculation, such that the only consideration for being repetitive is gas loading (no bubble factors are used with this model). Thus, this is only a demonstration of the allowable no-stop times for dives in different orders, it does not shed light on the basic question of whether the second example in each set is a reliable dive or not.

Results

Results are shown in Table 1. Dives are shown as Depth/time in fsw and min. Tdt, Total dive time, is the sum of the two maximum allowable no-stop dives. The "Change, as %," is the percentage the second dive is of the first dive in the set when done in reverse order. That is, the change as a percentage shown in the first row is 0.41, which is the percentage that the second allowable no-stop time is of the first dive, where 12 min become 5 min, so the second dive is 5/12 or 41% of the first dive. For the second row, 72 becomes 45 so 45/72=0.63, and so on.

Table 1. Sample Reverse Dive Profiles.

Sample reverse profiles Depth (fsw); Time (min); Travel (30 fsw/min)						
First		Interval		2nd	Tdt	Change, as %
120/12	+	0/30	+	50/45	57	41
50/72	+	0/30	+	120/5	77	63
100/19	+	0/120	+	40/100	119	0
40/111	+	0/120	+	100/19	130	90
110/15	+	0/60	+	30/232	247	73
30/281	+	0/60	+	110/11	292	83

We can see first that deep after shallow (the second one in each pair) gives more <u>total</u> dive time. The reason for this is that the shallow dive is the longer one and loses more total minutes when it is repetitive and affected by the previous dive.

The change as a percentage is another comparison, and it is not conclusive. For the first and third example pairs, the percentage of allowable time is better for the shallower dive. For the second pair, the shallow dive is penalized more by being repet; this is because for such a long interval between dives relative to the dive times, the second deep dive (100/19) is only slightly affected by the earlier one and has the same allowable no-stop time.

This example, which was suggested, is perhaps not the best one for this kind of comparison, but the point is moot anyway with respect to the <u>reliability</u> of reverse profiles. There is really nothing new here, but we have always felt comfortable with these calculations.

Perspective

In our experience with this type of calculation for a wide variety of dives and dive conditions, there seems to be no special problem with the order of dives or dive parts - .if the dives are done right. "Done right" means calculated properly and executed as planned. What works, works.

Repetitive diving is a problem, even with all our tools. Doing it with some sort of condensed "look-up" tables is even more challenging. Deep, short dives are also a problem, especially when repetitive. Of the dives in the example, the ones that look the least reliable are the first pair, with a short surface interval followed by a relatively deep second no-stop repetitive dive.

We have to factor in the problem of possible bubble growth in the surface interval. This is perplexing at best, and this model does not address that at all. From other data, it looks as if multiple short "yo-yo" dives can work if the last one has a conservative decompression.

A Sur-D-O_2 profile is the ultimate short surface interval. According to some experience, including that of Michael Gernhardt in this workshop, Sur-D-O_2 seems to work better with less in-water stop time prior to the surface interval. When we calculate surface decompression dives with DCAP, we have the option of "freezing" the decompression outgassing during the surface interval so as not to calculate outgassing that is probably not realistic.

As with all dives, we have known for a long time that minimizing duration of exposure to supersaturation gets the best results (Hamilton *et al.*, 1980).

This workshop consists of a lot of smart people working without enough data. So let me repeat a familiar refrain: "We need more data." In the meantime, we should consider the stress of the individual dives a lot more than we do the order.

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V. Medical Session Discussion.
Charles E. Lehner, Moderator.

T. Neuman: Dick, in your comparison of incidents of reverse and forward dives, you stated that they weren't statistically significant. Nevertheless, you mentioned that you didn't do any further analysis, but do you care to speculate on the decompression stress that you predicted for these dives? Would they be consistent with the incidents?

R. Vann: Well, that's what we hope to do, and we just didn't have time to do it for this workshop, but that will be in the manuscript. We're going to look at the estimated stress for those dives. But they're going to be deeper, and they're associated with many more days of diving, so this is not a simple question. The reality of reverse dives is not, "Okay, I did my first dive to 40 feet; I did my second dive to 100 feet. Did I have a problem?" As you can see, it's mixed in with a great many other dives that really make it more difficult to make easy conclusions. What we have to do is try to control for the other variables in there, and that's our long-term goal.

G. Beyerstein: Did you have any sort of standardized post-dive checklist for a neurological exam or anything like that for interviewing these people post-dive?

R. Vann: No, we do not. This is something that we recognize that we need to do a lot of work with. Now, where our focus is to avoid underreporting, to get them to report everything there is, we can't do a neurological out on the dive site, and that's just going to be a limitation that we understand. We do want to have a standardized checklist that we would use during callback.

G. Beyerstein: We trained all our divers to do fairly competent neuros. It's not going to be medical quality, but I question whether or not you might be able to. We had a checklist on the back of our dive sheet.

R. Vann: Well that's something I think that we're willing to consider, and at this point, as I say, I'm looking for suggestions. I had some good ones last night, and we definitely need to define how we're going to collect the data, what we can do to ensure that we minimize the change of bias, and really how we define what decompression illness is. In discussions we had last night, we were trying to focus initially on what is decompression sickness. But, really, with these people you're going to have everything. You could have air embolism, you could have decompression sickness, and how do you need to differentiate? We don't have all these issues firmly worked out right now. This is a watershed for us to try to decide where to go in this area.

T. Neuman: From your slides, what about your unknown symptoms?

R. Vann: Well, we don't know. We need a set of rules in order to make that decision.

M. Gernhardt: Do you have a definition of DCS that the various DAN people are using or is it just up to the medical judgment of the diver?

R. Vann: There's no medical judgment at all here. These are simply symptoms reported by the field research coordinators who are divers, who know how to collect data, and all they do is simply ask if there are any medical problems at the end of the day from any one of the divers.

M. Gernhardt: So you're just taking all the raw data and then subsequently deciding whether it is DCS?

R. Vann: Probably what we're going to want to do is have a definition that's in the database so that all the information comes in. If on our 48-hour report someone says, "Yes, I did have symptoms," we'll call them back and do a standard questionnaire. It will go into the appropriate check boxes, and then based upon the definition that we agree on, the decision will be made. But it will be made as objectively as possible. A lot of the data that we have right now is not going to be good enough to really do that, but that's where we're headed.

J. Lewis: Yesterday, the issue came up of operational data versus experimental data and particularly the predictions of probabilistic models. We always thought that the operational instances were so low because the divers weren't diving to the depth and time of the experimental data. Now you have 13,000 dive profiles all recorded, and you have about 13 potential cases of decompression sickness, or roughly 1/1000. I'm curious what the probabilistic models would predict as the number of cases on these particular dives.

R. Vann: That's what I've shown. That was the slide with the cumulative total. The model was around 1/10 of a percent. The median was around 2/10 of a percent. As you just stated, it's much lower than the probabilistic models would predict at the limits of the no-stop dives.

J. Lewis: My question is how many cases did the probabilistic models predict for that subset of 2,000 dives?

R. Vann: Right. We haven't done that yet, and we realize that's an important question to answer. I think it's probably going to be over-predicted. We only have three individuals that have been recompressed, and whether those other ones needed recompression, we don't know. But I understand your question, and it's something that we're going to focus on.

M. Lang: Bill, could you provide us with a clarification for "we need more data?" We have been presented with Navy data, DAN data, dive computer data, and other operational data on reverse dive profiles. As researchers, we always need more data, and that's fine, but I want to make the point that had one or several of our colleagues done a conclusive, manipulative reverse dive profile experiment with human trials, validation and open water testing, we wouldn't be here for this workshop. What I've seen so far is that we've identified the problem, and observed that reverse dive profiles occur routinely without major problems much more than we expected to see.

B. Hamilton: What I think I've seen here are analyses like Paul did where he looked at data that was already there. Dick did more or less the same thing, and so did Karl and they didn't really find very much. There are these horror stories, these n's equal to one, and Eric Baker mentioned one yesterday. He didn't describe the profile, but he and others spent a lot of time trying to analyze a profile. I believe he found that the stress was worse when you dived forward versus reverse. I'm just saying the same thing that Wayne and others have said. We shouldn't place too much weight on the single isolated events when the people who pull together groups of data aren't seeing anything. Is that right?

M. Lang: The fact that you didn't see anything, doesn't mean you can ignore it.

B. Hamilton: No, but I'm saying that Paul looked at a number of reverse profiles. He compared them using maximum likelihood against the dataset. Now, the dataset had both kinds of dives in it, so it made a judgment of that. It didn't show reverse profiles to be any worse than forward profiles. The P(DCS) calculated was not any worse than the others.

M. Lang: That's what I was getting at by requesting more clarification. I mean, there are many operational reverse dives that we already have data from. The fact is, that up until now, we haven't found a difference in unacceptable risk between forward and reverse dive profiles.

B. Hamilton: We have data now. We're pulling together data that says, "Maybe this is not very much to worry about." I haven't changed that opinion.

P. Tikuisis: Bill, can I encourage you to talk about what's happening during the surface interval? They're two separate things. You do have bubble growth but you also have gas washout. Both things are happening. Really, what Ron was showing, and I think what was on the last figure that I used, is that if your surface interval is above half an hour, 40 minutes or so, then you've completed your bubble growth. You have got to have very short surface intervals to interrupt your bubble growth. There's that point, and the other point that I would want to make is that none of the repetitive dive tables that I've looked at make a big enough allowance for the slowing down of washout because of the presence of bubbles. That's an actual physical thing and you've got two ways of handling this. You come up with your first dive so that you don't form bubbles, and then you've got a lot of freedom for your second dive or you do as Ron was saying, you prolong, prolong, and prolong, and make your last decompression a good one.

B. Hamilton: I have no problem with that. I agree with you completely.

R. Vann: Michael, I was just going to make a quick statement that although there is a lot more data here than I think a lot of us expected, a good part of it is confounded by many other variables -- repetitive dives, multiday dives -- and I don't know that it keys out directly the effects of the reverse dive profiles and all other factors that are involved in other than a very small subset of what we see.

B. Wienke: A lot of what has been presented here focuses on an area where the changes for reverse profiles are relatively small (40 feet maximum). When you start going to greater depths and moving to greater subsets, I think that we can't say much out of this workshop. We've done some of that, and I presented some of the data that shows that the risk was higher. It's a small set statistically, but it's the best trend. What's coming out of this workshop is that for the data we've seen and every presentation that we've listened to, the range of analysis is relatively small, and that is also the realm that most of recreational diving is concerned with. If you look at the training records of all of the agencies, the incidence rate of DCS is like 1 in ten to the fifth; very, very small. Surely, everybody included reverse dive profiles.

R. Hamilton: But the incidence rate goes up as depth increases. So, by definition, if you're going to have this big difference between the first and second dive, you've committed yourself to a deep dive. I'm saying we have not removed this confounding factor of depth.

M. Lang: Can we save some of the general observations for the session this afternoon? We're getting there, and it's good to start thinking about it, but let's save the general discussion because we still have some more presentations that will add more information. We don't have to come up with a conclusion right now.

G. Beyerstein: I was just going to say that Michael is trying to get an answer. He's got a concrete situation to deal with, and he's looking for an answer. We've got all of you bright scientists here who are looking at why things happen and are developing models. In the commercial community, both Terry and I represented two companies for a period of years. We're really kind of surprised to even know reverse dive profiles are a problem. It was never a problem; it was never a consideration, and we never had that deep dive first rule. It was all up to what the Navy said. It was never written down anywhere, and we never acted upon it and felt totally unconstrained to do a deep dive last. It was just for practical reasons of bottom time, and sometimes that just happened.

I can speak for a period from about 1985 to 1998 when we changed our method of data collecting. I examine every bends case we have. We're probably somewhere close to 100,000 dives and probably somewhere just under 100 bends over that 12-year period.

Anytime we had a bend, we had a highly-trained dive force that was very good at doing neuros to collect data. We removed the penalties for a diver reporting and removed the penalties for the supervisor to shut down operations and treat the diver. We had a very good reporting system and all the impediments toward being treated taken away from divers.

But every time I examined the bends, we collected dive information from the past 72 hours, and I personally examined all of the different repetitive dive situations. I could probably collect data in some way, but I can tell you right now that I eliminated, in my judgment, any bias that repetitive diving might have had, other than table compromises. I never noticed any correlation between repetitive dives, either forward or reverse, and the incidence of bends. We had just as many single incidents from single dives where the person was clean for days; in fact, sometimes even more than we had for repetitive dives.

E. Baker: Dick, on the collection of data, I have a question on the reporting of symptoms. Can you make any distinction to acute symptoms that would normally be reportable versus very subtle symptoms, things like fatigue, drowsiness, some of the things that we've been focusing on in the technical community?

R. Vann: If you reported it, then it's in the system. We're encouraging all of those: shark attacks, attacks by spouses. The idea is not to eliminate or be exclusive. We'll have to apply a definition.

E. Baker: Are the field data coordinators encouraged and does the form itself make mention of that that they're encouraged to report?

R. Vann: Yes. Everybody has to volunteer for this, and they go through a briefing that asks them to report, and we ask if they volunteer to be called back in the event of an incident occurring.

M. Lang: One last observation to tie up this conversation is that I've spent a lot of time researching this topic and what's really going on. In the program maybe we should have moved up the training agencies' position statements saying that this is an industry-wide problem. We've now found out for the first time yesterday, that in the commercial diving industry and military diving community, reverse dive profiles are a non-issue. But in the recreational and scientific diving communities, as we'll hear this afternoon, we're still stuck with making the deepest dive first, followed by progressively shallower exposures. At the very least, what we've done here is said, "Well, that really isn't validated other than for operational effectiveness, there's really no *bona fide* physiological reason for not conducting reverse dive profiles." Part of this exercise is for clarification to the diving communities that, for almost 30 years, the concept of "dive deep first" has prevailed in the recreational and scientific diving communities.

QUANTITATIVE RISK MANAGEMENT OF DCS

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*Individuals do not need to justify personal risk decisions; organizations do. Organizations can appeal to tradition ("Do whatever is in the US Navy Diving Manual"), or to a lottery ("Do whatever *any* diving computer says is OK"), or to micromanagement ("Do not use reverse profiles"). An alternative approach for risk management uses a well-constructed probabilistic model (which measures the "risk"). After exploring the model's pedigree and limitations, the organization adopts a set of "acceptable risks" of the (calculated) probability of DCS. Within declared boundaries, diving then achieves maximum operational flexibility. A real case history from the Navy is illustrative.*

Introduction

Every dive carries some probability of decompression sickness (DCS). As any student of decompression has seen, a dive that produces DCS in one person is usually well tolerated by others, even on the "exact" same profile. So people do not respond the same way to the same decompression "stress." But the situation is actually even worse: an individual does not even reproduce herself on the same profile. In Table 1 is a sequence of precisely controlled dives in one test subject (Weathersby *et al.*, 1986). Note that the shallowest, *i.e.*, safest, dive resulted in DCS. However the next two deeper dives had uneventful outcomes, despite being more severe. Finally were two dives of the greatest severity. The first one resulted in DCS; the second did not. Clearly, there is no useful definition of what depth is "safe." The best we can do is control the risk or probability of DCS, denoted P(DCS).

Table 1. Subject 17 (Thalmann *et al.*, 1999). History of 30 min No-Decompression Dives.

Sequence #	Depth fsw AED	Outcome
1	60	DCS
2	86	Safe
3	99	Safe
4	107	DCS
5	107	Safe

Individuals do not need to justify personal risk decisions. How and how much to drive a car, when to eat shellfish, etc., are "managed" on an individual basis, using personal values and experience to "set limits." Organizations tend to manage the risks of their members, at least in functions performed on behalf of the organization. Managing the occupational risks of diving falls in that category.

Organizations can appeal to tradition ("Do whatever is in the U.S. Navy Diving Manual"), or to a lottery ("Do whatever *any* diving computer says is OK"), or to micromanagement ("Do not use reverse profiles").

Alternative Risk Management: Quantitative (QRM)

An alternative approach for risk management works with quantitative methods. It relies on a well-constructed probabilistic model that measures the "risk." The organization's management must first explore the model's pedigree and limitations. If found acceptably accurate, the organization then adopts a set of "acceptable risks" of the (calculated) probability of DCS. Within declared boundaries, diving then achieves maximum operational flexibility. Each of these steps can be illustrated using specifics from a model and tables developed for the U.S. Navy referred to as "USN93" (Survanshi *et al.*, 1997).

A successful model is central to the process. A family of probabilistic models based on risk or hazard functions matured by 1991 (Parker *et al.*, 1992; Thalmann *et al.*, 1997). They were calibrated with over 2300 well-controlled laboratory exposures from a database described by Weathersby and Gerth (these proceedings). The model's predictions were then tested in a prospective trial of about 700 dives with profiles of operational interest, but not strongly represented in the calibration data (Thalmann *et al.*, 1999). These included some "reverse" profiles, both on multilevel and repetitive dives. The model's predictions were quite consistent with the trial outcome. The trial data, and some other high-quality dives that became available, were added to the earlier data, and a full model recalibration performed (Survanshi *et al.*, 1997)

The final model was examined for its success in describing DCS outcome rates based on type of dive, on level of decompression severity, and even on whether symptom onset times were accurately predicted. One such comparison, by dive type, is reproduced as Table 2. The excellent agreement between model prediction and outcome is evident. Also apparent are the pretty wide confidence bands, both on propagating parameter uncertainty in the model, and on the binomial uncertainty remaining even in "big" groups of hundreds of subjects.

Table 2. Table A3 of NMRI Technical Report 97-36 (Survanshi *et al.*, 1997).

Table A3: Goodness of fit by dive type

			---- Predicted ----		
		Observed		95% Conf	
Data Set	Dives	DCS	DCS	Low	High
Single Air					
EDU885A	483	30.0	**26.6**	22.0	31.2
DC4W	244	8.4	**5.7**	4.2	7.1
SUBX87	58	2.0	**0.5**	0.0	1.2
NMRNSW	91	5.5	**5.2**	4.3	6.1
PASA	72	5.2	**2.7**	2.0	3.4
NSM6HR	57	3.2	**3.9**	3.1	4.7
Total ______	1005	54.3	44.6	35.6	53.7
Repetitive & Multi-Level Air					
EDU885AR	182	11.0	**11.7**	9.3	14.2
DC4WR	12	3.0	**0.9**	0.7	1.1
PARA	135	7.3	**9.6**	7.8	11.4
PAMLA	236	14.2	**17.6**	14.6	20.7
Total ______	565	35.5	39.8	32.4	47.4
Single non-Air					
NMR8697	477	12.8	**15.1**	12.4	17.8
EDU885M	81	4.0	**3.4**	2.6	4.1
EDU885S	94	4.0	**3.9**	3.1	4.7
EDU1180S	120	10.0	**7.3**	5.8	8.7
Total ______	772	30.8	29.7	23.9	35.3
Repetitive & Multi-Level non-Air					
EDU184	239	11.0	**13.9**	11.2	16.6
PAMLAOD	134	6.0	**7.3**	5.4	9.3
PAMLOAS	140	5.3	**5.9**	4.6	7.3
Total ______	513	22.3	27.1	21.2	33.2
Saturation					
ASATEDU	120	15.7	**15.0**	11.4	18.6
ASATNSM	132	20.1	**22.7**	16.9	28.6
ASATNMR	50	1.0	**4.5**	3.6	5.4
ASATARE	165	21.3	**18.8**	14.8	22.9
Total ______	467	58.1	61.0	46.7	75.5
Grand Total	3322	201.0	202.2	174.8	229.6

Model limitations were also consciously recognized. For example, USN93 was not expected to perform very well on dives with 100% oxygen, frequently used to accelerate decompression. Such high oxygen content dives were therefore excluded from the calibration data. Another exclusion was any cumulative effect of multiday intensive diving. Data selection required test subjects to have refrained from diving for 3 days before a trial.

Assembling a risk management team may not, in and of itself, be easy. As recognized in a sequence of high-level commissions, most recently the "Science and Judgment" of The National Academy of Sciences/National Research Council (1994) and another from a Presidential Commission (1997), "stakeholders" must be part of the process. A growing body of evidence shows that people left out of the decision-making process are those most likely to sabotage its successful implementation.

For the Navy example, a number of senior officers from different headquarters' organizations were joined by senior medical and laboratory staff in a series of meetings. The model developers presented the model pedigree and elicited the sequence of management decisions necessary to produce the desired procedures. Different participants followed different mental pathways in understanding the model's "risk" metric, and in using it to translate their own areas of comfort and concern. One common tie was the model's estimate of 2.0 to 2.5% risk of DCS (in highly controlled lab conditions) for no-stop air diving by 1957 U.S. Navy rules in the 50 to 100 fsw range, where each officer had some degree of personal experience. Part of the educational process was an appreciation of why field dives with those limits do not actually result in 2 treatments for DCS for each 100 diver days. The difference results from the compound bias of "field dives": not all time spent at the maximum depth, not the full allowed bottom time taken for the decompression limit "used," and the natural tendency to dismiss "marginal" symptoms, rather than seek a recompression treatment.

The scope of the diving need must be established early. Is the only diving to be No-decompression stops breathing air? What about breathing oxygen during decompression? How far outside the "normal" limits should fall-back/emergency procedures be provided? As verified in a recent survey by Bill Hamilton (pers. comm., 1999), the U.S. Navy's needs seem to be more complex than any other organization. The early definition of scope affects two issues: which probabilistic model to use, and how complex does the final package need to be. A wider scope will consume more development resources, and late changes in the scope increase the chance of undesirable partially-compatible "patches" being needed.

In the US Navy case, the desired package was extensive:

- Air tables to 190 fsw, deeper in "emergency" situations
- 0.7 atm O_2 in N_2 tables to 150 fsw
- Repetitive procedures, including rig switching
- Oxygen decompression rules
- Extensive (hard-copy) multilevel capability
- Real time computer algorithm, consistent with tables

And, of course, extensive re-writing of the Diving Manual and re-vamping the training curriculum would also be required.

Once its utility was understood and accepted by the Risk Management group of senior officers, the USN93 probabilistic model was used to produce the tables. An efficient algorithm was needed to find the fastest decompression that would fall below a defined level of Acceptable Risk (Survanshi *et al.*, 1996). Analysis and programming effort on the algorithm allowed it to execute faster than real-time even for > 1 hour of decompression stops, on Intel-286 hardware.

The numerical choices of Acceptable Risk were discussed for hours in multiple meetings. The 2.3% for no-decompression dives was set, based on nearly replicating the limits in the 50-100 fsw range from the earlier (1957) U.S. Navy rules. The algorithm was set to produce uniform risk across all depths (since in the real time application, the algorithm would be unaware of the diver's intent to go deeper or shallower). That real-time flexibility was chosen over an alternate strategy to keep all of the prior no-decompression limits. Thus, the new limits were more permissive on deeper air dives, and less permissive on long shallow exposures.

The risk of prolonged in-water decompression was viewed as sufficient to increase the risk of DCS on long dives. An acceptable level of 5.0% was chosen, out to a total stop time of 3 hours. Beyond that, the exposure was viewed as due to an emergency, and 10% DCS risk was accepted for that extreme situation. The same risk rules were chosen to apply to both air and rebreather dives. Numerous other ancillary decisions were required before the final package was concluded.

Conclusion

I think quantitative risk management should find appeal in organizations doing scientific diving. The published probabilistic models are better tied to the most relevant laboratory observations, and the connection uses accepted statistical techniques. The approach and results are "transparent" in that managers (and members) can follow the decision logic and implications. And by setting a quantitative safety standard with a widely available metric (the model), individual scientists can exercise their own creativity in formulating personal practices that can differ widely but still be acceptably safe.

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DOING IT "OUT OF ORDER"

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For the entire history of recreational scuba diving, reverse profiles, or diving "out of order" (diving shallow then deeper), has been a no-no. At ScubaLab we set out to test this hypothesis of decompression that states "you must do your deepest dive first and make each subsequent dive shallower." It is clear that this rule was valid and useful for dives conducted using decompression tables. But it has become increasingly clear that this rule is not necessary for modern diving using dive computers (DCs). A corollary is that it is also not necessary to start dives at the deepest point and move progressively shallower during any one dive, given the use of dive computers.

The Background

The logic of starting each dive, or series of dives, deeper and moving shallower is clear and sound. By being shallower later in the dive or on subsequent dives, at best outgassing would occur, and at the least, ongassing would be less or slower.

As decompression tables could make no allowance for these reverse profiles or for time at shallower depths, the rule was useful, safe and practical. But dive computers do not calculate dives as the tables do. Tables treat two dives as simply two large events, using the maximum depth and total time of each dive to determine decompression needs. Dive computers sense and make calculations based on pressure (depth) and time. This is done in constant and extremely short time intervals. Therefore, the diver's actual exposure to the theoretical gas uptake or release is being calculated continuously.

There is clear, although limited, evidence that repeated deep bounce dives done close together produce decompression sickness (DCS). Documented tests have also clearly shown that some older models of DCs will allow these repeated deep bounce dives and not go into violation.

Other documented tests have also shown that some DCs have restrictions, limitations or penalties in their programs that modify the fundamental decompression model being used and act to prevent deep dives after other dives have been performed. In some cases these restrictions simply create short unneeded decompression (deco) stops, but in other cases the restrictions may in fact be so severe as to create deco stops well beyond the divers needs or ability to perform them.

For over 15 years, divers have been diving with other DCs without these restrictions, surfacing without any required decompression stops, and not suffering from DCS. Many divers are regularly doing these reverse dive profiles, with these more liberal DCs, yet no direct connection between this type of diving and the incidence of DCS has ever been made.

This reverse profile "out of order" diving is far more extensive than most divers realize, including:

1. Recreational divers
   - On charter boats when conditions require anchoring at a deeper spot for subsequent dives
   - Because of an opportunity for photos/video or to view marine life

- Because the dive buddy throws off dive plans or due to a buddy change
- Because of peer pressure to do a particular dive
- Because of the need for dive operators to go to a shallow, easier dive site for the first dive of the day, with divers they do not know or who have been away from diving

2. Technical divers
   - In order to set up stage bottles or other gear before a dive
   - To survey the dive site for dive planning purposes
   - The need to ascend and descend during the dive to follow the way in and then back out of a cave system or wreck
3. Scientific divers
   - Following transect lines that are perpendicular to shore, repeated shallow to deep for multiple dives
   - Returning to multiple sites for studies, to meet the requirements of the studies versus the rules of diving
4. Commercial divers doing
   - Fishing
   - Harbor construction
   - Mooring work
   - Boat bottom cleaning followed by recovery work
5. Other diving professionals
   - Tour guides, dive masters and underwater instructors in the conduct of their regular work
   - Test divers conducting evaluations, such as ScubaLab
   - Public service divers during rescue or recovery operations
   - Divers working on filming, photo or video jobs
6. All divers
   - Any diver, but particularly recreational divers, who abort at a shallow depth on a first dive
   - Search and recovery diving
   - Missing the planned dive site or depth
   - Searching for a missing diver or a lost buddy
   - Misreading instruments or changing instruments
   - Not aware of the rule, or not caring to follow the rule.

Thousands of the logged and confirmed dives that have shown this to be a reasonably safe procedure came from the author's work on Catalina Island, installing moorings, filming for TV shows, guiding underwater tours and testing for ScubaLab.

The Testing Protocol

Test dives were established to follow the current thinking on safety for recreational diving, except that they would be done as reverse dive profiles. The following procedures were followed as closely as possible given the diving conditions:

1. Not exceeding 130 feet.
2. A one-hour surface interval (SI) between dives.
3. Following the ascent rate indicators of the DCs in use; if exceeded, slowing down until the indicator had caught up. Ascent rates varied from 20 to 60 feet per minute.
4. Using safety stops:
   - From dives of 60 feet or less: A short pause at 10 to 15 feet to check DCs and then surface slowly.
   - From dives to 130 feet: An approximate 3 minute safety stop at 10 to 15 feet, and then surface slowly.

All dives were conducted in the open ocean off Santa Catalina Island, California, with full scuba gear, including full wet suits, from August through October, 1998. The test sequences consisted of a dive for

30-45 minutes, swimming as close as possible to 60 feet, followed one hour later by a dive held as near 130 feet as possible until all the DCs in use were in decompression status.

The Actual Testing

Test subjects varied in age, gender, experience, skills, fitness, physical size, qualifications and recent diving activity, but were of an older average age (44), and most were underwater instructors who were also participating in other diving activities. In total, 6 different divers made 8 test sequences consisting of 16 dives, two for each test sequence. This provided 18 human exposures under demanding conditions with no cases of DCS. Fourteen of these dives were within the test protocol and four exceeded it, still with no DCS. Table I documents the 14 exposures that were within the test protocol and Table II profiles the six divers that were part of the tests.

Table I. Dive Profiles.

Date	Dive	Depth	Time	S.I.	Subject Divers
8-21-98	1	60	:42	1:00	A,B,D
	2	127	:20	—	
8-23-98	1	64	:46	1:00	B
	2	131	:23	—	
9-11-98	1	58	:33	1:00	B,D,F
	2	130	:18	—	
9-24-98	1	60	:32	1:00	B,D,E
	2	135	:18	—	
10-9-98	1	64	:37	1:00	B,C,D,F
	2	130	:17	—	

Table II. Diver characteristics.

	SEX	AGE	CERTIFICATION	YEARS DIVING
A	Female	50	Instructor	30
B	Male	59	Instructor	42
C	Female	30	Instructor	9
D	Male	34	Instructor	10
E	Male	43	Open water diver	30
F	Female	48	Instructor	32

Before, between, and after these test dives, the divers carried on their regular duties as boat crew or as instructors. During the dives, the divers swam to descend and ascend, and swam while at depth. Some dives also included heavy work, such as swimming in a strong current. Water temperatures ranged from 57°F to 68°F, but were most often between 60°F and 64°F. Short variations in depth occurred from time to time due to environmental conditions.

Although all divers participating in the test dive sequences had made many such dives before, with no known ill effects, it was agreed that on the first dive sequence they were prepared to abort the dive or have the test fail if:

1. No DC allowed the test dive sequence;
2. All DCs allowed the test dive sequence; or,
3. If any test diver suffered DCS.

Test dives were monitored on 4 to 8 DCs of different types. A Suunto Spyder was used to record, interface to a PC, and print out the dive profiles. No signs or symptoms of DCS were detected at any time during the test sequences.

The Conclusions

Given the success of this testing, the outcomes of multiple test dive sequences under real life conditions with no DCS, it is clear that:

1. "Out of order" diving is not the concern that it has been thought to be when divers were dependent on decompression tables.
2. The current practices of reduced no-decompression limits, slow ascents, safety stops, reasonable surface intervals and limiting the maximum depth, all work to reduce the likelihood of DCS.
3. This data can be used to give greater validity to the development of dive computer programs, providing greater freedom to dive without a significant increase in the risk.

It is not the intention of these tests to propose an irresponsible relaxation or broadening of the dive time available, but rather a considered and careful expansion of the flexibility and usefulness of dive computers.

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Appendix I.

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Avoid Reverse Profiles: An Obsolete Rule?
By Jon Hardy

Our answer to the question should you always make your deepest dive first is still ... maybe not.

RSD Editor's note: We received a number of concerned e-mails and letters about Jon Hardy's article "Are Reverse Profiles OK?" (July, 1999). Most questioned the validity of the test results we reported and expressed concern that Jon's conclusion could lead to unsafe diving practices. We stand by Jon's test methods and reporting. Here are his answers to some of the many questions and alarms sent to us:

What's wrong with the prohibition against reverse profiles? Why did you do the tests in the first place?

Because reverse profile dives (going deeper on the second dive than on the first) is an increasingly common practice. Not only do dive computers allow it, there is no body of evidence that says divers get bent simply by diving in the so-called "out of order" manner. We also wanted to know if the prohibition against reverse-profile dives, which is a product of dive tables, makes sense in a world of dive computers. Dive tables are obsolete. It's time to look at how computers can best be programmed and used. Logic tells us that a dive computer really doesn't care what order your dives are done in, unless the computer has been programmed to change the formula for these events. We wanted to test that logical hypothesis.

The limited testing you performed is not adequate to support your conclusion.

Our tests were not randomly selected but were specific to known reverse profiles: a 60-foot dive followed one hour later by a dive to 130 feet. We, along with thousands of other divers in the field, have done tens of thousands of such reverse profile dives with no harm. Also, our eight years of chamber and ocean tests for RSD (with no DCS) also indicated that this was a reasonable profile. We were not pushing the envelope of human performance; we were pushing the envelope of human understanding. We were simply confirming in a controlled and repeatable way what has in fact been going on. We make no claim that it or any other dive profile is risk free. Our conclusion was simply: Reverse profile dives done with computers do not present the same concerns as when divers are dependent on decompression tables.

Without performing Doppler bubble evaluation, as DAN studies do, you really didn't know the nitrogen disposition of your test subjects.

Doppler bubble detection is a valuable tool, but an imperfect one. It is used as an indicator of possible DCS, but just as the whole field of decompression is impossible to quantify in absolute terms, Doppler bubbles cannot be shown to be directly related to DCS. Certainly, logic and the research leads to the conclusion that there is a statistical relationship between these bubbles and DCS, but different divers tolerate completely different levels of bubbling. Also, Dopplers are very difficult to use effectively, with different evaluators giving different readings of the same recordings.

All your so-called "tests" prove is that none of your divers had gross symptoms of DCS. You did not account for microbubbles and subclinical DCS.

Of course we were aware of subclinical DCS, those physiological changes such as fatigue and headache that may be due to decompression stress. Most divers with years of significant decompression experience believe they have experienced subclinical DCS during their careers. But because the body heals itself and this is not a treated form of DCS, we know even less about it than about DCS in general. Decompression is based on theories and models that are validated through experience. The study of decompression is far from an exact science. And it is clearly a blessing that decompression algorithms work as well as they do, given the lack of understanding. Arguing about which algorithm in which dive computer is best makes little sense. Programmers of the computers make adjustments and apply restrictions or penalties to meet what they believe are reasonably safe profiles. And they vary widely. See the "Freedom vs. Risk" rankings of dive computers in past issues of RSD and on the web. These rankings are another example of the kind of research necessary for today's world of dive computers.

Your limited testing in no way compares to the extensive research performed by the U.S. Navy to produce their dive tables.

This is a myth. The U.S. Navy conducted research for its own purposes, not to create recreational dive tables. After years of significant experience, the Navy redid and tested new tables in the 1950s. These are still the tables used today. They did their research without Dopplers, without dive computers, without desktop computers to do the math. The Navy performed extremely limited testing (almost none) of repetitive dives in the depth/time ranges of interest to recreational divers. Then the Navy made hand calculations and extrapolated to other dive profiles to build their tables. Note that all dive computers use lesser NDLs on singular dives in the recreational dive ranges than the U.S. Navy does. And how did the Navy know when a table was too liberal? The divers suffered DCS. The most famous example, often cited, is that they had more than an acceptable number of bends cases at 60 feet for 66 minutes, so it was cut back to 60 feet for 60 minutes. Again, it is amazing that a system based on so little research has served the recreational dive community so well.

Your advice to dive reverse profiles is dangerous. It's going to get people hurt.

Again, we did not advise anyone to dive reverse profiles. We simply said that evidence indicates that reverse profiles are less of a concern when using dive computers than when using tables. When dive computers were first introduced from 1983 to 1989, the naysayers said DCS would become widespread. This simply has not happened, even with those computer programs from the early days that are not only very liberal, but are still in use today. The plain fact is: most cases of DCS while using dive computers can be traced back to misuse of the computer, the fitness of the diver, violations of safe practices, or unpredicted hits, not reverse profiles.

Your conclusions contradict the current training principles taught by the major certification agencies.

Some of the best work done for recreational divers in this area has been the research by DSAT (Diving Science and Technology) sponsored by PADI. This work made the RDP and Wheel possible, and opened up new opportunities for divers with more realistic repetitive and multilevel diving. PADI made this research available to the entire diving community. ScubaLab has used much of this work for our test profiles and many manufacturers have incorporated the DSAT results into their dive computers. DAN, of course, is doing significant work in gathering accident data on DCS, studying flying after diving and is now acquiring data from dive computers for actual diving practices. Nonetheless, there are no absolutes in the field of decompression, which must account for human variation, statistical probabilities and many unknown and uncontrolled factors. For example, there are several clearly documented cases of DCS on single dives to 60 feet for 30 minutes. The Navy limit is 60 at 60 and most dive computers use between 47 and 57 minutes at 60 feet. The divers in these cases had no known predisposing conditions or violations of safe diving practices. No dive table, no dive computer and no dive training agency can guarantee freedom from DCS.

You are not an expert in decompression theory. Your article pretends to be a research study but it was not reviewed by other experts, as happens with true scientific studies.

The complete report on the tests, which was summarized in the article, was sent to 15 experts in the decompression field, many of whom are very conservative and some of whom actually oppose the use of dive computers. Their comments and suggestions were considered in preparing the article. DAN was included in this review. They were not asked to take a position, as this would have been inappropriate, based on someone else's research, but they did share insight. They neither condemned nor supported the tests. Reverse profile diving has become such a significant issue that Michael Lang (Smithsonian Institution), has proposed a workshop on the topic, as he has done in the past on topics such as Repetitive Diving, Biomechanics of Safe Ascents, and Dive Computers. Fundamental decompression research is extremely limited and not well funded. The field of recreational diving is very small and the use of dive computers is only one even smaller aspect of this field. Also, DCS is a voluntary risk affecting very few people, it is not a significant public health issue, therefore funding for any major research is not likely. Given these facts, what are the options? Do no research at all? Or do the best research we can, carefully interpret the results, find legitimate flaws and retest using better methods and, hopefully, produce better results? We choose the latter. Divers are going to use dive computers and they are going to do reverse profiles, sawtooth dives and bounce dives, so let's explore what the opportunities, limits and risks are and quit hiding our heads in the sand.

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Reverse Profiles: A Tech Divers View
By Bret Gilliam

RSD Editor's Note: Technical divers are usually defined as those who venture beyond sport diving's no-decompression limits for bottom time, depth or lack of direct access to the surface. How do technical divers handle reverse profiles? We asked Bret Gilliam, RSD's tech diving editor and president of the world's largest technical diver training agency, TDI, Technical Divers International.

Reverse dive profiles have never been much of an issue within the tech ranks primarily because we've made a point of getting up to speed on how dive tables and custom decompression algorithms actually came to be. The nuances of M-values, inert gas loading and release, accelerated decompression, and matching gas mixtures exactly to the mission goal have long been a standard while the sport community still considered the Navy tables the only game in town. For tech divers at least, there is more than one channel playing on the radio.

From a purely physiological perspective, reverse dive profiles are of little consequence. Dealing with repetitive dives in general is simply an operational consideration. The elements of decompression, ascent rates, surface intervals and gas selection are all slotted neatly into the equation to produce a predicted diver profile, whether in a deep wreck or to reach the dark side of a new cave system. Most algorithms incorporated in custom table modeling or built-in to modern, high-end dive computers handle reverse profiles just fine since they modify the allowable profile to match the diver's prior gas loading and release. Typically a reverse profile schedule, where a deeper dive is preceded by a shallower dive, will dictate some additional decompression or add another stop. And this is no particular big deal since tech divers are already conditioned for such obligations. If the project requires ten minutes more deco or an added stop at 40 feet... so be it.

And let's remember that many technical dives and exploration projects have no choice but to include reverse profiles simply because of the way a wreck presents itself, or, in cave systems where excursions through shallow passages are encountered following deeper depths and must be re-tracked in order to get back out. Many dives are preceded by short shallower dives to place equipment, tie into a wreck or survey the area prior to the main dive. Far more important than the profile itself is the diver's adherence to the plan (and any contingency adjustments) along with scheduling adequate surface intervals between repetitive dives.

Does the simple fact of doing reverse profile exposures place divers at any greater risk to decompression illness? No. As long as the requirements of the dive are adhered to (as dictated by the table or computer), there is no credible medical or scientific evidence to suggest such schedules are more likely to produce bends.

REVERSE PROFILES IN ORCA EDGE TESTS

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Prior to its release in 1983, a series of human subject dives were performed to determine if the Orca EDGE decompression algorithm had any "hot spots." The series of ten dives were designed to mimic table-based multilevel dives performed at Caribbean resorts at the time. The series consisted of 3 dives a day for 3 days in a row, and a decompression dive on the fourth day. The third dive of the day was always deeper than the second, but shallower than the first. Within the dive series, 3 profiles held for 9-14 minutes at an initial depth and then proceeded to the maximum depth. One profile consisted of a dive to 130 fsw, followed by an ascent to 50 fsw, and then another drop to 130 fsw. Twelve subjects were exposed to these profiles. One subject developed detectable Doppler bubbles on the fourth day decompression dive, and none showed definite signs of decompression sickness (DCS).

Background

Descriptions and results of the 1983 Orca EDGE decompression algorithm tests have been published in other sources (Huggins, 1987; 1992a), most recently in the AAUS Proceedings of Repetitive Diving Workshop (1992b). This paper briefly reviews these tests and focuses on why reverse dive profiles were included in the series.

At the time of the development of the Orca model (1980-1983) this author and Craig Barshinger (founder and President of Orca Industries) had experience with table and empirically based multi-level diving techniques being performed by dive guides in the Caribbean. Barshinger, a dive guide and instructor in the Virgin Island, founded Orca Industries to produce a decompression monitoring tool that he saw a need for. The author had been exposed to table based multi-level diving in San Salvador and performed analysis of allowed multi-level profiles with the U.S. Navy model (Huggins and Somers, 1981). During this time, dive guides from the resort on San Salvador submitted samples of multi-level dives they had performed over a period of 1-2 weeks for analysis.

To determine if the Orca decompression model had any "hot spots," a series of human-subject exposures needed to be performed. Barshinger's experience and the profiles of the San Salvador dive guides formed the template for these Orca test dives. The dive guide dives included reverse dive profiles (Figure 1) and reverse profiling within a single dive (Figure 2). These features were included in the design of the test dives.

Methods

Three multi-level dives for three days were designed with the following criteria:

- Deep multi-level dive in the morning followed relatively rapidly by a long shallow dive (two-dive morning boat);
- Moderate multi-level dive in the afternoon or evening;
- Add some descent to deeper depths situations within some of the multi-level dives ("stepping down" as well as "stepping up"); and,
- Push the model as close to its limit as possible while staying in "no-decompression" mode.

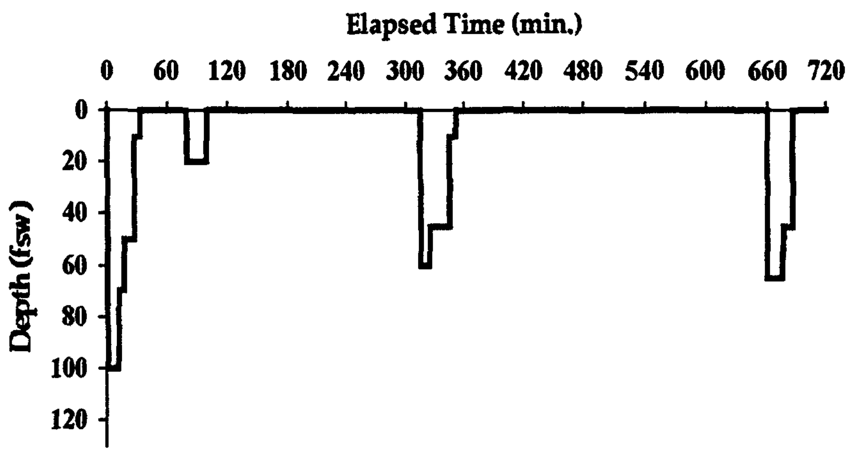

Figure 1. Dive Guide Profile (example # 1).

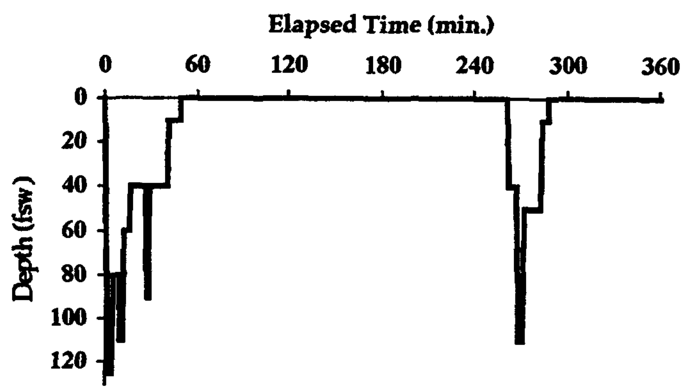

Figure 2. Dive Guide Profile (example # 2).

The decompression dive on the fourth day was to test a single-depth (30 fsw) decompression dive with the model. The dives conducted over the four days and the end-of-dive compartment loadings for the model are presented in Figures 3-6.

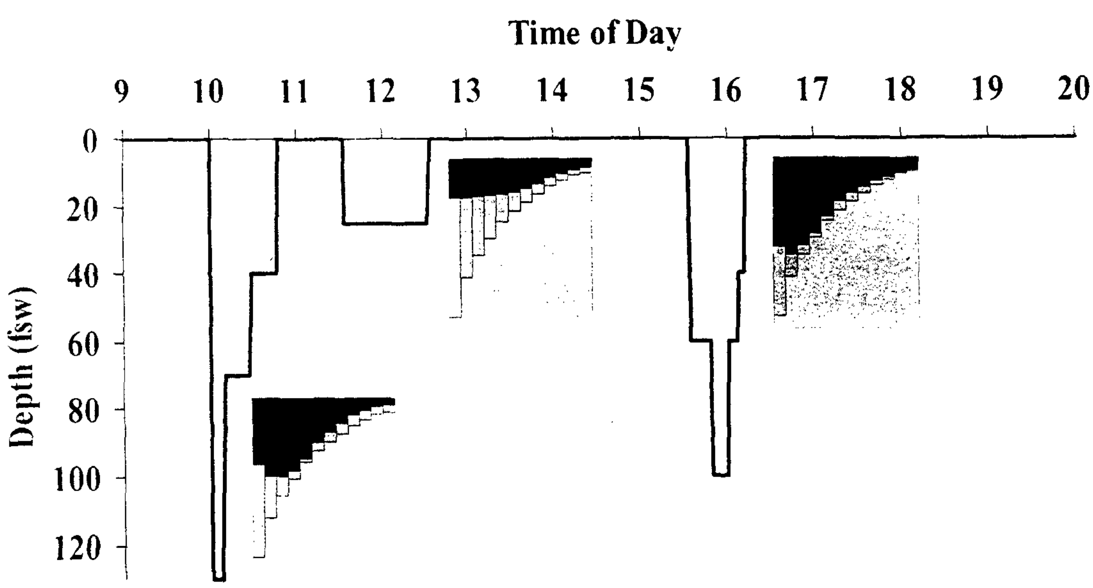

Figure 3. EDGE Test Dives – Day # 1 and End of Dive Compartment Loadings.

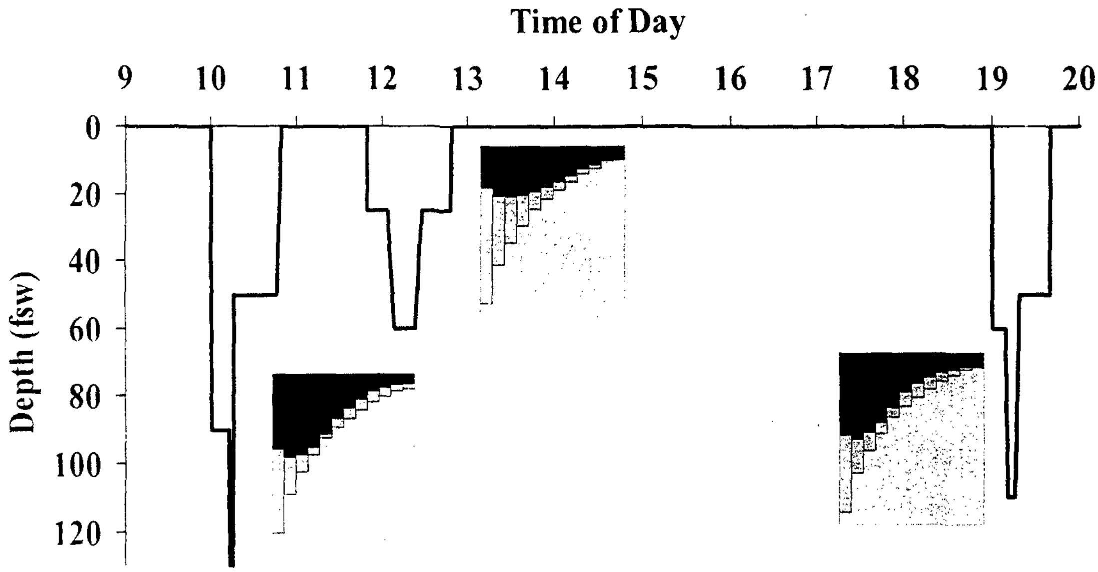

Figure 4. EDGE Test Dives – Day # 2 and End of Dive Compartment Loadings.

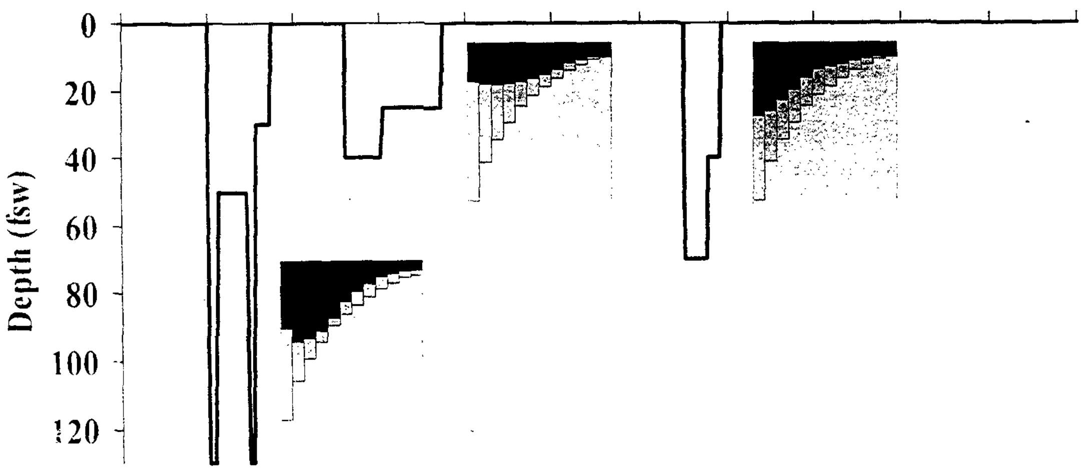

Figure 5. EDGE Test Dives – Day # 3 and End of Dive Compartment Loadings.

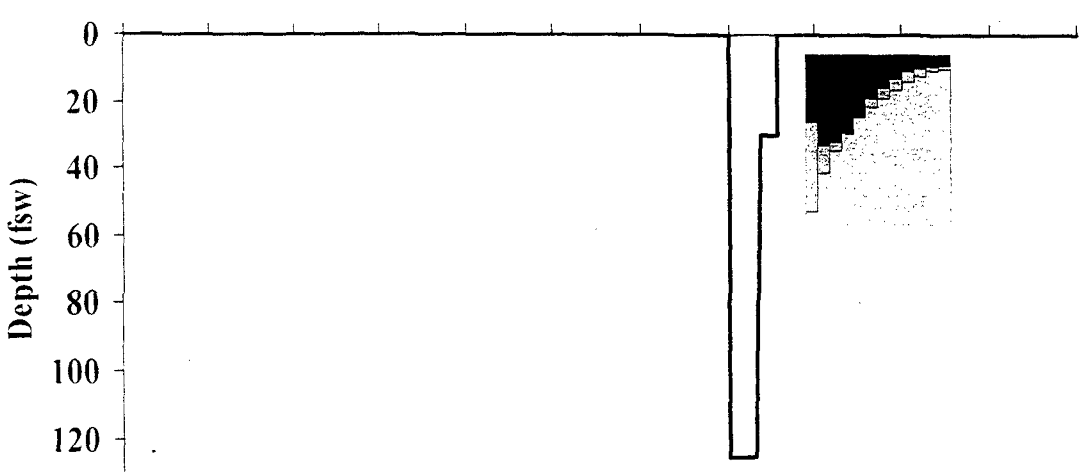

Figure 6. EDGE Test Dives – Day # 4 and End of Dive Compartment Loadings.

Twelve subjects were exposed to the three days of multi-level diving. One male subject did not participate in the decompression dive on the fourth day. The composition of the subjects was:

- 9 male
  - Age (25 - 62)
  - Weight (175 - 215 pounds)
- 3 female
  - Age (21 - 32)
  - Weight (125 - 135)

Three series with four subjects were run. Subjects were monitored with Doppler prior to and at intervals following the dives. The subjects were also asked to give a subjective post-dive evaluation on how they "felt."

Acceptance that there were no "hot spots" would be concluded if:

- No Doppler bubbles of Spencer Grade 2 or higher were produced;
- No symptoms of decompression sickness occurred; and,
- Occurrence of Spencer Grade 1 Doppler bubbles was less than 20%.

Results

A single instance of Grade 1 Doppler bubbles in one of the male subjects was detected following the decompression dive on the fourth day. Four cases of subjective "feelings" were reported:

- One occurrence of skin itches following the decompression dive on Day #4
- Two reports of "slightly fatigued" after Dive #1 on Day #3 (130 fsw - 50 fsw - 130 fsw - 30 fsw)
- One report of tingling in left leg following Dive #2 on Day #2 ("slightly stronger than normal")

Discussion

If each three-dive series each day is considered a single profile, then there was no occurrence of Grade 1 bubbles (or DCS) in 36 profiles. This gives a 95% confidence interval for occurrence of Grade 1 bubbles (or DCS) of 0.0 - 8.3%. If, however, you consider the entire three-day series as a single profile then the 95% C.I. expands to 0.0 - 25% (0/12). The results of the decompression dive on the fourth day give a Grade 1 bubble incidence of 9% with a 95% C.I. of 0 - 26%. These results do not instill much statistical confidence in the outcome of these tests, but due to financial limitations at the time, it was all Orca could afford.

It was hoped that additional funds would be made available at some future date to perform more tests, or that other dive computer manufacturers would perform and publish human-subject tests of their algorithms. In the sixteen years that have elapsed since this test series, there have been a plethora of dive computers placed on the market and only one extensive series of published data in this general area, the testing of the PADI/DSAT tables.

However, at the time, the results of this test met Orca's acceptance criteria. No "hot spots" were uncovered. The decision was made to release the EDGE dive computer without further modification to its decompression algorithm.

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EUROPEAN EXPERIENCE WITH REVERSE DIVE PROFILES

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Most European Divers have dive injury insurance, mostly through their diving club or DAN Europe. The data on diving accidents collected by these organizations represent a very inhomogenous group of divers, ranging from extremely active divers throughout the whole year in all conditions, to divers used to warm climates while diving during a holiday trip once a year or less. Available data on reverse dive profiles contributing to diving accidents of European divers are presented and the influencing factors are discussed.

Introduction

Most European Divers have dive injury insurance, mostly through their diving club or DAN Europe. The data on diving accidents collected by these organizations represent a very inhomogenous group of divers, ranging from extremely active divers throughout the whole year in all conditions, to divers used to warm climates and diving during a holiday trip once a year or less.

Materials and Methods

Data from European divers that have been treated for diving injuries at the Hyperbaric Services Thailand in Phuket, South Thailand (n = 42), during 1998 and on Bandos Island Resort in the Republic of Maldives during the period from November 1995 through February 1997 (n = 100) were analyzed. Also the DAN Europe Incident Report 1999 (n = 92), representing the data from 1996, was checked for the available information on reverse dive profiles. Furthermore, the database of the German Sports Divers Federation (VDST e.V.) with data about diving accidents from 1978 until 1991 (n = 274) was searched for information on the dive profiles.

Results

1. Hyperbaric Services Thailand in Phuket

The European divers who had to be treated in 1998 in Phuket (Ambriz, 1999) (total = 42 divers) originate from approximately 150,000 dives that are carried out annually during the peak season December - April. Most diving is done from liveaboard boats and on the islands in the Gulf of Thailand, and the distance from the dive sites to the Hyperbaric Facility is sometimes very far. Only the medical records were available for evaluation, but were found to be insufficient for dive data in most cases, so only a portion of all treated divers could be accounted for in the evaluation.

The findings were:

- 24 out of 27 divers (85%) engaged in multiday diving;
- 21 out of 28 divers (75%) engaged in repetitive dives;
- 6 out of 28 had buoyancy problems or did a rapid ascent; and,
- 5 cases were found that had done reverse dive profiles.

The calculated incidence contributing to the divers' incidents ranges from 12 – 24 %, depending on the number of divers used as the basis.

2. Bandos Medical Center and Hyperbaric Facility, Bandos Island Resort

The European divers (total = 100 divers) who required treatment at the Hyperbaric Facility on Bandos Island Resort in the Republic of Maldives between November 1995 and February 1997 represent many Swiss, French, Italian, and some German divers. Other nationalities are much less represented. In the archipelago of the Maldives, about 3 million dives are carried out annually. This gives a basis of approximately 4,000,000 dives for the Nov. 1995 – Feb. 1997 time period, and the Bandos Medical Center keeps excellent records of all cases requiring recompression therapy.

The findings were:

- 94 divers engaged in multi-day diving;
- 88 divers engaged in repetitive diving;
- 20 cases were found that involved reverse dive profiles; but,
- Only 13 cases were directly related to that fact; the rest had executed a rapid ascent and suffered from cerebro-arterial gas embolism

The calculated incidence ranges from 13 – 23 % depending on the number of divers used as basis.

3. DAN Europe

The DAN Europe Incidence Report (Marroni, *et al.*, 1999) (total = 92 divers requiring recompression therapy) represents the data from 1996. An estimated number of 1,143,284 dives were carried out during this year by the DAN Europe members. Diving is done worldwide, but the largest number of dives is carried out in the Mediterranean Sea and the Red Sea. The remaining dives are carried out locally in the divers' home countries.

The findings were:

- 32 (35%) engaged in multi-day diving;
- 38 (41%) were engaged in repetitive diving;
- 28/92 reported a fast ascent rate; and,
- Only 3 cases could be attributed to reverse dive profiles

The calculated incidence ranges from 3 – 9 %, depending on the number of divers used as basis.

4. German Sports Divers Federation

The German Sports Divers Federation (VDST e.V.) represents the largest association of recreational divers in Germany and is organized in small local diving clubs. All members have automatic insurance for diving accidents by the Gerling Konzern, one of the biggest insurance companies in Germany. The VDST is member of the World Underwater Federation, CMAS, and there are presently 70,000 diver members in the VDST.

General diving rules set by the VDST according to CMAS are:

- Maximum depth 40 msw;
- No planned decompression diving;
- No use of reverse dive profiles; and,
- Advocated decompression table: Hahn '92, with no additional safeguard information about reverse dive profiles.

Since 1974 the insurance company has recorded diving incidents of the VDST members. The records prior to 1978 showed no information about the dive profiles, so only the data from 1978 – 1991 could be analyzed. However, even these records were found to be unsatisfactory for the requested analysis. The records of these years give us a total of 274 diving accidents, including 70 fatalities. In a survey the VDST carried out in 1990, the estimated number of dives carried out by its members was 532,900 dives in the year 1989. The records of the insurance company were evaluated retrospectively.

The findings were:

- The number of divers engaged in multiday diving is unknown;

- Only 26 % (= 71 divers) engaged in repetitive diving; and,
- 8 cases were found that involved reverse dive profiles.

The calculated incidence of reverse dive profiles ranges therefore from 3 - 11 %, depending on the number of divers used as a basis.

Table I. Summary of Findings.

Database	total	l.c.	n	% low	high
Phuket/Thailand	42	21	5	12	24
Bandos/Maldives	100	88	20/13	13	23
DAN Europe	92	32	3	3	9
VDST/Germany	70	71	8	3	11
All database	508	212	36/29	6	17
Average				8	17

Total = total no. of injured divers, l.c. = lowest count of divers engaged in repetitive diving, n = no. of divers with reverse dive profiles.

Discussion

Data on the frequency of reverse dive profiles from European divers are not available completely, as records are insufficient about the dive profiles in most cases. The presented estimation of the incidence of reverse dive profiles contributing to the diving accidents remains therefore somewhat speculative. The only study that the author knows of that could give us some data to answer that question is DAN's Project Dive Exploration.

The prevalence of the contribution of reverse dive profiles to the divers' injuries seems to be highly variant in Europeans, as the divers' habits and dive patterns differ between the dive locations (tropical versus local waters). Strenuous dives in cold waters render repetitive diving less desirable.

Overall, within a 3% to 24% range of the divers' injuries might be attributed to cases involving reverse dive profiles. The high incidences are mainly derived from the environmental conditions that lead divers to repetitive diving in the first place. The problem of reverse dive profiles may therefore be overestimated in recreational diving, as the surface intervals normally exceed 2 hours. Especially in the regions with warm waters, the recreational divers are probably more prone to all possible causes of dehydration, which is more likely to contribute to the incidence of diving accidents in this population of divers.

Conclusions

An average estimated 11.5 % contribution of reverse dive profiles to the diving accidents of European divers seems not to be a very dominant figure. It could therefore be worth looking into the problem of reverse dive profiles in a future study that would have to be prospective and includes all data of the dive profiles (*e. g.*, DAN Project Dive Exploration).

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VI. Operational Experience Session Discussion Part 1.
Michael A. Lang, Moderator.

J. Lewis: What was the N on those dives, Jon?
J. Hardy: Six divers, 14 dives that actually fit the profile I described, four that exceeded.
J. Lewis: Fourteen per diver or 14 dives total?
J. Hardy: No, 14 dives total. Limited base but designed exactly to stress this point.

K. Huggins: Why did you reject a dive if all the computers said it was okay?
J. Hardy: Well, then we would have had no differentiation. We had to come to a point where we could actually differentiate that there was something effectively going on here.

G. Egstrom: I recall reading the profile of your subjects and had 115 years of diving experience in six subjects. I wonder, were these people diving regularly in your program, so that there may have been some acclimation.
J. Hardy: Five of them dive regularly, one not as frequently.

S. Sellers: Peter, if there were to be no difference between forward and reverse dives, wouldn't you expect the incidence to be equal for reverse dives and in fact what was shown is that reverse dives are safer in the effect on people you got? They should be equally distributed.
P. Mueller: Well, I don't know the other number. I just know how many got injured. The ones who didn't get injured, I have no information about their frequency of reverse dive profiles.

J. Hardy: Within your European population, you were saying 50 percent of those were diving in reverse. So, within that population you've got a lesser prevalence of hits with reverse dives than you did with the forward dives.
P. Mueller: It's statistically correct.
T. Neuman: All it says is only ten percent are doing reverse profiles. If the population is homogenous, this just happens to be a cut out of it, a sample in time.
B. Wienke: All he's saying is that only ten percent of them were doing reverse profiles. If those were the only people doing reverse dive profiles, then reverse dive profiles are real dangerous. If everybody is doing reverse dive profiles, then maybe it's not. There's a denominator that's missing.

J. Lewis: The one thing that I thought was really remarkable is that I've heard everybody crying about not having a denominator from year one. All of a sudden we've got denominators. Three examples of this were approximately a million dives with typically 100 accidents -- one out of 10,000. I don't know why I don't hear from other groups that there are denominators. I think that's a profound piece of data.
M. Lang: If I remember correctly, Tom Neuman suggested years ago to examine a captive island population, like Grand Cayman for example. You know how many scuba cylinders are being filled at the resorts and dive boats, you know how many people fly into the airport with dive gear bags, and hopefully, the same number leaves again.

W. Jaap: Peter, is there any overlap in your data between the various sources that you presented? I was wondering if the DAN and the VDST data were always independent or was there dual reporting?
P. Mueller: I'm quite sure that there is no overlap, especially between the Maldives and the DAN Europe data, because we have our own database. We keep it on Bandos, and that does not go into the annual incident report with DAN Europe. So, 1996 was the year we were looking at, and I was looking at the same time November 1995 through February 1997. So, we can call and have DAN for assistance but we treat them ourselves. If they have DAN diver accident coverage, they'll get reimbursed.

K. Huggins: Where does the total of three million dives in the Maldives come from? Over eighty-two hundred dives a day sounds like a lot to me.
P. Mueller: I had the privilege of preparing the new dive regulations for the Maldives in 1997, so I happen to know the numbers.
G. Egstrom: To that same issue, I'm always skeptical about what I call the rollover effect. If everything finishes on five's and zero's, you wonder what's really there, and when I see a whole string of zero's, then I'm ever more curious. I noticed that you went from three to four million.

P. Mueller: That's 14 months of coverage. The Maldivian government estimates three million dives from the number of tourists coming in and the percentage of them diving. The diving industry in the Maldives is very well organized, because they are totally regulated by the government. You just can't go there and open up a dive shop without going to the government first and asking for a permit. So, they have partial control of that. The number of divers being injured during that time are really the Europeans who come as tourists. We used to have a lot more injuries in the previous years when all the local dive guides, the Maldivian dive guides, got their severe hits, because they were doing many repetitive dives. Therefore, the regulations were changed to enforce a day off during the week and not more than three dives per day and a maximum depth of 30 meters now. Still, all the Italian and French divers that Till mentioned override the rules, go deeper, and get hit.

We're talking about dives after a one-hour boat ride to the dive site. When you go on a dive that lasts over an hour, and they give you a boat ride back, you go out for lunch and have your nap afterwards. Then you go on your afternoon dive, which will at least take you another 30, 45 minutes on the boat ride to and from the site. Whenever these injured divers asked me, "I was staying within the limits, what did I do wrong? Why did I get injured? I answer "Well, you were certainly severely dehydrated, because I look at your urine sample and can tell that. You didn't pass urine in four hours, your bladder is empty, and I've been resuscitating you with fluids, by the liter, and you're still dehydrated." It's mandatory to have fluids on the boat, not just a VHF radio to call for help. With fluids there, and divers drinking a lot of water before they go on their dives, will hopefully result in a decrease in the incidence numbers.

K. Huggins: I just wanted to follow up on what Jon was saying about us having the denominator for these datasets. Actually, I don't believe we do, because we still don't have the number of people who are doing reverse profiles. These data suggest that if we were to discover the risk being twice the non-reverse profile rates, operationally, the risks would be minimal. It's probably not accurate.

W. Jaap: Karl, when you were doing your testing, did you have stops built into that system on the surface coming back on the ascents?

K. Huggins: Just what was displayed. Most of them were direct ascents from 30 to 40 feet at the end of the dive.

R. Vann: Were your folks exercising in between?

K. Huggins: We had an exercise bike in the chamber that they would take turns on.

R. Vann: But they were dry?

K. Huggins: They were dry, yes.

T. Mutzbauer: Just to talk again about the 100 cases out of the four million, these were the most important and the ones probably having symptoms. That's something we have to mention. We observed in 1993-1994, the first year the chamber opened, 30 accidents, and the next year they had 70 accident cases reporting their symptoms and improving in the chamber. I doubt therefore that twice the number of dives were conducted for these incidences to be the same. I would stress awareness, and public education. We also have underreporting by people flying out with symptoms and returning home to report to the nearest chamber.

B. Wienke: Jon, you suggested that the day will come when tables will go away. I, personally agree with that, but I'm wondering what you think the impact of that is?

J. Hardy: Very good question that Bruce brings up, and those of us who are old enough to remember, submersible pressure gauges were resisted far greater than computers were. The first submersible pressure gauges we were told would be stolen, they would break, they wouldn't read accurately or they would blow up in your face - all these possible reasons why we shouldn't use submersible gauges. Yet when dive computers came along, the world had moved enough that there wasn't such a high resistance. Dive computers are getting less expensive, easier to read, and more like your home computer all the time. The training agencies are really conservative and slow to change. If you look at the safety stop in our industry, it took the training agencies ten years to adopt the safety stop that the rest of the instructors were using in the field. There will be a slow progression, but I think the agencies are certainly capable of making the change.

E. Baker: Do you think it's worthwhile for the public community to go to all the agencies to set a date and time for this to happen?

J. Hardy: Well, years ago we said, "Hey, it's time to admit that the power inflator works better than blowing into your BC by mouth too." I would sponsor that. I'd say that, yes, it's time to move on.

G. Egstrom: One of the reasons I think that the agencies are sometimes a little reluctant is, for example, I have one file that has 30 sets of decompression tables with different assumptions, different models - whatever. I took a sack full of dive computers and dived with them for four days. No two dive computers told me the same thing. In one case, even two of them were the same model. The question becomes which tables are the best dive tables? Which dive computer is the best dive computer? We'd all be happy to dive the one that was best.

J. Hardy: Can't you answer by saying they're all good? I haven't had any trouble with that.

G. Egstrom: Well, they're so divergent. I'm not indicating that it's bad; it's just that if we have risk and we know that some are better than others, why wouldn't we go with the best ones?

K. Shreeves: Well, we know how to eliminate risk in time, so it's a trivial answer.

A. Brubakk: I took all the tables I could find and simply looked at the no-stop decompression time at 30 meters, and that varies quite naturally wide, you will get an obvious table. And then, of course, it's totally different –

J. Lewis: No.

A. Brubakk: I can show you the data.

J. Lewis: From five minutes to 25 minutes?

A. Brubakk: Yes, yes. It is a very large difference. Go look at the tables themselves.

J. Lewis: Who advocates five minutes no decompression time at 100 feet?

A. Brubakk: It varies a lot. The whole point is what kind of decompression risk are you willing to take? What is actually an acceptable level of risk that was talked about here? Computer models have different levels of risk.

M. Lang: The risk issue is a very good point, as Paul Weathersby described. In some cases, the decision is made for the diver from a corporate level for a science program, military mission, commercial diving job, or a recreational dive guide. But when you're looking at a large recreational diving community, it's pretty much up to the individual diver. There you are going to find a wide variation of risk acceptance.

G. Egstrom: Karl has a marvelous slide on shrinking bottom times.

M. Lang: And you end up diving in the intertidal?

G. Egstrom: You start off with 100 feet for 25 minutes, and by the time you get down into Paul's country at the one percent maximum likelihood, you're down there around five to seven minutes, so that's not so farfetched.

J. Lewis: But it's not particularly acceptable either. It doesn't represent one percent by any stretch of imagination. It's more like ten to the minus four. It's one out of 10,000, and it's not diving five minutes in a test. That sort of thing, I think, is extremely simple.

G. Egstrom: But the assumptions that go into the development of the tables and computers, there are just too many of them.

J. Lewis: But Glen, by definition, they must be reject those silly assumptions a lot, because that absolutely makes no sense. The primary reason the reduction of no-decompression limits happened was because people were reluctant to accept the concept of an asymmetric relaxation of nitrogen loading. People just resisted that forever. As a result, there was a dramatic reduction of the no-decompression limits to avoid that. You can take NDL's down to five minutes, and you've still got a problem. So, that's just not the way to do it.

M. Lang: Order in the court please.

M. Gernhardt: I was just going to say a couple things in response to that last statement. The issue of probability is as follows: there's the laboratory trial, and there are the models, and they fit, and it's good science, and that's what it says. Then there's the reality of the operation. We struggle with that in the commercial field where to the laboratory data we fit our model, it said that we would be having one or two percent or even three percent DCS. But the divers knew we weren't going to have that. We analyzed the whole pattern of diving for over 25,000 dives. Given that for these dives (on an individual square-wave basis from the laboratory datasets) you would have three percent incidence, the fact is that we're not doing square-rated dives, rather, there are all of these depth variations. I see a pattern that is going away from assigning probabilities that you know you're never going to observe and that you can probably never even verify in the field, because the confidence intervals are bigger than you could ever document.

E. Flynn: There's also a rule question here about the point risk in a no-decompression curve or, what is the risk if you're right on the curve versus what is the accumulated risk of all the dives (from the very short dives all the way up to the longest)? We looked at all the Navy no-decompression dives out to 50 feet of seawater. There were 165,000 dives, and there were about 42 cases of decompression sickness. About 80 percent of those cases happened in the first 25 percent of the no-decompression dive limit. At 40 feet (200-minute no-decompression limit), most of the cases were between zero and 80 minutes. There were very few cases actually out near the no-decompression limit, because the frequency of dives at that limit had fallen off dramatically. The highest frequency was 30 to 60 minutes. So, when you set a no-decompression limit, you have to consider what the impact is all the way from time zero out to that point on the curve.

M. Gernhardt: You said that 40 for 200 limit should be 40 for 250. The overall impact on the situation wouldn't be that many more cases. It had already accumulated a huge number.

P. Tikuisis: This is for Paul Weathersby and it's a follow-up on what Bill Hamilton said. As I understood Paul's presentation, he looked at a set of reverse profiles that we had in the dataset, looked at the actual outcomes on those profiles, prepared a model prediction, and saw that those weren't that much different. That model had been derived from a large set of all types of proposals. That was generalized saying that this showed the reverse profiles were just as safe as forward profiles. And I don't think that conclusion is justified.

P. Weathersby: Those weren't my words.

P. Tikuisis: I know, but those were Bill's words, I believe. I didn't want to get that situation misrepresented. I think what it said was the model predicted the outcomes, but it didn't say the reverse dive profiles were either more or less dangerous.

P. Weathersby: Well, I'd be willing to generalize a little bit more from those particular simple long-duration depths. In an overall decompression system control structure, 'good dives' apply to reverse dives in our data as well as the forward dives.

K. Huggins: Actually, if there's time, I know that Glen had a nice chronology of when the reverse profile restrictions were put into play.

M. Lang: This afternoon there are more presentations from the recreational diving community that also present a chronology.

G. Egstrom: I went through over a 100 references of various kinds: a series of Navy manuals, foreign manuals that I had, documents that had been put out by private enterprise and pulled out a few things that I think might perhaps even be of some amusement to a couple of you.

First, the term "reverse profile" actually comes out of a Navy diving manual from 1959, only they didn't mean reverse profile the way we're looking at it here. They meant that, within a given dive, you were going deeper at the end than the beginning. When we got into the reverse dive profile terminology for this workshop, we weren't talking about the same thing as they were at that time.

It's of interest to me that if you went through all of the Navy manuals from 1954 up through 1993 they all say pretty much the same thing even though the language has changed a little bit. For example, in the 1956 U.S. Navy manual on submarine medical practice, they recommended only one dive in 12 hours, but then they said if more than one dive was to be made within 12 hours, the diver was to take the depth of the latest dive and use the combined time on the bottom, descent time plus actual bottom time, for all exposures. But they had no admonitions in there that you could not dive your deepest dive last. So, you would have at that point taken the shallow dive depth and the combined bottom times.

Then the 1959 version came out and indicated that decompression sickness is caused by inadequate decompression following a dive, but it does not necessarily mean that the decompression table has not been followed properly. There's no real differentiation as to whether you're going to do a deep dive first or last. They just say you take the deepest depth and add the bottom times.

Then, in 1968, Dennis Walder made the observation that divers should make the first dive a deep, short crush dive that will compress the body's micronuclei down to a smaller and safer size. He then stated that subsequent dives should be made progressively shallower. And that's the first place I was able to find that particular language.

In the Florida cave diving scene, as early as 1970, they recognized that due to the very nature of cave diving you dived progressively deeper as you made your penetrations and went to work in the caves.

I also have to point out that in the 1970s, the U.S. Navy diving manual had a repetitive dive worksheet, and the example that was given on the back of that worksheet was in fact a reverse dive profile. They didn't even have the forward dive, because that apparently wasn't enough of a mathematical challenge to deal with.

The 1975 manual indicated that during the 12-hour period after an air dive, the quantity of residual nitrogen in the diver's body will gradually reduce to its normal level. If, within this period, a diver is to make a second dive, called a repetitive dive, he must consider his present residual nitrogen when planning for the dive. Now, neither the repetitive dive flow chart nor worksheet contained any advice on making the deep dive first.

By the middle 1970's, there were a number of texts that were being written by various independent scuba instructors that had statements such as plan repetitive dives so that each successive dive is to a lesser depth. This will aid in the elimination of nitrogen and decrease the need for decompression stops. They nevertheless put the U.S. Navy diving manual's repetitive-dive worksheet with a reverse profile on the back. I thought that was kind of cute.

Dueker (1978) in his book on diving medicine, indicated that generally it saves time to take the deeper of two dives first. The conventional wisdom throughout this issue is that, mathematically, you could get more bottom time if you dived deep first.

As this proceeded forward, very gradually, the people started shifting from "This is a good thing, because it gives us more bottom time" into the concept that "This is a good thing, because it's safer." I still can't find the culprit on that one, but I think possibly that it was an interpretation of what Dennis Walder stated in his earlier paper.

By the time we got into the "era of the textbooks," *i.e.*, Jeppesson, NAUI and PADI, all began with comments such as, "When making a series of dives, plan repetitive dives to the same or shallower depth as the previous dive. This allows you to outgas nitrogen on progressively shallower dives instead of carrying a large amount of residual nitrogen on deeper repetitive dives." There's no indication in any of these texts whether there's any data to support this. It has grown in the literature and taken on a life of its own.

The PADI Open Water Manual (1988) has, in large letters on one of their illustrations, "Deepest Dive First." This is the first instance where the language shifted a little bit, and declared, "Never follow a dive with a deeper dive. Always plan your deepest dive first."

By 1991, Graver, in a chapter, indicated that when making a series of dives, plan repetitive dives to the same or shallower depth as the previous dive. This allows you to outgas nitrogen on progressively shallower dives instead of carrying this large amount of nitrogen around.

In the AAUS Repetitive Diving Workshop (1991), Gilliam reported on 77,680 dives, and stated that reverse profiles were conducted by many divers with no adverse effects reported. This is one of the earlier database numbers that came out.

Then Brylske (1995) wrote a book on "Beating the Bends," and he admonished the readers to avoid high-risk profiles. "While science still argues the reasons why such practices are dangerous, practical experience shows that certain profiles are more likely than others to get you a trip to the recompression chamber. In particular, take care not to dive reverse profiles or sawtooth profiles. On multilevel diving, spend the first part of your excursion in the deeper range, then move shallow. Never return to deeper water once you've come up into the shallower range."

By 1995, NAUI also said always make your deep dive first; plan repetitive dives shallower, and, again, the reason we're doing this is because it's going to give us this big advantage in terms of off-gassing.

The 1999 edition of the PADI Dive Master Manual is a very nicely done piece of work. I think it's going to be very helpful. But their rule number two on the use of the Recreational Dive Planner states "Plan repetitive dives so each successive dive is to the same or shallower depth. Don't follow a dive with a deeper dive. Plan your deepest dive first." It continues: "Although from a model point of view, there's no mathematical reason for this recommendation, reverse profiles seem to be associated disproportionately with DCS incidents." Then they said that "This recommendation also applies to the use of dive computers."

Therefore, the issue that Michael has raised and which apparently has never been a consideration in the commercial diving industry, has pretty obviously been with us in the recreational field for about 25 years, possibly even 30, where people have said in graded fashion, should not, must not, and some, cannot.

M. Lang: And that's how IT happens!

THE DEVELOPMENT AND USE OF REVERSE DIVE PROFILES, REPET-UP AND HANG OFF DIVING PROCEDURES IN THE OFFSHORE OILFIELD COMMERCIAL DIVING INDUSTRY

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The history and evolution of reverse dive, repet-up and hang-off diving procedures in the commercial diving industry are reviewed. The use of these procedures today by various commercial diving companies and the relative safety of the procedures is presented. How successful are these procedures in the field and how are reverse dive profiles treated in the commercial diving community?

Reverse Dive Profiles

Where is it written that a diver must make the deeper dive first, then make a shallower dive? This seems to be the unwritten rule in all diving courses, both recreational and commercial. Is there some reasoning behind this rule? What happens if a diver makes a shallow dive first, then a deeper dive? If he does, what are the barriers or restrictions to this type of dive? In the commercial industry, diving is performed using the procedure that earns the most money. The contractor will weigh the risk versus reward and consider the consequence for using a specific procedure or table. The use of a reverse dive profile is not very common in the commercial industry. However, the consequence for the use of this profile is a loss of bottom time. In the commercial industry this translates into lost revenue. If the tables are followed, with an appropriate surface interval, there has not been any increase in decompression sickness incidents. The procedure is not used very often, because the contractor is always trying to get the most work out of his resources, the diver and time. Preplanning of a diving job will take into account the depth and amount of work required to complete the task. Resources will be used to the best advantage and to maximize revenue.

What is the relative safety of the procedures being use by commercial diving companies? As there are no hard statistics on bends incidents in the commercial industry, one has to depend on reports from knowledgeable individuals within each company. A readily agreed upon incident rate for overall decompression sickness incidents in the commercial diving industry is one in 1500 to 2500 dives. Many companies have reported a record of one in more than 4500 dives, OCEANEERING being one of these. This is inclusive of all types of air dives, no-decompression, in-water decompression, and surface decompression using oxygen. In the commercial diving industry, dives are monitored from the surface; the depth and time are logged; and tables and job procedures are reviewed and planned before the dive. Diving procedures such as the 2 + 2 rule are utilized (*i.e.*, going to a deeper or longer table if the diver's depth or bottom time is within minutes of the planned dive.

The diver's bottom time is money. Someone is paying to have a task completed. Decompression incidents cause downtime on the job site and take up valuable resources while treating a bent diver. While it is accepted that there will be some bends incidents during a job, most commercial diving companies come prepared with decompression chambers and trained personnel to quickly and efficiently handle the situation. The quick and aggressive treatment of a bent diver will prevent lost revenue and possible lawsuits down the line. A company can not survive long in the industry, without a proactive approach to diver safety and efficient operations. The use of reverse dive profiles will continue. However, they do not contribute to the overall safety and efficiency of a diving operation. Repet-Up and hang-off dive procedures are some of the other types of unusual procedures used by commercial diving companies to complete an underwater task.

Repet-Up

This is a procedure in which a diver starts at a depth and works up at different levels performing his job. The idea is to maximize the diver's water time and remain within the company's established tables. The goal is to successfully decompress the diver back to the surface accomplishing the greatest amount of work. Many different procedures have been tried over the years, yet there are two basic procedures in use today. Both are based on the U.S. Navy Residual Nitrogen Time (RNT) Tables. One involves performing a dive, starting at the deepest depth, and calculating the RNT without a surface interval. The difference in the use of this procedure between companies is that some use the RNT as published in the table, others jump one repetitive group, and some jump two repetitive group letters.

The basic rules governing these procedures are: The diver starts at the deepest depth and works upwards. The repetitive group while working up will not extend beyond letter O. Decompression is initiated from the final working level for the depth and total residual nitrogen penalty using either in-water or Sur-d-O_2 decompression tables. The diver must ascend at least 30 fsw between the working levels. The shallowest working level is 40ft. Bottom time for the deepest working level (first level) is calculated from leaving the surface to arrival at the second, shallower, working depth. Subsequent working levels are calculated from arrival at that depth until arrival at the next shallower depth. Repetitive dives are not allowed following a Repet-Up. Some companies have established a procedure where the diver is decompressed on the table from the level that required the most decompression.

The other procedure involves following the RNT table from depth plus bottom time and adding this to the next level. This is the procedure used by OCEANEERING (Appendix 1). This procedure was reviewed by Dr. Thalmann in 1978, but is not to be considered an official opinion of the U.S. Navy. At that time, it was considered a safe procedure for Repet-Up and possibly could be used for Repet-Down with further testing and evaluation.

These tables came about because of a need by the commercial diving industry to perform inspection, maintenance, and repair on offshore oil platforms and risers, and in the inland areas for inspections of dams. Repet-Up in the commercial diving industry is not used very much any more. It is only used on air dives, not on mixed gas dives. A recent, informal telephone survey of the major offshore diving contractors and some of the inland companies found only 40 to 50 Repet-Up dives each year. There have been no reported decompression incidents in the last 5 years. There is no published industry standard, or set of decompression tables for these procedures. Each company establishes its own tables or follows the U.S. Navy Diving Manual.

Hang-Off Procedures

This procedure is used when waiting on equipment, assistance, and materials from the surface. It is similar to a yo-yo diving profile, allowing the diver's bottom time to be stopped to increase his working time at depth. There have not been any reported problems with decompression incidents using these procedures. Based on the previous informal telephone survey, only a few commercial diving companies use this type of dive profile. Only 10 to 20 estimated dives of this type are performed each year.

The procedure for a hang-off dive is as follows: The diver descends to the working depth and works until he must wait for topside support. He then ascends to 30ft at 25ft/min. Bottom time stops when he leaves the bottom and hangs off while waiting for the required support. When required, the diver descends back to the work location and bottom time resumes when he leaves the 30ft hang-off depth. He continues until he must decompress, or is again required to hang-off waiting for support. If at any time the diver's hang-off time exceeds a total of 20 minutes, he must be decompressed from the 30ft hang-off stop. If his 30ft decompression stop is in excess of the time spent at the 30ft hang-off depth, disregard the 30ft decompression stop and continue to the 20ft stop. If the 30ft decompression stop is longer than the time spent on the hang-off, complete the time for the 30ft decompression stop. This procedure can be repeated until the accumulated bottom time puts the diver into the O Repetitive Group, or he makes a total of four dives to the bottom, whichever comes first. He must then decompress on the appropriate table. This procedure is used for in-water and Sur-d-O_2 diving techniques. No repetitive dives are allowed following this procedure.

The following are some of the rules to follow using the Hang-off procedure: the diver can not exceed the first O repetitive group designation; hang-off time is limited to a maximum of 20 minutes; the maximum number of dives to the bottom, including the first one, is four; and, work must stop and decompression commences when the diver reaches the O group designation. Again, this procedure is not used with any frequency in the commercial diving industry.

Saturation Dives and the Unlimited Duration Excursion Tables

These tables are based on the U.S. Navy saturation and unlimited duration excursion tables. They are used in both up and down excursions and, in some cases, for a combination of both. The length of the up or down excursions depends on the initial storage depth and the deepest depth attained in the previous 48 hours. Excursion distance increases as the depth increases. Commercial diving companies tend to restrict excursion distances at depths greater than 800ft. Decompression from saturation is not allowed to commence with an upward excursion. These tables have been in use for many years, with only a few reported decompression incidents that could be attributed to an excursion.

Conclusions

Commercial diving companies infrequently use reverse dive profiles, Repet-Up and Hang-Off procedures. They do not take any additional steps beyond following their established tables and have not experienced any increase in decompression incidents when using these procedures. The use of these types of dives is directly dependent on the procedure providing an efficient use of the companies resources to complete the assigned task safely.

Appendices

The following five pages of Appendices are reprinted with permission from OCEANEERING's DIVING OPERATIONS MANUAL VOLUME II, October 1996, SEC 1-A5 pages 1 through 5. Riser Repet-Up Air Diving Procedure.

Riser/Repet-Up Procedures

During operations involving work on riser clamps and non-destructive testing of platforms etc., a single dive may require periods to be spent at a number of depths working up towards the surface.

To decompress from such a dive, some procedures require that the diver is decompressed for the deepest depth achieved during the dive for the total time from leaving surface to leaving the last and shallowest diving depth.

This is completely unnecessary and exposes the diver to excessively long decompression. The assumption is made that the diver is absorbing inert gas from his breathing medium at a rate consistent with being at maximum depth throughout the dive. In fact, the diver has had his inert gas uptake reduced progressively throughout the dive and tissues are decompressing at the shallower working depths.

Riser/Repet-Up Procedures provide the means whereby the inert gas (Nitrogen) uptake may be more accurately assessed and a more appropriate decompression schedule applied.

Rules

1. This procedure should only be used when the dive starts at the deepest depth and works upwards towards the surface.
2. When working a diver upwards, his repetitive group shall not extend beyond an 'O' Group.
3. Decompression can be initiated from the final working depth and total residual nitrogen penalty using either surface decompression or in water decompression techniques.
4. Ascent rates between working depths must not exceed 60 feet/minute.
5. After the last (shallowest) working depth, ascent rates are to be in accordance with the decompression schedule selected, i.e. 25 feet/minute for surface decompression using oxygen.
6. Use a minimum repet ascent of 30 FSW between working depths. Any ascent of less than 30 FSW should be considered as time spent at previous working depth.
7. Bottom time for first (deepest) working depth is calculated from leaving surface to arrival at the second working depth.
8. Bottom times for all subsequent working depths (other than the original [deepest] working depth) are calculated from arrival at that working depth until arrival at the next shallower working depth.
9. Subsequent working depths must never be shallower than the first stop of the previous depth/time exposure.
10. Repet-Up Procedure is not to be used shallower than 40 FSW.
11. Repetitive dives are not allowed following a Repet-Up dive.

Figure One is a worksheet and log to enable this procedure to be easily used.

Figure Two is a dive with the following dive profile as an example:

Dive Profile

Depth (FSW)	Time (Minutes)	Ascent to Next Working Depth
158	9	1 minute (118 FSW)
118	10	1 minute (79 FSW)
79	9	1 minute (43 FSW)
43	14	

While the ascent time between working depths will vary in relation to work of bringing up tools, tugger lines, down lines, etc., for the purpose of this example, ascent time between working depths is taken as 1 minute for convenience.

The procedure is:

Entering the Residual Nitrogen Table at the deepest depth attained during the first phase of the dive and proceeding down the column to the bottom time (including ascent time to next working depth) or the next greater increment and read horizontally across to find the repetitive group:

1. For the initial working depth of 158 FSW for 10 minutes, we use the 160 FSW column and 11 minute increment. This produces a repetitive Group of 'E'.

2. The diver then works for 10 minutes at 118 FSW and ascends to 79 FSW in one minute for a total time of 11 minutes at 118 FSW. By following the 'E' Repetitive Group line horizontally across the 118 FSW (120 FSW column) we find that the 10 minutes previously spent at 158 FSW is equivalent to 15 minutes at 120 FSW.

   The diver therefore carries a 15 minute Nitrogen penalty which is added to the 11 minutes spent at 118 FSW.

   By following the 120 FSW down we find the time increment or next greater to 26 minutes (28 minutes). This produces a Repetitive Group of 'I'.

3. The diver works at 79 FSW for 9 minutes and ascends to 43 FSW in 1 minute for a total time of 10 minutes at 79 FSW.

   By following 'I' Repetitive Group line horizontally across to 79 FSW (80 FSW column) we find that a residual Nitrogen penalty of 28 minutes incurred at 120 FSW is equivalent to 43 minutes at 80 FSW.

   The diver therefore carries a 43 minute Nitrogen penalty to add to the 10 minutes spent at 79 FSW. The nearest increment to 53 minutes is 54 minutes with a Repetitive Group of 'K'.

4. The diver works at 43 FSW for 14 minutes to complete his task and is now ready to decompress to the surface.

   By passing horizontally along the Repetitive Group 'K' line to 43 feet (50 FSW column) we find the residual Nitrogen penalty equivalent to 54 minutes at 80 FSW is 99 minutes.

   Adding the 14 minutes at 43 FSW to the penalty of 99 minutes (113 minutes) we find the nearest time increment to be 124 minutes with a Repetitive Group of 'M'.

5. On completion of his work at 43 FSW, decompression will be in accordance with 140 minutes (124 minutes residual Nitrogen) at 50 FSW. This requires a 10 minute stop at 10 FSW.

   Using the deepest depth for total time principle, this would constitute an exceptional exposure and not be acceptable operationally.

   Figure Three is a worksheet for the following series of dives, but decompression on the Surface Decompression Using Oxygen Schedule.

Dive Profile

Depth (FSW)	Time (Minutes)	Ascent to Next Working Depth
147	17	1 minute (115 FSW)
115	12	1 minute (86 FSW)
86	16	

FIGURE ONE

DIVE SERIAL NO________ **RISER/REPET-UP AIR DIVING LOG** DATE____________

CLIENT	VESSEL STRUCTURE	LOCATION	DIVER	MAX. DEPTH	DECOMPRESSION SCHEDULE

RESIDUAL NITROGEN TABLE

DIVE DEPTH (FEET OF SEA WATER)

Repetitive Groups	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
A	7	6	5	4	4	3	3	3	3	3	2	2	2	2	2	2
B	17	13	11	9	8	7	7	6	6	6	5	5	4	4	4	4
C	25	21	17	15	13	11	10	10	9	8	7	7	6	6	6	6
D	37	29	24	20	18	16	14	13	12	11	10	9	9	8	8	8
E	49	38	30	26	23	20	18	16	15	13	12	12	11	10	10	10
F	61	47	36	31	28	24	22	20	18	16	15	14	13	13	12	11
G	73	56	44	37	32	29	26	24	21	19	18	17	16	15	14	13
H	87	66	52	43	38	33	30	27	25	22	20	19	18	17	16	15
I	101	76	61	50	43	38	34	31	28	25	23	22	20	19	18	17
J	116	87	70	57	48	43	38	34	32	28	26	24	23	22	20	19
K	138	99	79	64	54	47	43	38	35	31	29	27	26	24	22	21
L	161	111	88	72	61	53	48	42	39	35	32	30	28	26	25	24
M	187	124	97	80	68	58	52	47	43	38	35	32	31	29	27	26
N	213	142	107	87	73	64	57	51	46	40	38	35	33	31	29	28
O	241	160	117	96	80	70	62	55	50	44	40	38	36	34	31	30
Z	257	169	122	100	84	73	64	57	52	46	42	40	37	35	32	31

DIVING SUPERVISOR	STANDBY DIVER	EQUIPMENT USED	LEFT SURFACE	ARRIVED SURFACE	TOTAL TIME UNDER PRESSURE

	TIME	DEPTH	BOTTOM TIME	TRAVEL TIME	RESIDUAL NITROGEN TIME	TOTAL DECOMPRESSION TIME	REPETITIVE GROUP
LEFT BOTTOM							
ARRIVED SECOND WORKING DEPTH							
LEFT SECOND WORKING DEPTH							
ARRIVED THIRD WORKING DEPTH							
LEFT THIRD WORKING DEPTH							
ARRIVED FOURTH WORKING DEPTH							
LEFT FOURTH WORKING DEPTH							
ARRIVED FIFTH WORKING DEPTH							
LEFT FIFTH WORKING DEPTH							

DECOMPRESSION SCHEDULE

WATER STOPS

	TIME	DEPTH	MINS
ARRIVED			
LEFT			
ARRIVED			
LEFT			
ARRIVED			
LEFT			
ARRIVED SURFACE			

REMARKS

CHAMBER STOPS

	TIME	DEPTH	MINS
LEFT SURFACE			
ARRIVED BOTTOM			
ON OXYGEN			
LEFT			
ARRIVED			
OFF OXYGEN			
ON OXYGEN			
LEFT			
ARRIVED SURFACE			

FIGURE TWO

DIVE SERIAL NO 1	RISER/REPET-UP AIR DIVING LOG				DATE 1 SEPTEMBER 1995
CLIENT	**VESSEL STRUCTURE**	**LOCATION**	**DIVER**	**MAX. DEPTH**	**DECOMPRESSION SCHEDULE**
Roger's Oil	Barracuda	Leman	Tapscott	158'	USN Standard Air 50/140

RESIDUAL NITROGEN TABLE

DIVE DEPTH (FEET OF SEA WATER)

Repetitive Groups	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
A	7	6	5	4	4	3	3	3	3	3	2	2	2	2	2	2
B	17	13	11	9	8	7	7	6	6	6	5	5	4	4	4	4
C	25	21	17	15	13	11	10	10	9	8	7	7	6	6	6	6
D	37	29	24	20	18	16	14	13	12	11	10	9	9	8	8	8
E	49	38	30	26	23	20	18	16	15	13	12	12	11	10	10	10
F	61	47	36	31	28	24	22	20	18	16	15	14	13	13	12	11
G	73	56	44	37	32	29	26	24	21	19	18	17	16	15	14	13
H	87	66	52	43	38	33	30	27	25	22	20	19	18	17	16	15
I	101	76	61	50	43	38	34	31	28	25	23	22	20	19	18	17
J	116	87	70	57	48	43	38	34	32	28	26	24	23	22	20	19
K	138	99	79	64	54	47	43	38	35	31	29	27	26	24	22	21
L	161	111	88	72	61	53	48	42	39	35	32	30	28	26	25	24
M	187	124	97	80	68	58	52	47	43	38	35	32	31	29	27	26
N	213	142	107	87	73	64	57	51	46	40	38	35	33	31	29	28
O	241	160	117	96	80	70	62	55	50	44	40	38	36	34	31	30
Z	257	169	122	100	84	73	64	57	52	46	42	40	37	35	32	31

DIVING SUPERVISOR	STANDBY DIVER	EQUIPMENT USED	LEFT SURFACE	ARRIVED SURFACE	TOTAL TIME UNDER PRESSURE
Bloggs	Haddox	Rat Hat Hot Water Suit	0000	0055:50	55 mins / 50 secs

	TIME	DEPTH	BOTTOM TIME	TRAVEL TIME	RESIDUAL NITROGEN TIME	TOTAL DECOMPRESSION TIME	REPETITIVE GROUP
LEFT BOTTOM	0009	158'	9	1	-	10	'E'
ARRIVED SECOND WORKING DEPTH	0010	118'			15		'E'
LEFT SECOND WORKING DEPTH	0020	118'	10	1	15	26	'I'
ARRIVED THIRD WORKING DEPTH	0021	79'			43		'I'
LEFT THIRD WORKING DEPTH	0030	79'	9	1	43	53	'K'
ARRIVED FOURTH WORKING DEPTH	0031	43'			99		'K'
LEFT FOURTH WORKING DEPTH	0045	43'	14	40 secs	99	113	'M'
ARRIVED FIFTH WORKING DEPTH							
LEFT FIFTH WORKING DEPTH							

DECOMPRESSION SCHEDULE

WATER STOPS

	TIME	DEPTH	MINS
ARRIVED	0045:40	10'	10
LEFT	0055:40	10'	
ARRIVED			
LEFT			
ARRIVED			
LEFT			
ARRIVED SURFACE	0055:50	REMARKS	

CHAMBER STOPS

	TIME	DEPTH	MINS
LEFT SURFACE			
ARRIVED BOTTOM			
ON OXYGEN			
LEFT			
ARRIVED			
OFF OXYGEN			
ON OXYGEN			
LEFT			
ARRIVED SURFACE			

FIGURE THREE

DIVE SERIAL NO 2	RISER/REPET-UP AIR DIVING LOG				DATE 1 SEPTEMBER 1995
CLIENT	**VESSEL STRUCTURE**	**LOCATION**	**DIVER**	**MAX. DEPTH**	**DECOMPRESSION SCHEDULE**
Helburn Oil	Barracuda	Katy	Rogers	147'	USN Sur D O_2 OI Mod 90/80

RESIDUAL NITROGEN TABLE

DIVE DEPTH (FEET OF SEA WATER)

Repetitive Groups	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
A	7	6	5	4	4	3	3	3	3	3	2	2	2	2	2	2
B	17	13	11	9	8	7	7	6	6	6	5	5	4	4	4	4
C	25	21	17	15	13	11	10	10	9	8	7	7	6	6	6	6
D	37	29	24	20	18	16	14	13	12	11	10	9	9	8	8	8
E	49	38	30	26	23	20	18	16	15	13	12	12	11	10	10	10
F	61	47	36	31	28	24	22	20	18	16	15	14	13	13	12	11
G	73	56	44	37	32	29	26	24	21	19	18	17	16	15	14	13
H	87	66	52	43	38	33	30	27	25	22	20	19	18	17	16	15
I	101	76	61	50	43	38	34	31	28	25	23	22	20	19	18	17
J	116	87	70	57	48	43	38	34	32	28	26	24	23	22	20	19
K	138	99	79	64	54	47	43	38	35	31	29	27	26	24	22	21
L	161	111	88	72	61	53	48	42	39	35	32	30	28	26	25	24
M	187	124	97	80	68	58	52	47	43	38	35	32	31	29	27	26
N	213	142	107	87	73	64	57	51	46	40	38	35	33	31	29	28
O	241	160	117	96	80	70	62	55	50	44	40	38	36	34	31	30
Z	257	169	122	100	84	73	64	57	52	46	42	40	37	35	32	31

DIVING SUPERVISOR	STANDBY DIVER	EQUIPMENT USED	LEFT SURFACE	ARRIVED SURFACE	TOTAL TIME UNDER PRESSURE
John	Bloggs	Rat Hat Hot Water Suit	0600	0748	108 mins

	TIME	DEPTH	BOTTOM TIME	TRAVEL TIME	RESIDUAL NITROGEN TIME	TOTAL DECOMPRESSION TIME	REPETITIVE GROUP
LEFT BOTTOM	0617	147'	17	1	-	18	'H'
ARRIVED SECOND WORKING DEPTH	0618	115'			25		'H'
LEFT SECOND WORKING DEPTH	0630	115'	12	1	25	38	'L'
ARRIVED THIRD WORKING DEPTH	0631	86'			53		'L'
LEFT THIRD WORKING DEPTH	0647	86'	16	2:24	53	69	'O'
ARRIVED FOURTH WORKING DEPTH							
LEFT FOURTH WORKING DEPTH							
ARRIVED FIFTH WORKING DEPTH							
LEFT FIFTH WORKING DEPTH							

DECOMPRESSION SCHEDULE

WATER STOPS				CHAMBER STOPS			
	TIME	DEPTH	MINS		TIME	DEPTH	MINS
ARRIVED	0649:24	30'	3	LEFT SURFACE	0656		
LEFT	0652:24	30'		ARRIVED BOTTOM	0657	50'	10
ARRIVED				ON OXYGEN	0700	50'	
LEFT				LEFT	0707	50'	25
ARRIVED				ARRIVED	0708	40'	5
LEFT				OFF OXYGEN	0708	40'	
ARRIVED SURFACE	0653:24	REMARKS		ON OXYGEN	0713	40'	
				LEFT	0738	40'	
				ARRIVED SURFACE	0748		

REVERSE DIVE PROFILES - A THREE PART PERSPECTIVE

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This paper reviews the results of a literature search for the origins of the deepest dive first guideline in diver training. Additionally, it will report on decompression sickness incidence following reverse dive profiles reported for the period of 1991 - 1998. Finally, a controlled study of reverse dive profile data from the multi-day repetitive test of the recreational dive planner conducted by Diving Science and Technology (DSAT) is reviewed.

Part I. Literature Review for the Origins of Deepest-Dive-First Guideline in Diver Training

Introduction

The guideline of making deep dives before shallow dives has been a standard recommendation in recreational diving for well over a decade. While there appears to be anecdotal and practical support for this guideline, its exact origination remains unclear. The authors made a comprehensive, though not exhaustive, search through recreational diving training materials and those individuals influencing recreational diver training dating back to the late 1950s to determine approximately when the guideline appeared. This investigation suggests that the deepest-dive-first guideline appeared in diver training in the early 1970s and became accepted as a standard recommendation by the mid 1980s.

1950s and 1960s

Research turned up <u>no</u> references to the guideline in any diver training manuals earlier than 1972. This was not surprising in the oldest texts (*Dive. The Complete Book of Skin Diving*, Carrier, 1955; *Mask and Flippers*, Barada and Bridges, 1960; *The Science of Skin and Scuba Diving*, CNCA, 1957) because these reference the 1952 U.S. Navy tables; divers calculated repetitive dives by adding all the bottom time from previous dives to the actual bottom time and applying it to the deepest depth of any of the dives. This results in such short no-stop limits or such excessive decompression requirements that repetitive diving probably was not as common. Further, one can speculate that the heavy decompression penalties would to some extent offset difficulties (if such difficulties in fact exist) caused by reverse dive profiles. Therefore, on both counts it's not surprising that the guideline didn't appear in the material of the period.

In 1959, the U.S. Navy published the current tables that introduced surface interval credit for repetitive dive calculation. Early recreational dive literature that embraced the 1959 USN tables also did not reference the deepest-dive-first guideline (*Basic Scuba*, Roberts, 1963; *Diving for Fun*, Strykowski, 1969, 1971; *The New Science of Skin and Scuba Diving*, CNCA, 1962; *The Silent Adventure*, Dixon, 1968; *The Skin Divers Bible*, Lee, 1968). Many of these simply repeat the Navy's table instructions verbatim, and at least one text included a reverse profile in repetitive dive calculation examples (Roberts, 1963, pp. 318-319). It's reasonable to conclude that the deepest-dive-first guideline was not in widespread use, if it existed at all, in sport diving through the 1960s.

1970s

Research finds the first diver training references to the deepest-dive-first guideline in the 1970s, although these are not uniform. The deepest-dive-first guideline did not appear in the *U.S. Navy Diving Manual*, 1970 edition, which even lists (p. 123) a procedure for calculating a repetitive dive to an equal or greater depth than the first dive separated by a short surface interval. This procedure also appears in the 1979 edition (pp. 7-17) of the manual. Similarly, the *NOAA Diving Manual*, 1975 edition, doesn't mention the guideline, but gives a reverse dive profile as an example in its explanation of how to use the Navy tables (pp. 10-11). The 1979 edition of the *NOAA Diving Manual* (pp. 10-12) repeats the procedure for a repetitive dive to an equal or greater depth than the first dive and separated by a short surface interval, as found in the 1970 and 1979 editions of *U.S. Navy Diving Manual*.

The earliest reference the authors found to the guideline appeared in the 1972 PADI *Basic Scuba Course Manual* (p. 122). The manual stated the guideline as a rule: "One very important rule. We always make our deepest dive first when using the dive tables." The manual doesn't explain the reasoning behind the rule, but an explanation appears in *Discover the Underwater World* (Erickson, 1974, pp. 106-107). In the discussion on dive table use, Erickson says: "Another point needs to be made. You outgas according to a differential curve. That is, the more tissue saturation the faster the initial rate of outgassing. It takes about 12 hours to completely free your tissues of residual nitrogen, but the greater the degree of saturation, the faster the desaturation. So if you make two dives, one deep and one shallow, you will saturate your tissues as a function of depth and exposure and accumulate a given amount of gas absorbed into tissue. If you dive deep first you will outgas faster after a dive so when you add the residual nitrogen to the new shallower exposure you get less computed exposure than if you dive shallow first, outgas slower, and still have to add residual nitrogen to the later deeper exposures. That is, do your deep dive first and the likelihood of a decompression problem is reduced." Note that while this states the deep-dive-first principle, it states it more as a recommendation rather than as a rule.

Although these appear to be among the earliest published references in diver training materials, conversations with Ralph Erickson, who was (and still is) president of PADI, confirms that the reverse dive profile guideline did not originate with PADI in 1972. According to Erickson, the references in the *PADI Basic Scuba Course Manual* and *Discover the Underwater World* came from an appropriate source or sources, probably in the undersea medical community or scientific community. Unfortunately, after 25 years he was unable to identify what those sources were. (Erickson, 1999)

After 1971 and throughout the 1970s, references to the guideline become more common in sport diving literature (though it's not found in all scuba texts). John Cramer (1975) stated on p. 128 "Repetitive dives should be planned so that the deepest dive is first and each successive dive is to a lesser depth. This provides for the dissipation of nitrogen and may reduce the need for decompression stops, especially when the surface interval is kept to a maximum."

In reference to planning repetitive dives, Chris Dueker, (1978) on p. 110 says, "Generally it saves time to take the deeper of two dives first." He follows this with an example of two dives, one to 90 fsw and the other to 60 fsw, and how making the 60 ft dive first affects the allowable dive time. In this case, the author supports the guideline on a pragmatic, dive-time basis, not a decompression-risk basis.

Amid the recreational diving literature search, the authors also observed that in *Decompression in Depth: The Proceedings of the Seminar* (PADI, 1979) there's no reference to the deep-dive-first guideline in the published decompression-related proceedings presented by several authors. However, while not stated, all illustrations of table use adhere to the guideline, except for a "contingency" plan example.

1980s and 1990s

By the mid-1980s the recreational training literature clearly presents the deepest-dive-first guideline as a standard operating procedure. The 1984 edition of the PADI *Diver Manual* (p. 119) says "Plan repetitive dives so each successive dive is to a lesser depth. This aids in nitrogen elimination and decreases the need for decompression." The 1984 edition of the PADI *Advanced Diver Manual* (p. 198) also reminds divers to plan their deepest dive first. The 1988 edition of the PADI *Open Water Diver Manual*

(p. 198) asserted more strongly, "Plan repetitive dives so each successive dive is to a shallower depth. Never follow a dive with a deeper dive. Always plan your deepest dive first."

By 1990, the guideline appears regularly in diver literature. Graver says in *Scuba Diving* (1993, p. 179) "Because you absorb nitrogen as pressure increases and it takes time for you to eliminate it, you should always make your deepest dive the first dive of the day; then make each successive dive to a progressively shallower depth." Similarly, the 1999 edition of the PADI *Open Water Diver Manual* (p. 204) states, "Plan repetitive dives so each successive dive is to a shallower depth. The dive medical community recommends that you avoid following a dive with a deeper dive, because this type of 'reverse profile' has a higher incidence of decompression illness. Always plan your deepest dive first."

Discussion

Based on this research, it appears clear that the deepest-dive-first guideline was not widely known or practiced prior to the early 1970s. At that time, it made its way into diving, probably originating with someone or an entity based on the Haldanean model, and reinforced by the pragmatic benefits of planning a deep dive first with respect to residual nitrogen penalty. No references were found that asserted the need for the guideline based on actual DCS incidence or a proven risk. Based on literature of the period, it seems that the guideline did not originate with the U.S. Navy, or that if it did, it wasn't deemed consequential enough to include in the *U.S. Navy Diving Manual*, even as late as the 1979 edition.

By 1980, the guideline seems to have become well-established, and considered a standard recommended practice by the late 1980s to the present.

Part II. Reported DCS in Divers Performing Reverse Dive Profiles for the Period of 1991 - 1998

Introduction

A search of all reported incidents of decompression sickness (DCS) filed with the Professional Association of Diving Instructors (PADI) between 1991 and 1998 was conducted. A total of 936 decompression sickness incidents reported during this period were reviewed for reverse profile diving patterns.

Of the 936, 51 DCS cases were found where the divers reported performing a reverse dive profile in a repetitive dive sequence, for an overall incidence of .0545 (see Table 1).

Table 1. Total Number and Incidence of Reverse Dive Profiles Involving DCS

Year	Total Reported DCS	Reported DCS with Reverse Dive Profiles	Incidence of Reverse Profile DCS by Year
1991	67	0	0
1992	79	9	.11
1993	117	4	.034
1994	127	8	.063
1995	131	7	.053
1996	119	9	.076
1997	164	6	.036
1998	32	8	.060
Total:	936	51	.0545

Procedures

PADI Members are advised to complete and file incident report forms any time they witness or are involved in a dive incident of any nature. As a result, PADI receives incident reports for events occurring during pleasure diving, working dives, training dives and supervisory dives.

The researchers found that 936 cases of DCS were reported by PADI Members to PADI for the period of 1991 - 1998, worldwide. Next, the researchers examined the profiles of these incident reports and selected repetitive dive series that involved reverse dive profiles.

For the purposes of this research, a reverse dive profile was defined as "conducting a deeper dive that was preceded by a shallower dive in any repetitive dive series." A total of 51 incident reports met this definition. These 51 cases were analyzed and tabulated in Table 2.

Table 2. PADI Reports of DCS with Reverse Dive Profile Patterns

Case #	M/F	Age	Symptoms	Profile	Other Info	Year
1	F	41	Numbness, visual disturbance	Day 1: 88' for 44 min. 111' for 45 min. Day 2: 83' for ?? min. 98' for ?? min.	2 days of reverse profile diving. Loss of weight belt on final dive resulted in a rapid and uncontrolled ascent to the surface.	1998
2	F	28	Numbness	21 m for 35 min. 20 m for 35 min. 39 m for 10 min.	3 repetitive dive series	1998
3	F	31	Tingling/ numbness	11 m for 53 min. 23 m for 43 min.	Possible PFO involvement	1998
4	M	42	Pain	64' for 28 min. 75' for 21 min.	Diver performed a rapid ascent from 30 feet to the surface in an attempt to assist buddy.	1998
5	F	33	Pain	64' for 28 min. 76' for 21 min.	Diver confused LPI with deflator button, resulting in a rapid ascent from 30 feet to the surface.	1998
6	F	54	Tingling	60' for ?? min. 70' for ?? min.	—	1998
7	M	Unk.	Pain	94' for 22 min. 102' for 16 min.	—	1998
8	F	43	Skin itching	84' for 44 min. 50' for 47 min. 75' for 47 min. 89' for 43 min.	4 repetitive dive series	1998
9	M	31	Pain	15' for 19 min. 39' for 21 min.	Diver flew to 900 feet in an unpressurized plane post diving	1997
10	M	60	Numbness, vestibular disturbance	67' for 50 min. 76' for 51 min. 73' for 60 min.	3 repetitive dive series	1997
11	F	Unk.	Tingling/ numbness	39' for 42 min. 52' for 47 min.	4000' altitude dive	1997
12	M	26	Pain	35' for 10 min. 50' for 20 min.	Diver experienced a rapid and uncontrolled ascent from 25 feet to the surface	1997

13	M	44	Numbness, swelling, skin rash	48' for 55 min. 42' for 44 min. 96' for 46 min.	3 repetitive dive series in multi-day dive series	1997
14	F	34	Tingling	28' for 30 min. 22' for 48 min. 38' for 33 min.	3 dive repetitive series	1997
15	M	Unk.	Suspected DCS	16 m for 54 min. 15 m for 47 min. 21 m for 45 min.	3 repetitive dive series	1996
16	M	25	Dizziness, tingling	50' for 50 min. 60' for 33 min.	—	
17	M	37	Pain/rash	43' for 24 min. 44' for 24 min. 65' for 21 min.	3 repetitive dive series	1996
18	M	34	Pain	43' for 24 min. 44' for 24 min. 65' for 21 min.	3 repetitive dive series	1996
19	F	24	Pain/numbness	57' for 42 min. 86' for 29 min. 18' for 34 min. 18' for 34 min. 96' for 17 min. 81' for 17 min. 66' for 30 min.	Multi-day dive series 7 repetitive dives	1996
20	M	44	Pain/tingling	Day 1: 114' for 31 min. 120' for 35 min. 105' for 39 min. 80' for 27 min. Day 2: 148' for 35 min. 118' for 35 min. 96' for 50 min. 106' for 38 min.	Live aboard, multi-day repetitive dive series	1995
21	M	21	Pain/tingling	12 m for 45 min. 25 m for 45 min.	Dehydration	1996
22	M	Unk.	Tingling	150'+ for 45 - 60 min.? 200'+ for 45 - 60 min.?	Depth and bottom time unknown	1995
23	M	39	Pain	88' for 48 min. 105' for 48 min. 82' for 65 min.	3 repetitive dive series	1995
24	F	29	Pain	62' for 29 min. 56' for 44 min. 57' for 49 min. 103' for 36 min.	4 repetitive dive series	

25	M	46	Numbness	Day 1: 94' for 54 min. 114' for 54 min. Day 2: 109' for 71 min. 128' for 42 min. 116' for 45 min. 109' for 34 min.	Multi-day repetitive dive series, 4 repetitive dives	1995
26	F	58	Numbness	54' for 51 min. 68' for 45 min. 35 for ? min.	Diver took: Triptone, Advil and Imodium all within 1 hour of dive Dehydration, severe sea sickness	1995
27	M	39	Tingling	48' for 59 min. 60' for 57 min. 55' for 45 min.	3 repetitive dive series	1995
28	F	39	Tingling	69' for 51 min. 73' for 38 min. 73' for 34 min.	Untreated DCS symptoms experienced 2 months previous to dive profile 3 repetitive dive series	1995
29	M	17	Pain	80' for 25 min. 50' for 40 min. 73' for 39 min.	3 repetitive dives series	1995
30	F	44	Pain/tingling	59' for 43 min. 65' for 50 min.	—	1995
31	F	25	Tingling	Day 1: 22' for 33 min. 45' for 32 min. Day 2: 51' for 32 min. 56' for 35 min.	—	1994
32	M	39	Pain	Day 1: 35 m for 43 min. 31 m for 45 min. 39 m for 42 min. 30 m for 52 min. Day 2: 35 m for 53 min. 36 m for 55 min. 18 m for 52 min. 26 m for 40 min.	Multi-day repetitive dive series, 4 repetitive dives series	1994
33	F	25	Tingling	29' for 39 min. 56' for 30 min. 50' for 20 min.	Long surface swim, 3 repetitive dive series	1994
34	M	32	Pain	46' for 35 min. 58' for 35 min.	5-day delay in reporting symptoms	1994
35	F	Unk.	Numbness	12m for 24 min. 21m for 24 min. 10m for 8 min.	Diver blacked-out underwater, 3 repetitive dive series	1994

36	M	40	Numbness	Day 1: 130' for 30 min. 65' for 41 min. 63' for 44 min. Day 2: 103' for 38 min. 81' for 43 min. 80' for 41 min.	2 weeks of repetitive dives preceded DCS, multi-day repetitive dive series	1993
37	M	Unk.	Great pain	160' for ? min. 200'+ for ? min.	Excessive depth and unknown bottom time	1993
38	M	Unk.	Great pain	160' for ? min. 200'+ for ? min.	Excessive depth and unknown bottom time	1993
39	M	20+	Pain	50' for 37 min. 60' for 33 min.	—	
40	F	44	Pain	45' for 47 min. 50' for 58 min. 43' for 55 min.	multi-day dive series, 3 repetitive dive series	1993
41	F	25	Tingling, dizziness	20' for 44 min. 50' for 5 min. 80' for 15 min. 50' for 7 min.	4 repetitive dives	1993
42	M	16	Dizziness, nausea	60' for 40 min. 100' for 23 min. 60' for 40 min. 70' for 47 min.	4 repetitive dive series	1992
43	M	54	None treated	32m for 37 min. 43m for 45 min.	Decompression profile	1992
44	F	36	Numbness, vision disturbed	23m for 53 min. 30m for 50 min. 25m for 48 min.	3 repetitive dive series	
45	M	30	Numbness, nausea	90' for 21 min. 12' for 40 min. 102' for 23 min.	3 repetitive dive series	1992
46	F	Unk.	Tingling	133' for 54 min. 22' for 64 min. 87' for 57 min.	3 repetitive dive series	1992
47	M	42	Blurred vision, pain	5 weeks previous: 100' for 25 min. 70' for 30 min. 70' for 30 min. 100' for 25 min.	Diver ignored previous DCS symptoms from dive series 5 weeks previous to 4 repetitive dive series	1992
48	F	48	Pain	59' for 30 min. 62' for 39 min. 54' for 35 min. 61' for 27 min.	4 repetitive dive series	1992
49	F	20	Tingling	20' for 35 min. 60' for 39 min.	—	1992

50	F	43	DCS	12 dives over 5 days Day 1: 91' for 31 min. 80' for 75 min. Day 2: 112' for 26 min. 90' for 36 min. 80' for 40 min. 60' for 36 min. Day 3: 45' for 55 min. 50' for 50 min. 50' for 42 min. Day 4: 42' for 50 min. 52' for 49 min. Day 5: 108' for 30 min.	Multi-day, multi-dive repetitive dive series, 12 dives spanning 5 days	1991
51	M	25	Tingling	90' for 20 min. 60' for 30 min. 50' for 30 min. 60' for 35 min.	Out of air, emergency ascent from 70 feet, 4 repetitive dive series	1991

Discussion

Divers used dive computers to monitor dives in 34 of the 51 reported cases (66.6%). From the data collected, it is difficult to conclude what, if any, contribution reverse dive profile patterns had or did not have on divers suffering decompression sickness.

In some cases, other factors may have had a more direct causal relationship with DCS. For example, uncontrolled, rapid ascent to the surface occurred in five cases (Case # 1, 2, 5, 13 and 51). Excessive depth and unknown bottom time occurred in three cases (Case # 22, 37 and 38). In two cases, the diver dived with previously unreported DCS symptoms prior to the reverse dive profile pattern (Case # 28 and 47). In two cases, the diver reported dehydration and/or severe seasickness (Case # 21 and 26). In one case, the diver reportedly blacked out underwater (Case # 35). In two cases, altitude or flying after diving was reported (Case # 9 and 11). And, in 32 cases, three or more repetitive dives were reported (5 were in combination with other factors, 27 were discreet). In total, 42 cases were reported (Table 3) with other relevant factors in addition to reverse dive profiles for an incidence of .823.

Conclusions

The data do not conclusively support the premise that reverse dive profile patterns are a causative factor in the DCS in these individuals. Too many factors in these cases, acting in isolation or combination, may be involved. Nor do the data indicate a DCS incidence in divers conducting reverse dive profiles that appears disproportionately high. In the cases reviewed by the researchers, 5.45% of the total DCS reported for the period of 1991 - 1998 had reverse dive profile pattern characteristics.

Table 3. Relevant Factors in Reported Cases of DCS for Reverse Profiles

Additional Relevant Factors	Number	Incidence
Uncontrolled/rapid ascent to surface	5	.098
Excessive depth/unknown duration	3	.058
Dive with untreated symptoms	2	.039
Dehydration/severe seasickness	2	.039
Blackout underwater	1	.019
Attitude or flying after diving	2	.039
3 or more repetitive dives	32*	.627
Total:	42*	.823*

*Of the thirty-two cases, five occurred in combination with other relevant factors. Twenty-seven multiple repetitive dive cases were discreet to themselves without any other relevant factors. Therefore, a total of forty-two cases occurred with other relevant factors for an incidence of .823 (42/51 total).

Part III. Reverse Profile Data from the Multiday Repetitive Tests of the Recreational Dive Planner

Determining whether reverse dive profiles are, or are not, associated with increased DCS risk requires objective empirical human testing data. While such data appear relatively scarce, PADI, Diving Science & Technology (DSAT) and the Institute of Applied Physiology and Medicine (IAPM) contributed in a small way during the Phase II multiday, repetitive diving trials for the Recreational Dive Planner (Hamilton *et al.*, 1994).

The original Phase II program (now referred to as Phase IIa) called for six dives daily for six days to simulate aggressive liveaboard boat repetitive diving. The test began with four subjects, but terminated as required by the study protocols after two days and a single dive on the third after one subject experienced Type I DCS in his right knee. The subject who experienced DCS didn't make the single dive on the third day, and subsequent inquiry revealed that the subject had sustained bilateral knee injury previously in a motorcycle accident (Hamilton *et al.*, 1994).

Beyond the aggressive dive exposure and multilevel profiles, the IIa study included significant reverse dive profiles during the two days before the DCS event. Exposures also went slightly beyond those permitted by the Recreational Dive Planner:

Day One

Dive	fsw/mins	Surface Interval
1	95/22	1:00
2	65/30	1:03
3	45/61	2:10
4	55/54	1:00
5	90/10 — 60/9 — 35/57	1:35
6	120/6 — 80/8 — 50/17 — 35/42	

Day Two

Dive	fsw/mins	Surface Interval
1	60/55	1:16
2	45/65	2:10
3	85/20 — 45/26	1:00
4	75/16 — 40/34	1:00
5	80/12 — 40/34	1:27
6	110/7 — 65/10 — 50/11 — 40/19	

Day Three

Dive	fsw/mins	Surface Interval
1	110/16	Testing Terminated

Phase IIa resulted in 51 human compressions. Doppler monitoring found detectable bubbles in 24.6% of the test runs, with higher than Grade 1 in 16.2% of the runs. Interestingly, subject who experienced the DCS incident had the lowest overall Doppler detectable bubbles (10.3% of total), whereas one subject accounted for 62.1% of detected bubbles and experienced no DCS symptoms (Hamilton *et al.*, 1994)

Discussion

The Phase IIa tests clearly included significant reverse dive profiles, but it's not possible to clearly attribute the DCS incident to this factor. The subject's injury history, the aggressive number of dives and a design that slightly exceeded Recreational Dive Planner limits (apparently to assure the model was rigorously tested) can all be reasonably considered contributing factors. Furthermore, the remaining three subjects had no DCS symptoms, even after completing an additional dive beyond those completed by the subject who experienced DCS.

Phase IIa ended inconclusively due to the small data set collected. It might, to some extent, hint that reverse dive profiles are a DCS risk factor, but with the limited data and other contributing factors it would appear unreasonable to draw any firm conclusions.

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NAUI APPROACH TO REVERSE DIVE PROFILES

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NAUI Training adopts a conservative view on reverse dive profiles, contraindicated over many hour time intervals. Within the NAUI Tables (U.S. Navy Tables with reduced NDLs), implications of this approach are discussed and quantified. NAUI Training has an admirable record of diving safety and surety, and statistics underscore this fact.

Introduction

Specifically, we first describe the model and framework for diving tables, discuss the NAUI multi-level modifications to the standard U.S. Navy Tables, briefly analyze reverse dive profiles within the NAUI Tables while discussing ramifications of the modifications, and then report some NAUI statistics. A self-consistent method used to link critical tensions, no-stop time limits, and tissue halftimes is recounted in the Appendix.

Table Model and Protocols

Historically, Tables use the Haldane approach, based on dissolved gases, and the NAUI Tables employ the U.S. Navy representation as the starting point. Exchange of inert gas, controlled by blood flow across regions of varying concentration, is driven by the local gradient, that is, the difference between the arterial blood tension, p_a, and the instantaneous tissue tension, p. Such behavior is modeled in time, t, by simple classes of exponential response functions, bounded by p_a, and the initial value of p, denoted p_i. These multi-tissue functions satisfy a differential perfusion rate equation,

$$\frac{\partial p}{\partial t} = -\lambda(p - p_a) \tag{1}$$

and take the form, tracking both dissolved gas buildup and elimination symmetrically,

$$p - p_a = (p_i - p_a)\ exp\ (-\lambda\ t) \tag{2}$$

$$\lambda = \frac{.693}{\tau} \tag{3}$$

with perfusion constant, λ, defined by the tissue halftime, τ. Compartments with 5, 10, 20, 40, 80, 120-minute halftimes, τ, are employed, and halftimes are independent of pressure.

In a series of dives or multiple stages, p_i and p_a represent extremes for each stage, or more precisely, the initial tension and the arterial tension at the beginning of the next stage. Stages are treated sequentially, with finishing tensions at one step representing initial tensions for the next step, and so on.

To maximize the rate of uptake or elimination of dissolved gases the *gradient*, simply the difference between p_I and p_a, is maximized by pulling the diver as close to the surface as possible. Exposures are limited by requiring that the tissue tensions never exceed M, written,

$$M = M_0 + \Delta M\, d \tag{4}$$

as a function of depth, d, for ΔM the change per unit depth. In absolute units, the corresponding critical gradient, G, is given by,

$$G = \frac{M}{.79} - P \tag{5}$$

with P ambient pressure, and M critical nitrogen pressure. Similarly, the critical ratio, R, takes the form,

$$R = \frac{M}{P} \tag{6}$$

The U.S. Navy set of critical tensions, M_0, and, ΔM, are given by,

$$M_0 = 104,\ 88,\ 72,\ 58,\ 52,\ 51\ fsw \tag{7}$$

$$\Delta M = 2.27,\ 2.01,\ 1.67,\ 1.34,\ 1.26,\ 1.19 \tag{8}$$

for τ = 5, 10, 20, 40, 80, and 120 min. The NAUI set is reduced as described in the next section, consistent with reduced no-stop time limits and multi-level diving considerations.

At altitude, some critical tensions have been correlated with actual testing, in which case, the depth, d, is defined in terms of the absolute pressure,

$$d = P - 33 \tag{9}$$

with absolute pressure, P, at altitude, z, given by (fsw),

$$P = 33\ exp\ (-0.0381z) = 33\ \alpha^{-1} \tag{10}$$

$$\alpha = exp\ (0.0381z) \tag{11}$$

and z in multiples of 1000 ft. However, in those cases where the critical tensions have not been tested nor extended to altitude, an exponentially decreasing extrapolation scheme, called *similarity*, has been employed. Extrapolations of critical tensions, below P = 33 fsw, then fall off more rapidly in the linear case. The similarity extrapolation holds the ratio, $R = M/P$, constant at altitude. Denoting an equivalent sea level depth, δ, at altitude, z, one has for an excursion to depth d,

$$\frac{M(d)}{d + 33\alpha^{-1}} = \frac{M(\delta)}{\delta + 33} \tag{12}$$

so that the equality is satisfied when,

$$\delta = \alpha d \tag{13}$$

$$M(\delta) = \alpha M(d). \tag{14}$$

The similarity extrapolation is limited to 10,000 ft elevation, and neither for decompression nor heavy repetitive diving.

Operational diving requires arbitrary numbers of dives to various depths over periods of hours, and often days. Once a standard set of decompression tables has been constructed, with bounce diving the simple case of no-stop decompression, a repetitive dive procedure is a necessity. After any air dive, variable amounts of dissolved and free residual nitrogen remain in body tissues for periods of 24 hr, and more. Similarly, elevated tissue tensions can promote, or sustain, bubble growth over the same time scales. This residual gas buildup (dissolved and free) will shorten the exposure time for subsequent repetitive dives. The longer and deeper the first dive, the greater the amount of residual tissue nitrogen affecting decompression on subsequent dives. No-stop depth-time allowances for repetitive dives are reduced in such circumstances. Within bubble models, residual free gas phases are also included in procedures, imposing additional constraints on repetitive diving. The many possibilities are easily tracked in continuous time mode by computers, as mentioned, but tables face a more difficult task.

Considering only dissolved gases, one standard table approach, developed by Workman, groups combinations of depth and exposure times according to the surfacing tension in the slowest compartment. Then it is possible to account for desaturation during any arbitrary surface interval. The remaining excess nitrogen at the start of the next dive can always be converted into equivalent time spent at the deepest point of the dive. So called penalty time is then added to actual dive time to updated appropriate tissue tensions. Surfacing tensions in excess of 33 fsw (absolute) in the slowest compartment are assigned letter designations (groups), A to O, for each 2 fsw over 33 fsw. Any, and all, exposures can be treated in this manner. To credit outgassing, a Surface Interval Table, accounting for 2 fsw incremental drops in tensions in the slowest compartment, is also constructed. Such procedures are bases for the U.S. Navy Air Decompression and Repetitive Surface Interval Tables, with the 120-min compartment (the slowest) controlling repetitive activity.

Standard U.S. Navy Tables provide safe procedures for dives up to 190 fsw for 60 min. Dives between 200 and 300 fsw were tested and reported in the exceptional exposure U.S. Navy Tables, including a 240 min compartment. The Swiss Tables, compiled by Bühlmann, incorporate the same basic procedures, but with a notable exception. While the U.S. Navy Tables were constructed for sea level usage, requiring some safe extrapolation procedure to altitude, the Swiss Tables are formulated and tested over a range of reduced ambient pressure. The controlling repetitive tissue in the Bühlmann compilation is the 635 min compartment. Similar approaches focusing on deep and saturation diving have resulted in decompression tables for helium-oxygen (heliox), helium-oxygen-nitrogen (trimix), and recent mixtures with some hydrogen (hydrox). Clearly, the U.S. Navy and Swiss Repetitive Tables can be easily converted to other (longer or shorter) controlling tissues by arithmetic scaling of the 120-min or 635-min compartment to the desired controlling tissue halftime (simple ratio). To scale the U.S. Navy Tables to 720 min, for instance, repetitive intervals need only be multiplied by $720/120 = 6$.

While it is true that the table procedures just described are quite easily encoded in digital dive computers, and indeed such devices exist, dive computers are capable of much more than table recitations. Pulsing depth and pressure at short intervals, dive computers can monitor diving almost continuously, providing rapid estimates of any model parameter. When employing the exact same algorithms as tables, computers provide additional means to control and safety beyond table lookup. When model equations can be inverted in time, computers can easily compute time remaining before decompression, time at a stop, surface interval before flying, and optimal ascent procedure. Profiles can be stored for later analysis, and the resulting database used to tune and improve models and procedures.

Considering utility, functionality, and cost these days, rote dive computer usage is increasing in diving, supported by technological advances in computing power, algorithmic sophistication, and general acceptance, though it will probably be some time though before tables are supplanted. In any case, NAUI Instructors are (still) required to teach the use of dive tables, particularly the NAUI Tables.

NAUI Tables

The U.S. Navy Tables, sketched above, are famous, but the NAUI modifications based on consideration of multi-level activity (ascending or descending profiles) need further explanation. For reference and comparison, a set of NAUI (modified) U.S. Navy Tables is given in Figure 1, exhibiting reduced no-stop time limits, consistent with present safety margins associated with lower Doppler scores (Spencer reduction). But there is much more to the NAUI modification of the basic U.S. Navy Tables, based on multi-level considerations. And that modification, coupled to recommended 1 hr surface intervals (SI) for repetitive diving, also impacts reverse dive profiles favorably, as will be shown.

WARNING EVEN STRICT COMPLIANCE WITH THESE TABLES WILL NOT GUARANTEE AVOIDANCE OF DECOMPRESSION SICKNESS CONSERVATIVE USAGE IS STRONGLY RECOMMENDED

RNT RESIDUAL NITROGEN TIME
\+ ADT ACTUAL DIVE TIME
TNT TOTAL NITROGEN TIME

(USE THIS FIGURE TO DETERMINE END-OF-DIVE LETTER GROUP)

TABLE 1 - END-OF-DIVE LETTER GROUP

(00) MAXIMUM DRIVE TIME (MDT)
00 / 00 DIVE TIME REQUIRING DECOMPRESSION / NO MINUTES REQUIRED AT 15 STOP (5M)

START DEPTH M	FEET	A	B	C	D	E	F	G	H	I	J	K	L
12	40	5	15	25	30	40	50	70	80	100	110	(130)	150 / 5
15	50		10	15	25	30	40	50	60	70	(80)		100 / 5
18	60		10	15	20	25	30	40	50	(55)	60 / 5		80 / 7
21	70		5	10	15	20	30	35	40	(45)	50 / 5	60 / 8	70 / 14
24	80		5	10	15	20	25	30	(35)	40 / 5		50 / 10	60 / 17
27	90		5	10	12	15	20	(25)	30 / 5		40 / 7		50 / 18
30	100		5	7	10	15	20	(22)	25 / 5			40 / 15	
33	110			5	10	13	(15)	20 / 5			30 / 7		
36	120			5	10	(12)	15 / 5			25 / 6	30 / 14		
39	130			5	(8)	10 / 5					25 / 10		

NEW GROUP	A	B	C	D	E	F	G	H	I	J	K	L
A	24:00 / 0:10	24:00 / 3:21	24:00 / 4:49	24:00 / 5:49	24:00 / 6:35	24:00 / 7:06	24:00 / 7:36	24:00 / 8:00	24:00 / 8:22	24:00 / 8:51	24:00 / 8:59	24:00 / 9:13
B		3:20 / 0:10	4:48 / 1:40	5:48 / 2:39	6:34 / 3:25	7:05 / 3:38	7:35 / 4:26	7:59 / 4:50	8:21 / 5:13	8:50 / 5:41	8:58 / 5:49	9:12 / 6:03
C			1:39 / 0:10	2:38 / 1:10	3:24 / 1:58	3:57 / 2:29	4:25 / 2:59	4:49 / 3:21	5:12 / 3:44	5:40 / 4:03	5:48 / 4:20	6:02 / 4:36
D				1:09 / 0:10	1:57 / 0:55	2:28 / 1:30	2:58 / 2:00	3:20 / 2:24	3:43 / 2:45	4:02 / 3:05	4:19 / 3:22	4:35 / 3:37
E					0:54 / 0:10	1:29 / 0:46	1:59 / 1:16	2:23 / 1:42	2:44 / 2:03	3:04 / 2:21	3:21 / 2:39	3:36 / 2:54
F						0:45 / 0:10	1:15 / 0:41	1:41 / 1:07	2:02 / 1:30	2:20 / 1:48	2:38 / 2:04	2:53 / 2:20
G							0:40 / 0:10	1:06 / 0:37	1:29 / 1:00	1:47 / 1:20	2:03 / 1:36	2:19 / 1:50
H								0:36 / 0:10	0:59 / 0:34	1:19 / 0:55	1:35 / 1:12	1:49 / 1:26
I									0:33 / 0:10	0:54 / 0:32	1:11 / 0:50	1:25 / 1:05
J										0:31 / 0:10	0:49 / 0:29	1:04 / 0:40
K											0:28 / 0:10	0:45 / 0:27
L												0:26 / 0:10

TABLE 2 - SURFACE INTERVAL TIME (SIT) TABLE

M / FT.	12 / 40	15 / 50	18 / 60	21 / 70	24 / 80	27 / 90	30 / 100	33 / 110	36 / 120	39 / 130	NEW GROUP
	7 / 123	6 / 74	5 / 50	4 / 41	4 / 31	3 / 22	3 / 19	3 / 12	3 / 9	3 / 5	A
	17 / 113	13 / 67	11 / 44	9 / 36	8 / 27	7 / 18	7 / 15	6 / 9	6 / 6	6	B
	25 / 105	21 / 59	17 / 38	15 / 30	13 / 22	11 / 14	10 / 12	10 / 5	9	8	C
	37 / 93	29 / 51	24 / 31	20 / 25	18 / 17	16 / 9	14 / 8	13	12	11	D
	49 / 81	38 / 42	30 / 25	26 / 19	23 / 12	20 / 5	18 / 4	16	15	13	E
	61 / 69	47 / 33	36 / 19	31 / 14	28 / 7	24	22	20	18	16	F
	73 / 57	56 / 24	44 / 11	37 / 8	32	29	26	24	21	19	G
	87 / 43	66 / 14	52	43	38	33	30	27	25	22	H
	101 / 29	76 / 4	61	50	43	38	34	31	28	25	I
	116 / 14	87	70	57	48	43	38	AVOID REPETITIVE DIVES OVER 100 FEET			J
	138	99	79	64	54	47					K
	161	111	88	72	61	53					L

TABLE 3 - REPETITIVE DIVE TIME TABLE

00 / 00: TOP NUMBERS ARE RESIDUAL NITROGEN TIMES. RNT
BOTTOM NUMBERS ARE ADJUSTED MAXIMUM DIVE TIME

The NAUI Tables are modified U.S. Navy Tables with:

1. reduced NDLs (moved left a group or two compared to the U.S. Navy Tables;
2. suggested ascent rates of 30 fsw/min;
3. multi-level consistency (no critical tensions, M, violated for back-to-back repetitive sequencing, ascending or descending profiles, within a single dive segment);
4. suggested minimum surface intervals of 1 hr between repetitive dives; and,
5. suggested limit of 3 repetitive dives per day.

Figure 1. NAUI Repetitive Diving Tables.

Schemes for multi-level diving are employed in commercial, scientific, and recreational sectors. In addition to validation, questions arise as to method consistency with the formulation of the U.S. Navy Tables on critical tension principles. One approach employs back-to-back repetitive sequencing, assigning groups at the start of each multi-level dive segment based on total bottom time (actual plus residual nitrogen) of the previous segment. Such procedure applies to ascending (deepest segments first) and descending (shallowest segments first) profiles, with reverse dive profiles an extension of the latter case. At times, the method allows critical tensions, other than the controlling (repetitive) 120-minute compartment tension, to be exceeded upon surfacing. In the context of the U.S. Navy Tables, such circumstance can be avoided. So, by tightening the exposure window and accounting for ascent and descent rates, such a multi-level technique can be made consistent with the permissible tension formulation of the U.S. Navy Tables.

To adequately evaluate multi-level diving within any set of tables, it is necessary to account for ascent and descent rates. While ascent and descent rates have small effects on ingassing and outgassing in slow-tissue compartments, they considerably impact fast-tissue compartments. Model impact is measured in nitrogen buildup and elimination in hypothetical compartments, whose halftimes denote time to double, or half, the existing levels of nitrogen. Buildup and elimination of nitrogen is computed with Haldane tissue equations (exponential rate expressions), and critical tensions, are assigned to each compartment to control diving activity and exposure time. In multi-level diving, computed tissue tensions in any and all compartments must be maintained below their critical values. This is a more stringent constraint than just flooring the 120-minute compartment tension, the approach used in the U.S. Navy Tables for repetitive diving.

In the context of the U.S. Navy Tables, from which many tables with reduced no-stop time limits derive, six compartments with 5 ,10, 20, 40, 80, and 120-minute halftimes limit diving through maximum tensions (M -values) of 104, 88, 72, 58, 52, and 51 fsw, respectively. The 5 and 10-minute compartments are fast, the 80 and 120-minute compartments are slow, and the others are often between, depending on exposure profile. Dive exposure times, depths, ascent and descent rates, affecting slow and fast compartments in a complicated manner, are virtually infinite in number, thus suggesting the need for both a supercomputer and meaningful representation of the results. A SGI Origin 2000 supercomputer addressed the first concern, while the U.S. Navy Tables provided a simple vehicle for representation of results.

Calculations were performed in roughly 1-minute time intervals, and 10 fsw depth increments for all possible multi-level dives up to, and including, the standard U.S. Navy no-stop time limits, and down to a maximum depth of 130 fsw. Ascent and descent rates of 30 fsw/min were employed. Tissue tensions in all six compartments were computed and compared against their M -values. Dives for which the M -values were not violated were stored until the end of the multi-level calculations, for further processing. Dives violating any M -value, at any point in the simulation, were terminated, and the next dive sequence was initiated. The extremes in times for permissible multi-level dives form the envelope of calculations at each depth. The envelope turns out to be very close to the NAUI no-stop limits for the U.S. Navy Tables, that is, the NAUI Tables shown in Figure 1. Within a minute, on the conservative side, the envelope tracks the reduced no-stop limits. Approximately 16 million multi-level dives were analyzed on a SGI Origin 2000 in about 8 minutes CPU time, including construction of the envelope, with 10 fsw and 1-minute resolution. The SGI Origin 2000 has raw speed near 400 megaflops per CPU.

Adjunct to Figure 1, one can summarize with regard to Origin 2000 calculations:

1. ascent and descent rates are 30 fsw/min;
2. the deeper the initial depth, the shorter the total multi-level dive time;
3. maximum permissible multi-level dive times (total) vary between 100 and 60 minutes, depending on initial depths;
4. miminum permissible multi-level increments vary from 30 fsw to 10 fsw as the depth decreases from 130 fsw to 40 fsw;
5. multi-level U.S. Navy Table dives falling within the envelope never exceed critical values, below or at the surface, in all compartments; and,
6. the multi-level envelope is the set of reduced no-stop limits.

For the modified Tables (Figure 1), multi-level dives that stay to the left of the no-stop time limits never violate critical tensions, and are (hypothetically) sanctioned. Dive computers, of course, perform the same exercise underwater, comparing instantaneous values of computed tissue tensions in all compartments, throughout the duration of the dive, against stored M-values to estimate time remaining and time at a stop.

The set of NAUI NDLs corresponds to a reduced set of critical tensions, M_0, ΔM, given by,

$$M_0 = 102, 86, 70, 57, 51, 50 \text{ fsw} \tag{15}$$

$$\Delta M = 2.27, 2.01, 1.67, 1.34, 1.26, 1.19 \tag{16}$$

in round numbers for the same set of tissue halftimes, τ. With risk analysis performed by U.S. Navy investigators, the relative probability, p, of DCI in (always) diving to the NAUI NDLs limits is bounded by,

$$1\% < p < 5\% \tag{17}$$

yet remembering that divers rarely dive to any Table limits. Interpolating between bounding NDLs, the estimated incidence rate, p, is

$$p \approx 2.5\% \tag{18}$$

at the limit point of diving to NAUI NDLs. Simple difference weighting between bounding NDLs and NAUI NDLs was invoked for the estimate.

Reverse Dive Profiles

Consider the scripted reverse dive profiles within the NAUI Table framework. In a rather simple sense, these reverse dive profiles represent multi-level diving with non-zero surface intervals, at least when only dissolved gases are tracked. However, with bubble growth under decompression fueled by high tissue tensions, such extensions and analogies probably break down.

Table 1. NAUI Tables and Reverse Dive Profiles

Algorithm	Dive 1 (fsw/min)	Deco 1 (fsw/min)	Surface Interval (min)	Dive 2 (fsw/min)	Deco 2 (fsw/min)
NAUI Tables	100/15	none	30	60/30	15/5
	60/30	none		100/15	15/15
	100/15	none	60	60/30	none
	60/30	none		100/15	15/15
	100/15	none	120	60/30	none
	60/30	none		100/15	15/5
	100/15	none	240	60/30	none
	60/30	none		100/15	none

Clearly, the step nature of table decompression formats is evident in Table 1. The decompression stops at 15 fsw do not smoothly decrease in time as surface interval time increases. NAUI, of course, requires all training to be no-stop diving, so such profiles would not occur routinely.

NAUI Training Statistics

In the 10 years since NAUI introduced these Tables, nearly 1,000,000 divers were certified at an entry level. This represents some 5,000,000 actual dives, mainly performed above 60 fsw, with surface intervals beyond 60 min, and no more than 2 dives per day. Reverse profiles are contraindicated, and training regimens also mandate minimum 60-min surface intervals, depth floors at 60 fsw, and less than 3 dives per day. To build diver confidence, much activity occurs at depths in the 20 – 30-fsw range. All recreational NAUI diving is limited to 130 fsw, as are the NAUI Tables.

Accident in the reports gathered by NAUI average 50 incidents per year (required for insurance and liability coverage). Of these 50 reports, only 5, on average, relate to DCI afflictions. This suggests an incidence rate, p, on the order of 1×10^{-5}, certainly a very low annual rate.

Possible reverse dive profiles probably range 30 - 40 fsw as far as depth increment, Δd, in training maneuvers. This is small, as are actual training depths. Based on low DCI incidence rate, NAUI Table conservatism, small reverse dive profiles increment, and shallow staging depths, reverse dive profiles appear to have not been a major problem for NAUI Training Operations. But as reverse dive profiles depths and increments increase, the situation becomes less clear and probably much riskier (Wienke and O'Leary, 2000).

Appendix: Consistent Halftimes, No-stop Limits, and Critical Tensions

For Haldane computational algorithms, the process of constructing closed sets of time limits, tissue halftimes, and limiting tensions becomes an important activity. We detail a method for this closure, applying the approach to some exposure relationships. The approach maximizes the tissue perfusion equation, subject to a depth-time law (theoretical, fitted, inferred, or otherwise) at the exposure time limit, coupling exposure limits, halftimes, depths, and maximum tensions in the process.

Dissolved gas models limit tissue supersaturation, assuming that gas exchange is controlled by perfusion or diffusion in blood-tissue media. A perfusion equation quantifies bulk gas transfer,

$$\frac{\partial(p - p_a)}{\partial t} = -\lambda(p - p_a), \tag{19}$$

with the exchange of inert gas driven by the local gradient, that is, the difference between arterial blood, p_a, and local tissue tension, p. Obviously the exchange process is very complicated, and models are only approximate. The solutions are well known, simple classes of exponential functions, bounded by arterial and initial tissue tensions, p_a and p_i,

$$(p - p_a) = (p_i - p_a) \exp(-\lambda t), \tag{20}$$

with λ the decay rate, defined in terms of the halftime, τ,

$$\lambda = \frac{.693}{\tau} \tag{21}$$

with instantaneous tissue tension, p, in that compartment. Compartments with 2, 5, 10, 20, 40, 80, 120, 240, 360, 480, and 720-minute halftimes, τ, are employed in applications, and halftimes are assumed to be independent of pressure.

Next, algorithms limit degrees of dissolved gas buildup, p, hypothetical absolute compartment supersaturation, by *critical* values, M, such that,

$$p \le M, \tag{22}$$

across all compartments at all times during exposure, and upon surfacing. Equivalently, critical ratios, R, and critical gradients, G, are also employed, with,

$$R = \frac{M}{P}, \tag{23}$$

$$G = M - P, \tag{24}$$

for ambient pressure, P. Critical parameters evolved from self-consistent application of assumed tissue response functions to sets of exposure data, a trial and error bootstrapping of model equations to observed exposure time limits.

In a diffusion framework, no-stop air limits, t_n, roughly satisfy a bulk transfer law,

$$d t_n^{1/2} = 465 \ fsw \ min^{1/2}, \tag{25}$$

at depth, d, (Hempleman square-root law), generalized by writing,

$$d t^a = b, \tag{26}$$

for a and b some constants. Ranges subtended today in tables and meters include:

$$0.25 \le a \le 0.65 \,, \tag{27}$$

$$250 \, fsw \; min^a \le b \le 500 \, fsw \; min^a \,, \tag{28}$$

A separated phase model for no-stop air diving suggests,

$$\delta d \, (t_n + 1/\lambda) = 8750 \, fsw \; min \;, \tag{29}$$

for number factor, δ, collectively representing bubble seeds excited by compression-decompression, from surface pressure, P_0, to ambient pressure, P, and back to P_0,

$$\delta = \frac{P}{P_0} - 1. \tag{30}$$

The phase law generalizes to,

$$\delta \, d \, (t + 1/\lambda)^a = \frac{d^2}{P_0 + d} \, (t + 1/\lambda)^a = b, \tag{31}$$

with,

$$P = P_0 + d \,. \tag{32}$$

The depth-time law and tissue equation present a minimax problem, with the maximization of the tissue equation at depth subject to the constraint of the depth-time law. The standard approach sets the depth derivative of the tissue equation (tension) to zero at the exposure time limit, under the primary constraint of the depth-time equation. First writing ambient gas partial pressure, p_a, as

$$p_a = p_0 + fd \;, \tag{33}$$

for surface partial pressure, p_0, mole fraction, f, and then differentiating tension, p, with respect to depth, d, we find in general,

$$\frac{\partial p}{\partial d} = f - f \, exp \, (-\lambda t) + (p_0 + fd - p_i) \lambda \, exp \, (-\lambda t) \frac{\partial t}{\partial d} = 0, \tag{34}$$

as the maximization condition. The time derivative with respect to depth, $\partial t/\partial d$, is evaluated from the assumed exposure law, and then inserted above. The resulting expression couples halftime, τ,to exposure limit, t_n, and the value of the tissue tension at those values is the (maximized) critical tension, M_0.

Table and computer algorithms still rely heavily on (Haldane) dissolved gas treatments to schedule diving, with square root-like no-stop limits folded into a multi-tissue perfusion framework. As an example, consider the bulk relationship,

$$\frac{\partial t}{\partial d} = -\frac{t}{ad}. \tag{35}$$

Setting $p_i = p_0$, substituting the derivative, and maximizing at the no-stop limit, t_n, there results,

$$1 - exp \, (-\lambda t_n) - \frac{\lambda t_n}{a} \, exp \, (-\lambda t_n) = 0. \tag{36}$$

At no-stop time, $t = t_n$, the tissue tension is maximized, that is, $p = M_0$, so that,

$$M_0 = p_a + (p_i - p_a) \frac{a}{a + \lambda t_n}. \tag{37}$$

The maximization condition links λ and t_n together, while M_0 falls out of the tissue equation. The quantity λt_n is pivotal to the solution. Table 2 gives thumbnail solutions to

$$exp\ (x) = 1 + \frac{x}{a}, \tag{38}$$

for a, as function of dimensionless parameter, $x = \lambda t_n$.

Table 2. Maximization Parameters.

a	$1/a$	x
.157	6.37	3.00
.323	3.09	2.00
.435	2.29	1.50
.455	2.20	1.40
.488	2.05	1.30
.500	2.00	1.25
.517	1.93	1.20
.549	1.82	1.10
.581	1.72	1.00
.771	1.29	0.50
.951	1.05	0.10
1.00	1.00	0.00

In the separated phase model, we have differentiating,

$$\frac{\partial t}{\partial d} = -\frac{2(t + 1/\lambda)}{ad}, \tag{39}$$

so that,

$$1 - exp\ (-\lambda t_n) - \frac{2(\lambda t_n + 1)}{a}\ exp\ (-\lambda t_n) = 0, \tag{40}$$

as the maximization constraint. Or, equivalently, one needs,

$$exp\ (y) = 1 + \frac{2(y + 1)}{a}, \tag{41}$$

with $y = \lambda t_n$. Then, the critical tension, M_0, is given by,

$$M_0 = p_a + (p_i - p_a)\ \frac{a}{a + 2(\lambda t_n + 1)} \tag{42}$$

Results for selected air limits are summarized in Table 3, using a standard nonlinear least squares (NLS) approach in fitting t_n to the depth-time relationship, with usual L_2 error norm. The labels RGBM, DCIEM, ZHL, Spencer, and USN reference the various Haldane limits and parameter sets in terms of trade names.

The procedures for constructing a consistent set can be summarized as follows:

1. First, from experiment, wet or dry tests, Doppler, or otherwise, a set of no-stop time limits, t_n, at depth, d, is obtained;
2. Next, the set is fitted to the two-parameter power law given above, and the constants a and b determined;
3. Then, with a and b determined, the controlling halftime, τ, is obtained from t_n at d; and,
4. Finally, from τ, t_n, d, and a, the critical tension, M_0, is extracted, closing the whole set.

The set a, b, τ, t_n, d, x, y, and M_0 then close self-consistently when derived according to the above set of equations and constraints.

Table 3. Fits, Limits, Halftimes, and Critical Tensions.

	RGBM	DCIEM	ZHL	Spencer	USN
			Fit Parameters		
a	.94	.48	.46	.39	.41
$b(fsw\ min^a)$	6119	362	385	290	355
x	1.40	1.34	1.39	1.65	1.58
y	2.00	1.08	1.65	1.16	1.57
$L_2(fsw)$	12.8	57.7	62.3	85.5	56.5
			No-stop Limits $t_n(min)$		
$d(fsw)$					
30	200	150	290	225	
40	110	90	125	135	200
50	70	70	75	75	100
60	50	50	54	50	60
70	35	35	38	40	50
80	26	25	26	30	40
90	20	20	20	25	30
100	16	15	20	20	25
110	13	12	17	15	20
120	11	10	15	10	15
130	9	8	11	5	10
			Halftimes $\tau(min)$, Critical Tensions $M_0(fsw)$		
$d(fsw)$					
30	69, 46	98, 44	122, 45	134, 45	178, 45
40	38, 53	53, 49	68, 51	60, 52	88, 52
50	24, 60	33, 55	42, 57	37, 58	52, 57
60	17, 67	22, 61	28, 63	23, 64	33, 64
70	12, 74	17, 67	20, 69	16, 71	23, 69
80	9, 79	12, 73	15, 73	11, 77	16, 76
90	7, 87	10, 87	12, 82	8, 84	12, 83
100	6, 94	8, 85	9, 88	7, 90	10, 89
110	5, 101	6, 91	8, 84	6, 96	8, 95
120	4, 108	5, 96	6, 100	4, 103	6, 101
130	3, 114	4, 102	5, 106	3, 109	5, 107

Acknowledgments

Thanks to all those NAUI Instructors throughout the world who provided online validation of the NAUI Table (DCI estimated incidence rate near 1 x 10^{-5}, to Jim Bram and NAUI Headquarters Staff, to the new breed of Technical Diving Instructor demanding modern and efficient decompression algorithms, and to colleagues in the recreational, scientific, military, and commercial diving sectors.

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SSI POSITION STATEMENT ON REVERSE DIVE PROFILES

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Scuba Schools International follows the conventional thinking on reverse profile diving, essentially, advising against it.

- The SSI Open Water Diver Manual, © 1995, covers the topic on page 139 with:

  "Two things make this repetitive dive plan successful. First, the depths are moderate, and second, the deepest dive was done first and shallower dives were done as the day progressed. Following these two general rules in repetitive dive planning will give you more flexibility with surface intervals and bottom times. If you plan deeper dives followed by shallower dives, and keep the depths of your repetitive dives moderate, you'll allow yourself longer bottom times and shorter surface intervals in general. It can be annoying and can really limit the day's activities if you use the tables unwisely."

- The SSI Specialty Diver manual on Deep Diving, © 1991, which is part of the Advanced Open Water Course, deals with reverse dive profiles on page 41 with:

  "If you are planning on making a repetitive dive, there are a few basic rules you will need to follow; always make the deepest dive first, and pre-plan both dives to ensure you will have enough bottom time left to complete your second dive."

- The SSI Divecon Manual, © 1993, provides the following on page 7-8

  "If divers go to the deepest depth first, and proceed to successively shallower depths, then multi-level diving can be safe. If divers alternate between deep and shallow depths, however, then it is less safe."

In summary, the current SSI position is: "Always make the deepest dive first."

YSCUBA POSITION ON REVERSE DIVE PROFILES

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The forty-year history of YSCUBA was reviewed to establish the YMCA's position and rationale on the reverse dive profile issue. The "reverse dive profile" working definition used was: "Any repetitive dive deeper than the previous dive during a 12-hour period." The literature search included the YSCUBA's Standards and Procedures Manual, the YSCUBA Open Water Diver Instructor Manual, and The New Science of Skin and Scuba Diving (YSCUBA's first scuba text). Members of YSCUBA's past and present leadership were also consulted. Lastly, I drew from my own 30-year experience as a YSCUBA instructor.

- **The YSCUBA Training Program is dive-table oriented.**

Students are taught to utilize and obey the YSCUBA Sports Diving Tables when planning and performing diving activities. Introductory level students are familiarized with the function and proper use of dive computers, but the major emphasis is placed on understanding the dive tables. These tables are conservative and were developed with a "safety first" mindset. The tables recommend that the recreational diver not exceed a depth of 100 feet and only perform no-stop dives. The maximum bottom time for any given dive is determined by the diver's deepest exposure during that dive. Therefore, the restraints on a diver using the dive tables are obviously greater than those on a diver using a dive computer while performing a comparable dive profile. So, any discussion concerning YSCUBA diving operations should take this into consideration.

- **The YSCUBA position on reverse profile dives is simple.**

This issue has not been directly addressed or even acknowledged. The Program does clearly define what it considers the proper order of dives to be, that is, "all repetitive dives should be conducted with deeper dives first and each successive dive equal in depth or shallower than the previous dive." A definitive rationale for this position or supportive data could not be found. Some instructors thought this position was based on safety concerns over the potential for increased decompression problems, yet they could not produce any supportive data. Certainly, performing reverse dive profiles decreases the margin for error during the second deeper dive. However, if the dive tables are followed correctly such a dive should be safe.

- **Why does YSCUBA recommend forward dive profiles?**

A review of YSCUBA's training material and from my personal experience as a scuba instructor, I conclude that this position was primarily based on more practical considerations. Generally, it just makes more sense to go from deeper to shallower depth dives. Forward dives allow for greater bottom time when compared with mirror-image reverse dive profiles. It is a matter of bottom time husbandry (bottom time is enhanced by going from deep to shallow during repetitive dives). Often the tables do not even allow a second deeper dive without exceeding the maximum no-decompression bottom time. Or, if allowed, it requires an excessive surface interval. Therefore, during routine recreational dives the YSCUBA recommendation has been, and is, that each repetitive dive should be shallower or equal in depth to the previous dive.

The question of a diver who goes from a shallower exposure to a deeper exposure during the same dive is a different matter. Such a scenario would alter the dive profile of that particular dive, but would not be considered a repetitive deeper dive. By going deeper, the diver decreases his allowable maximum bottom time to that value represented by the deepest depth of the dive. Therefore, from the perspective of the YSCUBA dive tables, the diver should only perform this maneuver, if by doing so, he does not exceed the no-decompression limits for that dive. If this maneuver causes the diver to inadvertently exceed the no-decompression limits for that dive, he must treat it as a decompression dive and respond accordingly.

YSCUBA recognizes that reverse dive profiles are being performed by the recreational dive community.

REVERSE DIVE PROFILE ACTIVITY IN THE SCIENTIFIC DIVING COMMUNITY

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Introduction

The AAUS Standards for Scientific Diving Certification and Operation of Scientific Diving Programs (1996 ed.), Section 3.28 and Appendix 12 address the diver's determination of decompression status with the following conditions:

- A set of diving tables, approved by the Diving Control Board, must be available at the dive location.
- Dive computers may be utilized in place of diving tables, and must be approved by the Diving Control Board.

Further guidelines on dive computer use are from Lang, M.A. and R.W. Hamilton (eds.). 1989. Proceedings of the Dive Computer Workshop. USC Catalina Marine Science Center. AAUS, Nahant, Massachusetts. 231 p. and state:

1. Only those makes and models of dive computers specifically approved by the Diving Control Board may be used.

2. Any diver desiring the approval to use a dive computer as a means of determining decompression status must apply to the Diving Control Board, complete an appropriate practical training session and pass a written examination.

3. Each diver relying on a dive computer to plan dives and indicate or determine decompression status must have his own unit.

4. On any given dive, both divers in the buddy pair must follow the most conservative dive computer.

5. If the dive computer fails at any time during the dive, the dive must be terminated and appropriate surfacing procedures should be initiated immediately.

6. A diver should not dive for 18 hours before activating a dive computer to use it to control his diving.

7. Once the dive computer is in use, it must not be switched off until it indicates complete outgassing has occurred or 18 hours have elapsed, whichever comes first.

8. When using a dive computer, non-emergency ascents are to be at the rate specified for the make and model of dive computer being used.

9. Ascent rates shall not exceed 40 fsw/min in the last 60 fsw.

10. Whenever practical, divers using a dive computer should make a stop between 10 and 30 feet for 5 minutes, especially for dives below 60 fsw.

11. Only 1 dive on the dive computer in which the NDL of the tables or dive computer has been exceeded may be made in any 18-hour period.

12. Repetitive and multi-level diving procedures should start the dive, or series of dives, at the maximum planned depth, followed by subsequent dives of shallower exposures.

13. Multiple deep dives require special consideration.

Item 12 specifically discourages reverse dive profiles with the use of dive computers. This is in agreement with recommendations from dive computer manufacturers and decompression model developers.

Dive Program Survey

Prior to this workshop, an e-mail survey of the AAUS Diving Safety Officers was conducted. The question asked was "Does your dive program allow reverse dive profiles? If yes, what table/dive computer is used to conduct these dives?"

- 20 responses received of which 18 organizations did not allow reverse dive profiles or discouraged them.
- 10 of the 18 programs acknowledged that reverse dive profiles occur. Of these 10 organizations, most stated that they occur infrequently and generally the depth difference was within 10 fsw.
- 4 organizations discouraged reverse dive profiles but did allow them to occur. Two of these allowed reverse dive profiles within a 10 fsw depth range and the other two organizations gave no specifics for allowed reverse dive profiles except that they were always no-decompression dives.
- 2 organizations stated that they allowed reverse dive profiles in their programs. One organization used NAUI tables and various computers for reverse dive profiles. The other organization used the Suunto Solution dive computer, with the profiles referenced to the U.S. Navy dive tables.

Actual Reverse Dive Profile Data

- There have been no reported DCS incidents resulting from a reverse dive profile from any AAUS member organization.

- Two AAUS organizational members, University of Hawaii and East Carolina University, reviewed their diving records from the last 5 years to determine how much reverse profile diving was occurring in their programs.

- University of Hawaii 1995-1999 dives (compiled by Richard Pyle) for which dive times, depths, and duration were known
    - total of 9,686 dives were conducted. 981 (10.1% of all dives) dives were conducted that were deeper than the previous dive on the same day (reverse dive profile).
    - additionally, 460 (46.9%) of the reverse dive profiles were at least 10 fsw deeper than previous dive.

- East Carolina University 1995-199 dives
    - total of 5495 dives were conducted of which 2345 were repetitive dives. Of these, 468 (20% of repetitive dives) dives were conducted that were deeper than a previous dive on the same day (reverse dive profile).

- depth differentials for these reverse dive profiles were:

10 fsw or less	387
11 - 20 fsw	54
21 - 30 fsw	20
31 - 40 fsw	4
41 - 50 fsw	3

Conclusion

Reverse dive profiles are being conducted in the scientific diving community and to date there have been no reported DCS incidents from these dive profiles. Although the vast majority of these profiles have a depth differential of 10 fsw or less, reverse dive profiles have been conducted at greater depth differentials without incident.

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VI. Operational Experience Session Discussion Part 2. Michael A. Lang, Moderator.

A. Brubakk: When we demonstrated the 300 meter dives, we went to saturation excursion. We had a lot of gas in 12 out of 14 dives.

T. Overland: We've looked at your data, we limit ours to about 75 percent of the excursion distance, and 50 percent below 800 feet.

A. Brubakk: So they don't use the U.S. Navy excursion table?

T. Overland: We do use the tables.

A. Brubakk: The other thing is in Norway, which has quite limited excursions, some years back we had to limit excursions. We had a series of decompression accidents during saturation, maybe eight or nine, easily. The way we solved it was with limited excursion limits. Then it went away. I don't know if that is true.

We also did some measurements of the gas problems in the decompression phase in relation to excursions. We could see that when we have had an excursion - those were exactly on the limit, and they had to take 13 hours on the excursion. They had significantly more gas problems during saturation.

And the last point is the one I made here in my presentation - that is all in the data. Some divers, over 60 percent of them, have had clinical symptoms without ever telling anyone. In our data, 13 out of the 15 divers lost their lives due to medical reasons and had severe problems and never told a soul.

T. Overland: We don't use the Navy saturation decompression schedule.

A. Brubakk: No, we don't either.

T. Overland: Just the excursion.

A. Brubakk: We don't either. But we also limited the excursion.

T. Overland: We use a higher partial pressure on our decompression from sat. It probably took care of us.

G. Beyerstein: A long time ago we used to have sat bends and I'm just trying to remember. It seems to me that the Navy changed their excursion limits. We knew Navy excursion limits are about where we set our initial limit after we had some bad experience. It was about a 20 percent reduction. Later on we reduced it again another ten percent from that original, so about 30 percent down from the original is what we used. As Terry said, when we go down over 700 feet, then we go down to 50 percent of the excursion. Because that's where we started having problems with excursions.

T. Overland: Because if she does the Navy tables so that if you're going farther and farther in your excursion and we found that's that, you go down about 800 feet and you start backing the diver in. One thousand feet, you better keep a balance.

G. Beyerstein: From the tables that Subsea did that resulted from Mike's model, we used them as multi-level, in a different way than you've been using it here. We allowed both up and down repets for an unlimited number of times within the same dive. We had about 300 exposures without any problems. I support what Terry said. It's a tool that's in the bag, and if the operational situation comes up where a supervisor can use it, then he has it and sometimes it can be a lifesaver.

T. Overland: It is very expensive I would say. Somebody is paying us a lot of money to do this work, so we've got to produce a job.

M. Gernhardt: The repet procedure is probably based on the global dynamics. The actual architecture in the way it's implemented is very similar to the RNT approach. There are equivalent dive times at different depths worked out that use the same bubble growth. But the diver doesn't even know any of that. He actually operates the tables in much the same way that you do this type of procedure, the way that Terry does it.

E. Flynn: So they are constrained one way or another in terms of how to shorten the times because they're going down versus if you just went steadily up, would your table look exactly the same as the one you published or would you have to make some compensation for the fact you might be going down as well as up?

M. Gernhardt: For the multi-depth tables that we did at Ocean Systems, we actually modeled every possible combination of diving - took the worst case. For the final versions of that table, I'm sure that they defined a worst case in different parts of the matrix and built it around that. But I want to stop short of saying I know that, because I didn't actually hear it.

G. Beyerstein: We did and it's designed so you can follow and track on the back of every log.

T. Overland: Unfortunately, there's very little data on commercial dives in the United States. People don't collect it. We have a database and my repet-up was a reverse profile and I just called it a repet. Every once in a while somebody will remember to put the U in it instead of an R, so I know it's a repet-up. But if they don't put it in the computer, we'd have to get it out of the file. So, we don't have any good data.

M. Lang: Does ADC not collect data? Is there no reporting requirement?

G. Beyerstein: No, we couldn't even get accidents from our members.

A. Brubakk: I have a question about the technology. You've been talking a lot about the fact that tables may become obsolete here shortly with all the computer technology available. I was just wondering why you wouldn't have the respective algorithms that you're using in real time on a computer chip and just calculate each diver's profiles independently based on the actual profile.

T. Overland: That was tried in the North Sea. Shell put up a lot of money and I don't know why. We participated in it for about a year or so. They logged all the dives and the company tables or whichever ones you were diving, were put in the computer. All you were doing was watching the line when it got close to starting decompression.

They were just square-wave tables; it just depended on where the diver went on the deepest part of the table. I don't know what happened to all that data.

A. Brubakk: Someone started that and the main problem was that no one had really thought about how to analyze the data before they collected it. But it also has to be said that in the analysis that they did on the actual accidents in the North Sea, it was fairly clear that the only thing that was related to the accidents was actually the depth/time combination. It was totally irrespective of what part of the decompression profile you used. They all came out the same. I think it was something like 30 different procedures.

T. Overland: I think if you follow the tables you're using, you're probably going to have a pretty safe dive. Most of the commercial companies have demonstrated that, all over the world.

D. Richardson: One observation: In the late 1970's, we used to teach repetting-up in commercial diving school. The recreational industry at that point in time started to watch that trend and it was presented at a NAUI-IQ. In 1979, there was Dennis Graver's publication about decompression and depth, where repetting-up was suggested to the recreational community, that he supposedly invented. It's interesting to note the reverse, just from the diving behavioral pattern. In the 1970's, recreational divers didn't do multi-level diving per se. The deepest depth of your dive, that's how you monitored it. Now, I find it interesting that the commercial community is doing a lot of it.

T. Overland: To get the bottom time and now we've gone the other way.

D. Richardson: I've sort of changed careers in the meantime. I see you guys have pulled out of it and we're full into it.

G. Beyerstein: Actually, who started it? I don't think we've pulled out of it so much as just the work conditions have changed to some degree and the need isn't there.

T. Overland: You've got more people on the job so you don't really need to do it.

G. Beyerstein: It's not like we dropped the procedure for any reason. It's just that it's there and it's either getting used or it isn't and it varies from year to year, in my experience.

D. Richardson: Now the point is, you may not want to claim it, but you actually made a contribution to the general public when your diving patterns stimulated some of the thinking in other people.

T. Overland: I'd like to see somebody take a look at that jogging up and down on the RNT table and see if it works. We've never had a problem. We were diving deep, 190 feet and we were doing short ones coming up shallow.

R. Vann: The problem with reverse profiles is that the time between the dives is important. Has anybody analyzed your data, or can you? The DAN data analyzes the relationship between time, in these reverse profiles the relationship between the time between dives and the incidence of decompression sickness. Has anybody looked at that?

D. Richardson: We haven't looked at that. In the paper, all the data are presented - they are available. Where it was reported, some divers didn't remember exactly what their surface intervals were, but from most of the profiles - you could extract that.

R. Vann: One of our cases occurred with flying after diving with symptoms presenting during the flight, a couple of days after. It's just not specific, when several days later it occurs.

B. Wienke: I'm sorry, but I couldn't help think as we were riding over here on the bus this morning that if something should happen to that bus, if it were taken out so to speak, decompression theory and analysis might be set back about a week or two. It's well known that at a conference like this, it's the seniors that come to the gathering and leave the young workers at home to do the work. So even a couple of weeks might be exaggerated.

B. Hamilton: In 1991, at the Repetitive Diving Workshop (Lang and Vann, eds.) at Duke University we reviewed the incidents in recreational diving and the order was considered to be about one out of ten times. You improved that by a factor of 100.

B. Wienke: This is based on reports coming in from NAUI Headquarters.

B. Hamilton: It said one out of a million on the graph.

B. Wienke: It's five out of 500,000, so it's one out of ten to the fifth. I'm only talking about training dives here.

B. Hamilton: Not for all incidents? Okay, that explains it.

D. Richardson: I wasn't talking about only training dives!

B. Wienke: You weren't?

D. Richardson: No. Basically, the original denominator is what I put up there, but if you want to do the rough points you can look at each year we certify 800,000 new divers, you can do the numbers there. You're looking at a couple of million just in the training scheme. But the data we collected shows out of that total of 51 incidents, there were 12 that occurred in the training frame. Out of the 936, they were all over the map, people just diving on scuba who happened to be affiliated with PADI.

B. Wienke: So your training incidents are on the order of one in a million, something like that.

J. Lewis: I have a comment. I don't think that most people, and, I in particular, have a real sense or know the difference between ten minus four and ten minus two. In terms of speaking to the public at large, we should try to reference the ten to the minus to something else, some other accident rate for another sport to give a better sense of what those numbers really mean. I don't know what the proper example is, but I think that somebody should come up with one.

D. Richardson: DAN did that somewhat with the National Sporting Goods Association.

Comment: And DAN got in trouble with it a few years ago for comparing it to bowling.

Comment: How many cases of decompression sickness did AAUS have in the 70,000?

T. Maney: Two Type I cases and I think the other one was a case of suspected DCS.

VII. General Session Discussion
Michael A. Lang, Moderator.

M. Lang: Ladies and gentlemen, I'm rolling up my sleeves. What that means is it's time to get down to business here. We would like to be courteous and respectful of other people's opinions, obviously, but we also don't want to be shy and hold back the bright ideas. Therefore, if anyone has ideas or opinions based on data and presentations we've heard over the past few days, as they relate to reverse dive profiles, please plant the seed. When we get to the final general discussion and develop our take home message, whatever that's going to be, there may be a number of points we would like the community in general to know about. We'll work on that until we produce something that the majority of us can agree on and think is a good reflection of the workshop consensus. With these kinds of workshops I like to have one or two people sit back, take it all in and then give us their perception or perspective on, as a starting point for the discussion. I have asked Richard Moon and Tom Neuman to perform this function.

Individual Perspective - Richard E. Moon, Duke University/Divers Alert Network

Before one can discuss a "reverse dive profile," it is essential to define it. One definition of a reverse dive profile is one in which a deeper dive is performed after a shallower one within a defined time frame, which in practice is usually a day.

Why might a reverse dive profile be more likely to cause decompression illness (DCI) than a pair of dive profiles in which the deeper dive is followed by the shallower one? In this workshop we have heard several theoretical possibilities. For example, *in vitro* gelatin models have been used to predict that a deeper dive following a shallower one results in greater bubble formation. The assumptions used in developing the U.S. Navy Air Tables predicted higher tissue inert gas loads when the second dive is deeper than the first. This principle is evidenced by the shorter bottom times that these tables allow when the deeper dive is performed after the shallower one.

Besides inert gas kinetics one can speculate upon physiological factors that might be possibly induce some asymmetry in outcome between "deep-following-shallow" and "shallow-following-deep."

1. Asymptomatic bubbles induced by decompression from the first dive may be either amplified or 'treated' by the second dive, depending on its depth and time.
2. Asymptomatic bubbles occurring after the first dive might initiate pathophysiological processes that could alter the probability that the second dive could produce DCI.
3. The physiological response to the second dive could be related to non-dive factors associated with the first, such as immersion diuresis, dehydration and exposure to cold.
4. There may be a diurnal variation in susceptibility to DCI that could be erroneously interpreted as due to "deep-following shallow" versus "shallow-following-deep" asymmetry.
5. Finally, there are more things that can go wrong with a deep dive, thus a deep dive with pre-existing gas load (from an initial dive) may be theoretically more dangerous than a shallower one.

Are there any human data that reverse dive profiles are inherently more dangerous? Neither prospective laboratory studies by the Navy nor field data from either commercial or recreational diving have supported the concept that reverse dive profiles are inherently problematic. Nevertheless, studies designed specifically to address the question have not been performed. Furthermore, small differences in P(DCI), which are unlikely to have any significant effect upon outcome in military or commercial diving, where on-site chamber facilities are the rule, could be important in situations (such as recreational diving) where delays to treatment are prolonged, or the economic cost for the diver or dive boat operator extreme.

However, provided decompression algorithms can account for any differences in DCI probability, and appropriate tables/computer profiles are implemented, then differences shouldn't matter. Commercial diving practice, in which reverse dive profiles have not traditionally been interdicted, and in which decompression illness is rare, suggests that methods of constructing decompression algorithms are adequate to overcome any inherently greater risk of reverse dive profiles.

To summarize the presentations, if performing a deeper dive after a shallower one is more dangerous than the other way around, then current technology and data have insufficient resolution to detect the difference. Therefore, provided accepted decompression procedures are implemented, along with other measures that are safe, there is no reason to disallow reverse dive profiles.

P. Weathersby: One comment Richard, about what I said yesterday about the Navy Yard data. I just want to reiterate that what I had illustrated for the Navy tables is that there could be a forward and reverse difference for decompression data.

R. Moon: Yes that's right, for no-stop diving you didn't find any difference.

P. Weathersby: I did not evaluate the other methods in that context. So the conclusion I came to that there might be a difference for decompression diving under the Navy tables, I might have also found that for other methods. I didn't look at the other methods.

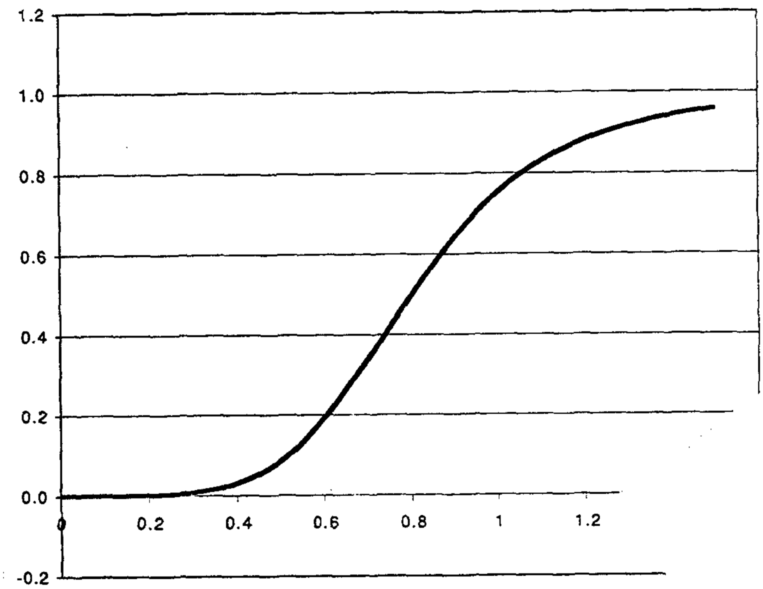
Tom S. Neuman, University of California, San Diego.

The issue of reverse dive profiles from my perspective, almost to the letter, agrees with the observations Richard made. I'm going to use slightly different examples and say it in a slightly different way. Richard phrased the question exactly, word-for-word, the way I phrased the question. "Are reverse dive profiles inherently more dangerous than forward dive profiles using our current algorithms for determining tables?" Wayne Gerth clarified this by stating "it doesn't make any difference whether these profiles are inherently more dangerous or not. You give me the requested dive profiles, I'll determine the appropriate decompression based upon the algorithm that you're using." It's very important we answer these questions with our current decompression algorithms. But that's the key question: "Are these reverse dive profiles inherently more dangerous than doing it the other way around."

Why we wound up doing our dives the way we do, forward dives, with deeper depths first, is perhaps of historical interest. We heard a number of different reasons, but we do have to remember that this is the way we dive and that's the data set that we're looking at. We have to be very careful about looking at our current data set because the vast majority of it is not testing the area we really want to look at. We could ask the same question about whether our reverse dive profiles are more inherently dangerous in a slightly different way when we ask "do we have to modify the algorithms that we currently use to deal with reverse dive profiles?" Now let's change these words and delete reverse dive profiles and deal with exercise, age, gender, and dehydration. Do we have to modify our algorithms for those variables?

I think it was Richard Moon or maybe Richard Vann who showed that for certain kinds of dives, around 190 feet for 30 minutes, doing a lot of exercise on those dives compared to non-exercise on those dives, tripled your decompression requirement. Keep that fact in mind when we talk about this whole business of reverse dive profiles, because clearly exercise, under some circumstances, can dramatically alter the way we deal with decompression profiles. We haven't addressed age or gender yet, and I just put dehydration up here five minutes ago, because I'm afraid dehydration is another one of those issues that may turn into "reverse dive profiles" over the next ten years. We've got no data that says dehydration causes decompression sickness. We have some data that suggests people who get bent are intravascularly hemo-concentrated. Is that dehydration? Maybe. But it's a leap of faith or magic, if you will, to the fact then that dehydration causes decompression sickness. It's an even greater leap of faith, that if you drink alcohol you get dehydrated and then you're going to get decompression sickness. And still a greater leap of faith that I can't have a beer at lunch anymore when I go diving in the afternoon on plenty of dive boats in the Caribbean. So, this whole business about whether or not we have to deal with a change in our algorithm to deal with other things is something that's not unique to reverse dive profiles. The answer to this question is: maybe we do have to change our way of thinking.

On this dose-response curve, the x and y-axes are not meant to represent anything absolute. These were just numbers that were used to generate the shape of the arc-tangent curve. Look at its shape and imagine that the curve is a dose response. The x-axis represents decompression stress. More decompression stress is to the right and the y-axis is an estimation of the risk of decompression sickness. It just turns out the zero to one worked out very nicely. Now why is it then that it seems to make absolutely no difference whatsoever if you exercise on a 60-foot dive for 60 minutes, but where on the 190-foot dive for 30 minutes, you exercise makes such a big difference? This is precisely what I think Richard would say - that in some areas, we're approaching zero on the risk of getting decompression sickness curve. Whether this is zero down here or some infinitesimally small number, we could argue about a lot. That's not the point I'm trying to make. When you're down here, if you do something to shift yourself over in one direction or another, it doesn't have a terribly big affect. But if we take that 190-foot dive for 30 minutes (over to the right of the curve) and the exercise induces more stress, all of a sudden the incidence of decompression sickness goes up dramatically.



In certain kinds of circumstances, *i.e., when you are already gas-loaded, small errors can have a big effect.* Not only financially if you're off diving in the Coral Sea, but physiologically as well. To my way of thinking about it from a biological point of view, given the statistics for most of the diving that scientific and recreational divers are doing, age, gender, alcohol, exercise and probably to a certain extent reverse dive profiles don't make any difference. I'm specifically excluding the technical divers who are in the center portion of the curve.

I would like to put a word of caution in before I say reverse dive profiles don't seem to be a big problem. First of all, the points that Richard made, I think, are extremely important. Little things going wrong at the end of a deep dive lead to real bad things happening to divers. That doesn't fit into any mathematical model. If you've got a big gas load from a deep dive and all of a sudden you find yourself out of air, it's a whole lot better if you're out of air at 20 feet than if you're out of air at 100 feet. This is a very real operational issue for the diver or from the point of view of the diving supervisor who takes care of people who are hurt. A lot of things can go wrong on a deep dive that tend to be more dramatic than when they go wrong on a shallow dive. For that reason, personally, I would much rather have a smaller gas load when I'm making my deep dive than a larger gas load.

Now let me make a physiological observation for you as to why a deep first dive might be inherently safer than a shallow first dive. This is hypothetical, and I'm putting this up clearly as a straw man, so that people can work it over because I'm not at all sure that it's going to wind up being true. But it's at least something to think about. If you make a deep dive and you look at the time course of Doppler bubbles, it looks something like that. If you make a shallow dive to the limit of the no-decompression tables, let's say then that the Doppler profile of bubbles looks like that and tails off somewhat later. I'm not sure what these times would be at the bottom, I'm just talking about the shape of the curve. In theory, if you're doing it to the limit of the NoD tables, the area under the curve ought to be the same, but I'm not sure about that slipping into mathematics. If you make your deep dive first and then have a surface interval, by the time you make your second dive, these bubbles are gone. If they're gone, you've not only gotten rid of the bubbles, you've gotten rid of some micro-nuclei, but more importantly, when you make your shallow dive now and you're decompressed from your shallow dive, you don't have a place to put that gas.

On the other hand, if you do it the other way around and you make the shallow dive first, then when you make your deep dive you've already got a nucleated gas phase. You've already got lots of bubbles. Supersaturation is not nearly as easy to maintain and you can shove gas into those bubbles and conceivably make decompression sickness worse. This is only a construct to account for why there may be asymmetry between the two situations. I don't really mean for it to be true. You can like the idea better that there's asymmetry between the situations for a different reason. And so there is conceivably a difference between them. But on the other hand, in fairness, I think the data as they exist seem to indicate that within the confines of their very limited nature and the small delta P's and surface intervals that we've seen in no-decompression dives, *it doesn't seem to make a big difference.*

I would be very careful not to extrapolate that out to decompression dives or very deep dives or repetitive deep dives. I would certainly not take that to altitude or any place else other than the very little narrow envelope in which we have a little bit of data.

V. Flook: With due respect, Tom, may I suggest that the overhead you drew was a little bit simplistic. You can certainly get the long lasting shallower curve, which sort of comes from a deep dive and the sharp, quickly decaying bubbles coming from the shallow dive.

T. Neuman: Absolutely. It was not meant to be anything other than one conceivable explanation for why there may be asymmetry. You could just as easily say different variability of tissue in response to the number of bubbles, as I think Richard suggested. All I was looking for was a biological, not a mathematical reason for asymmetry.

R. Nishi: Just from the measurements that we've done from all the end dives, regardless of how you do them, if they are long bottom times or short bottom times, the curve would mostly look like the first shape you've drawn. The only data that I've seen where they actually stay for a long time are surface decompression dives. For some reason these bubbles have that particular shape. But the bubbles stay in the circulation for a long time. If there is a significant amount of bubbling from the first dive, you can detect bubbles for many, many hours in the primary circulation. The usual surface interval time between dives will probably not be enough to eliminate the gas. But you are right in one respect and that is, in one of the pictures I showed the example of when there is gas and you do the second dive, then the amount of gas that you produce on the second dive is significantly higher than if there was no gas. In that respect you're right but I don't think there would be a difference between a long shallow dive and a shorter, deeper dive.

R. Vann: Just a couple of observations there. First of all, there are only two possible outcomes to this workshop, I think. One was that we could have concluded that reverse diving is incredibly hazardous and should not be done. The other one is that you can't conclude absolutely that it is not. This is proving the negative, which is virtually impossible. I believe in gas nuclei, that they are depleted, possibly crushed on a first deeper dive, which might make it safer to do a forward series. I certainly don't find any evidence in the data that it's true. While we cannot absolutely conclude that there is no difference at all, at least with the limited data that we have in hand for recreational, commercial and military diving, there is no evidence that leads us to a smoking gun. I probably can't say anymore than that.

P. Weathersby: I think I can be concise and maybe it should be in the form of a question to Richard and Tom. With the evidence that we've seen in the last day and a half and with you guys given 24-hours to prepare a ten minute summary, would you not be about equally successful in coming up with the same caution and similar, plausible rationale why we shouldn't be doing forward dives?

T. Neuman: No, because we've got a lot of data on forward dives. We've got literally millions of dives that were made, repetitive dives that are made with an acceptable incidence of decompression sickness. I choose the word "acceptable" carefully. The question is: Is there an order of magnitude greater difference in doing the dives in the reverse fashion? I think the answer, within some narrow limits of what we've looked at so far, is that the evidence doesn't suggest that it's magnitudes higher in risk. But that's only within the very narrow confines of the kind of diving that we generally do. I would be loath to take it to other edges of the envelope. Bruce Wienke showed us data that makes me concerned that when the delta P gets to be quite large or from what Wayne Gerth showed us - when we start getting into decompression areas - that such asymmetry may exist. They certainly haven't shown that it does exist, but there we have to recommend more caution. Within a delta P in the no-stop limits of 30, 40, 50 or 60 feet, we can say that we don't have evidence that there is a smoking gun there and that it is probably not orders of magnitude more dangerous. Of the forward profiles, we can say they are acceptably safe. There's enough data for that.

R. Moon: Paul, what I said may have been misconstrued. The bottom line would say that there's no reason to be concerned provided that one diver follows the appropriate procedures. I'm not in any way, except in perhaps a couple of fine print areas, saying that reverse dive profiles are any more dangerous than going to 100 feet versus going to 60 feet, for example, which probably is more dangerous.

E. Baker: I want to throw up a couple of these pressure graphs (appended to Yount *et al.*, 2000) and sort of amend the discussion Tom and Richard had. It gets back to the conclusion that I personally made and Drew Richardson mentioned yesterday that there's probably nothing inherently more dangerous about reverse profiles than forward profiles. However, if you look at our conventional algorithms that we apply to calculate those profiles, there may be a potential that it could compute a more dangerous decompression profile. Start out by looking at the first dive using the VPM bubble formation criteria that you can believe or not believe. But if it's true, then we have gas loadings that come in about 0.6 µm on initial distribution. Let's assume a long, shallow dive that created some bubbling. Now we look at the repetitive dive to 100 fsw after a two-hour surface interval. One of the issues we really haven't talked too much about is the behavior of gas loading. How fast these gas loadings, especially in the fast compartments, can build up. That's really a major factor. How does your decompression algorithm keep control over those fast gas loadings? This is based on a Bühlmann table, but you can see that some of those gas loadings are probing about the 0.7 µm range. Based just on this you couldn't really conclude that there was anything particularly dangerous about that unless other factors, dehydration, exercise, or the individual physiology took place. But then you compare the 100-foot dive to the no-decompression limit on a first dive and that shows you a little difference. That was the difference between six minutes bottom time and 17 minutes bottom time with some residual nitrogen loading on the other one. That shows you that it doesn't take much of a difference in gas loading to get you much deeper into the radial distribution of nuclei to form bubbles. The point that I wanted to make is how did the notion that reverse dive profiles are dangerous get so widespread and established? It may have started as an observation based on dissolved gas considerations. Yet it grew and expanded to become something much more. If the conclusion of this workshop is that reverse dive profiles are not inherently dangerous but yet the same models are being used, it could be read the wrong way. Divers could see that as a license to be much more liberal in their practices, so there's a potential danger. Unless they adopt a newer algorithm that would have a gradient-reduction mechanism for repetitive dives, they should acknowledge the fact that bubbles are formed on the first dive.

S. Angelini: I have one comment in regards to something that has been said by Richard Moon and Tom Neuman. They would rather do a deep dive first because if things go wrong then they don't want to have the loaded gas. However, one could say that if you do the deep dive second you have inherently less time at the deeper depths, so you have less time where things could go wrong. In addition, I'm a mechanical engineer so I don't know about physiology. On a first dive you accumulate nitrogen and therefore you have some pressures that are higher than the point A on the surface. If the first dive is shallow, the gradients about your body are somewhat softer. On the second dive you apply steeper gradients over something that already exists and therefore they also becomes softer, could that have an advantage maybe?

T. Neuman: There are all kinds of theoretical arguments back and forth and I don't deny that. As far as the more time for things to go wrong, from the guy on the end of seeing patients in the chamber, the thing that always goes wrong is running out of air.

S. Angelini: So, you have less time to run out of air and are better off with the reverse profile.

T. Neuman: No, you're better off shallow because they'll stay down until they are out of air.

M. Gernhardt: I was just going to concur with what was said and the argument is that on the second dive you have a deeper dive so you have less bottom time than on the first dive and so you're going to have more air. Another thought to throw out for consideration, is that your cerebral supersaturations will be less with a shorter bottom time on that second dive. It would be worth looking at the data to see if the risk of Type 2 DCS is distinguished more on a reverse profile.

T. Neuman: Again, that's fine if they stay down for less time, but they won't.

J. Hardy: No, let me be more specific. On a 100-foot dive you have 25 minutes on the first dive, right? If you do that on the second dive, following say a 60 for 60, you're going to have five or six minutes after the surface interval.

T. Neuman: But they'll stay down until they're out of air.

J. Hardy: If you don't follow the algorithm, you can't predict anything.

B. Wienke: I strongly concur with the flow of this conversation. I really had the preconceived notion, before I got here that reverse dive profiles weren't going to make a big difference for the kind of diving that we're looking at. I am a strong advocate of micronuclei excitation and if there are affects on micronuclei where there are slingshot affects for reverse dive profiles on the second dive, they probably aren't interfering with bodily function to eliminate them. Whatever the recommendations are somehow or other it should come out loud and clear that these reverse dive profiles are probably confined to delta P's around 40 to 50 feet. There are lots of problems that can possibly occur when we go deeper.

D. Yount: I'm pulling together the last three comments in a sense. Eric was very keen to make the point that we mustn't go away from here and gradually allow the myth to build up that reverse diving is safe or even safer than forward profiles. That's very true and this kind of pulls in also with what Bruce is saying because I'm limited by my model, but think that what I'm seeing intuitively is that the precise profile matters enormously as to whether the reverse dive is safer or not. The exact, precise depths of each of the two dives and the length of the surface interval, all play a part. The real answer may well be that neither is safer. It depends on what you're doing, what depths you want to go to. Which is the safer option to take? I want also to pick up on Mike Gernhardt's comment because I do think and I tried to bring out yesterday *that whether the reverse dive is better or not, also depends on what tissue you're concerned about*. If you're concerned specifically to avoid central nervous system DCS, then the answer might be quite different from, if your concern is to avoid pain-only DCS. It's so complex, let's not accidentally come to another firm statement that's going to be magnified and firmed up over the years.

J. Lewis: My observation of what we've seen so far is if we were here to make a rule, there's absolutely, totally insufficient evidence to do so. You would not be doing it. It's slightly modified in a sense that we're here to perhaps change a rule, which makes it somewhat more difficult, but I don't think much, but some, nevertheless. I do think that it got us the conclusion that it is important to note exceptions. What I happen to particularly be familiar with and note that indeed is a problem are repetitively deep dives. There seems to be a preponderance of evidence that that is problematic and so no matter what we did with this reverse profile rule and it does tend toward that. Reverse, by definition, is getting you into the deeper range. Jon Hardy's recent experiments indicate that perhaps that is not as serious an issue as the repetitively deep diving. It's important to add that comment specifically addressing that issue and perhaps others. But *repetitively deep dives with direct ascents to the surface are a problem* and people should recognize it.

K. Huggins: I agree with what Mike Gernhardt was saying for most of the table-based dives. Yes, you will end up with a shorter amount of time for that repetitive deep dive. However, with most of the dive computers being utilized, you've relaxed the fast compartment significantly during the one or two-hour surface interval. Maybe enough so that when you go to that deep dive you in essence would be picking up the same amount of dive time on that second deep dive as you would have on the first dive going to that depth.

G. Beyerstein: It's important to separate the difference between theoretical considerations and the practical sense of what we have from the data that we've examined in the last two days. We've seen many presentations that say there doesn't seem to be much difference as far as the amount of DCS. Tom Neuman pointed out that we're not looking at the data set that we would need to be because we're not doing those reverse profile dives. Certainly in the limited managed situation where the AAUS is involved, they're not, by mandate, doing those that much. But we've had Jon Hardy tell us and other intimations from some of the recreational associations, that they are in fact doing a lot and the data set that we see may be more complete than we think. Therefore it may be that what's actually happening out there is not really what our conclusion is, that there's not that much difference in actuality.

T. Hines: I guess at the risk of commenting on some things that are obvious and partly semantics, I would just say a couple of things. Listening to all the technical side of things, it's a little disconcerting when you try to think about how you're going to practically manage diving programs and divers out there to say that things are more or less safe. Everybody is technical on this but we know some common sense things. We know that diving deeper is more dangerous than diving shallower. It's reflected in the bottom time that we allow at that depth. If it weren't more dangerous we wouldn't pay any attention to that bottom time. If you calculate a reverse dive profile, do you get more bottom time or less bottom time? If it's less bottom time that you're allowed then it is intrinsically more dangerous. It seems like common sense to me at least. Now you do dive to deeper depths that are more dangerous and we set certain rules about how we go about doing that in order to minimize that risk. You can do the same thing potentially, I'm hearing now, with reverse dive profiles. But to start off with a premise and say it's not inherently more or less dangerous, is not the correct message that I think we should be projecting. It should say that things that result in less bottom time are reflecting inherently more dangerous situations. And you're going to go ahead and manage that in some technical way. If the diver chooses to conform to those rules, then there's an acceptable risk. But if they don't, then there will be increased risk. That's what I would recommend, at least as a starting point.

P. Tikuisis: From a theoretical point of view we haven't seen any models presented or any theoretical considerations that would tell us that we should interpret or apply our models differently to reverse dives and forward dives, nor should we interpret results from those investigations. Now, from a practical point of view we've heard that perhaps forward dives are a better procedure. If that's the case, then perhaps you could consider to what group a recommendation should be applied. Perhaps for the recreational divers, forward diving may be a correct way for training purposes over and above when it comes to scientific or commercial diving. From what we've heard so far, reverse dives can be considered just respect the dives the same way you would respect treatment of a forward dive. Perhaps it's not reversed dives, per se, but it's the depth that's important.

R. Moon: I assume we want to come out of here with something in our pocket and not just end it with a discussion. Tuck Hines said it beautifully. The point is the question has to be formulated in an appropriate manner. The question is not, is one form of profile any more dangerous than the other, but rather *do the current algorithms appropriately manage one profile versus another?* We've heard some theoretical arguments that under some circumstances with large delta P's, very deep dives, etc., that the algorithms may not appropriately manage those profiles.

J. Lewis: I believe that's true.

R. Moon: The operational data would suggest that that might not be the case. But I think if the question is formulated appropriately, it may be possible to come out with something that approaches a consensus. The way to approach this, though is not to argue about which one is more dangerous than the other is, as we have been.

M. Lang: We're trying to summarize the information we have that in some way, in part, dispels what everybody believes. As you've heard from the training associations and our textbooks, it says "thou shall not make a reverse dive." The second thing we need is a statement on the conduct of reverse profiles with a recommendation on how to do them within the parameters we've talked about.

J. Lewis: Sorry to keep coming back and this is not strictly relevant to reverse dive profiles. I want to take issue with the statement that we have no evidence that uptake and washout is asymmetrical. We've only got to look at the duration of pulmonary artery bubbles after exposures and there's a lot of experimental evidence from all kinds of animals, including humans. The one that I would court, which I liked best, is the data that came out of submarine escape work in Britain. After a two and a half minute exposure, admittedly to deep depths, from beginning of compression to end of decompression, the bubbles lasted six hours. That is definitely asymmetry as far as I'm concerned.

T. Mutzbauer: I want to comment on what Richard Moon just said. Under certain circumstances, let's say larger delta P's perhaps, the algorithms have to be adjusted. The idea I had was under what circumstances should we make a treatment of just giving normal oxygen? Just to prevent symptoms from arising.

T. Neuman: Michael, why don't you propose something?

M. Lang: No, I want to hear from some more people first. For example, I would like to hear from Drew Richardson, Jon Hardy, Duke Scott, Ted Maney and Bruce Wienke and ask what they going to take back from this workshop to tell their training associations. Was this exercise a waste of time or what are we going to do with this information? On the one hand, we're partaking in an academic exercise here where we have formal presentations critically examining the reverse dive profile data. On the other hand, there's also an applied side to this that says, okay, so what? We know a little bit more about reverse dive profiles maybe and have put the issue into focus but what's the take home message? What information are we going to disseminate?

R. Vann. Why don't we start off with saying *there is no overwhelming evidence that reverse dive profiles are more dangerous (or more likely to produce DCS) than forward profiles.* And then we say, but. Let's confine our discussions to the but.

R. Vann: There's no convincing or overwhelming evidence that reverse dives are more hazardous than forward dives and perhaps we should qualify this by saying, for decompression sickness. I guess one can also add that any deep dive has a greater risk of an air embolism than a shallow dive.

G. Egstrom: It's been a long time since yesterday morning, but one of the things that strikes me is first of all, the identification of hazard should be based upon existing evidence that can show a cause/effect relationship. What has happened here in the last 48 hours is that there doesn't appear to be a hazard in the sense that we were looking at it from the beginning because there's no cause/effect relationship. We can't say one way or the other that there is a hazard here.

The second thing is that the dose-response relationship would require that an objective decision be made as to the degree of differential pressure of nitrogen and the causes that trigger an observed effect. We aren't able to say that reversing profiles brings about that kind of situation. Which then puts us in a position where we can't really identify a likelihood of the effect of this change in profiles with any likelihood of increased risk.

Finally, we're stuck with the potential public exposure that will depend upon what kind of damage is caused if in fact we identify that there is some. This is where all these intervening variables come in, which we don't have a good handle on. As part of the informed consent for those people who are going to read these proceedings, they have to recognize that you're giving them the best information that you can, but they still have to make the decision about whether or not they're going to want to do a reverse dive profile. Ultimately, some kind of risk should be assigned to it. With the limited data that's been reviewed, it would appear that the risk that we're talking about is a very, very small one.

D. Yount: I'd like to remind you of a figure I showed. This is a reverse dive profile of Type 2, as Michael explained, where you do the deepest part of the dive second. This profile produces about 500 bubbles and this other profile will produce zero bubbles. The statement that there's no evidence is probably not a good statement. There's a very narrow range in which we can make a statement that there's no evidence in here for reverse dive profiles. Maybe what that means is we're going from one out of ten to the fourth to one out of ten to the third. We can't tell the difference and in that sense there's no evidence that there's any difference.

B. Wienke: We have to stay within that very narrow range and we're not going to stray very much outside that range. To feed this along I suggest that one of the buts should be, if our comments are confined, in the range down to *about 130 feet of seawater* and *probably maximum delta P's around 40 fsw.* I think that summarizes in my mind a lot of the things that have been presented today.

M. Lang: Should we do 45 fsw? Down the road we'll have these arbitrary numbers and no one will remember where they came from. That should be a first objective, to come to some agreement on the delta P value.

Comment: Why not just say for the narrow range of situations discussed, because if this comes in the proceedings all the rest of the information is there too, instead of putting limits on it.

M. Lang: Operationally that doesn't help us anything. I could live with the 130 fsw maximum because that's what the recreational diving community has in place. I don't think any of us would have a problem with it in the science community. We can't have the diver off the street have to read through the whole proceedings to simply find a certain conclusion

Comment: Isn't it up to each organization to take the general statement and then put their limits on it?

M. Lang: We're not trying to write operational guidelines, per se, for all these different diving communities. We should be able to, as a group, say something about reverse dive profiling though.

W. Gerth: A couple of comments. Dr. Hines, who spoke about using bottom time as an index of stress brings into focus one of the central features of this discussion. Namely, we're not talking about whether or not dives are more or less risky as forward or reverse. We're talking about do we have methods that can handle scheduling of such dives, whether they are forward or reverse. Because if you'll recall having evaluated different methods, I assure you for NoD dives, as provided by those methods, the bottom times were actually longer on reverse dives, just a little bit. There wasn't that much of a difference. With computers, with the tables, with everything else. So they were a little bit more risky and they confused bottom time as a measure. But when held up to the available data we have and the NMRI data set, those differences weren't significant. They just weren't significantly different. And I'd like to add my concurrence to what Bruce Wienke said, that we ought to limit this admonition or lift the admonition against doing reverse dive profiles only for a certain range. I would advocate that that be for dives that remain within the recreational dive limits of 130 feet and that remain no-stop and only one repetitive dive. Because that's the only thing we've been able to analyze up to this point. And then we can say that there is evidence that the current methods we have, as Bruce said, might become more risky when applied to reverse profiles if we get into the decompression range.

Comment: There's no convincing evidence in humans that reverse dive profiles are associated with a greater risk of DCS than forward dive profiles, if the diver is following the instructions of a reliable table or dive computer and is limited to the depth and the delta P, staying away from decompression diving.

T. Maney. This is exactly what the science community wants in guidelines with a delta P, an acceptable depth and within a NoD type of profile.

K. Huggins. If we're looking at the potential of some increasing risk, then it might be appropriate to put in that the risk may be increasing as the delta P increases. If we're looking at divers throughout their diving, we say there may be an increase in risk with age, we don't say older divers shouldn't dive. If we're saying a person who may be out of shape and more obese may be at a greater risk, we don't say people who are obese and out of shape should not dive. Rather, they should add additional safety factors into their diving. Another tack would be to say, if you're doing repetitive dives that have reverse profiles, add more safety factors in and stay further away from the limit for those types of dives.

M. Lang: I like that because it follows the logic of the flying after diving risk statement, the longer you wait to fly after a dive, the further you decrease the risk of DCS.

B. Hamilton: I'm trying to get people to step back and say is there anything wrong with doing something this way? Here's where we should look at what you want to do and say, is there anything wrong with it? Can we see any convincing reason why you shouldn't do it?

B. Wienke: The first part of the statement says what we've concluded and the second part of the statement says, but by doing reverse dive profiles there maybe problems and so on. Those are the things we think about or those are the things we suspect. The first part covers the data that we've examined.

P. Tikuisis: Excuse me, before you get carried on about the statement, aren't these contradictory? Aren't you saying from the first statement that there's nothing there to suggest that there's a difference in safety here. The second statement implies that there's a difference. Are you saying there's going to be additional safety measures attained? That implies that the reverse dive profile is risky.

B. Wienke: Unless you limit it for the greater depths or for the greater delta P's.

M. Gernhardt: I don't think it's wise to put a bunch of qualifications that we know nothing about. We have a little bit of theory. I don't think that we can draw conclusions that are any stronger than the data that we have. I think that people do things for us at NASA and when they come back with stuff that's stronger than the data it becomes a hot potato to deal with. I would suggest, and this is not necessarily my problem to solve, but I would do something like the original statement. *There was no evidence to show that there's an increased risk with reverse dive profiles for no-decompression dives to 130 feet.* That pretty much envelops the data that was presented. I would even go on to say, however, forward dive profiles are recommended because they are more efficient with respect to available bottom time. Let's not get into this zone where we don't have a lot of data and are going to get ourselves in a big mess legally. I don't know how switched on all these sport divers are, but they are going to interpret these things in different ways and get confused.

D. Richardson: Karl Shreeves, one of PADI's wordsmiths has been working up something that could read: "Reverse profiles have historically not been recommended, due primarily to a lack of data. However, within the scope of no-stop diving, it does not appear that reverse profiles lead to a measurable risk increase provided that the depth difference is 12 m (40 ft or less), and that the dives in question are shallower than 30 m or 100 ft. Then perhaps something to Mike Gernhardt's point about forward dive profiles being generally recommended because there's a pragmatic reason, and so forth. It's a point of fact that we hear others say reverse profiles have not generally been recommended. We came in here with that and we're leaving with that. It's in all the literature, due primarily to a lack of data. We're talking now about whether you want a guideline for the lay person that won't be misinterpreted. *However, within the scope of no-stop diving, it does not appear that reverse profiles lead to a measurable risk increase provided that the depth difference is 12 meters, 40 feet or less, and that the dives in question are shallower than 30 meters, or 100 feet.*

J. Lewis: I think it all sounds fine, with the exception of that 40 feet. Where did that come from? Just omit that and it sounds fine. Wienke made it up on an extreme case from 50 to 180 feet. Besides, was there any data?

B. Wienke: If I can speak to the 40 feet and why I wrote it in there. We're looking for a consensus, which is the least common denominator among all of us here. And some of us may believe that you can be 70 feet. Some of us may believe that 40 feet is imaginary, just like some of us might believe this isn't an issue even with decompression diving. At least what I've heard is that everyone would agree that the envelope we just described would appear to have no additional measurable risk. Now there were some people who believed the envelope could be larger. If we're looking for a consensus, that's our least common denominator I was trying to hit. That's the most conservative position anyone here will take.

G. Beyerstein: The initial question was stated with current decompression algorithms. Any time we come to a consensus in a body like this and it gets written down, it tends to become engraved in stone and has a life all of it's own. In the initial preamble, you might want to state a truism that it's not the magnitude of exposure that causes a problem. Otherwise we could never do saturation because that's the maximum exposure and we do that safely all the time for both depth and bottom time. It's not the magnitude of the exposure, it's the quality of the decompression. If we have a statement in there that says in the initial question with current decompression algorithms, then perhaps a tail statement on to that would be that there are ongoing developments. The new models, use of dive computers and so on, even in the no-decompression range could alter these recommendations in a favorable way or whatever, if you think that is worthwhile.

R. Moon: I have two points to make. One is that, Gary, I'm not sure that's a good phrase to put in because Wayne Gerth has provided some evidence that the USN air tables may not be as safe with reverse dive profiles as with forward dive profiles. With that proviso perhaps with current algorithms would be okay. But the other point I wanted to make was that quite a few people have said within the no-stop limits, but we've seen plenty of evidence from Paul Weathersby, Gary Beyerstein and Terry Overland, and Dick Vann that there's no reason to limit it to no-stop limits.

W. Gerth: The profiles that Paul showed were dived according to an algorithm that was the basis for the probabilistic models that were used. Not any of those, not even the tables or any of the other methods that were evaluated with that generalization of the NMRI data. Those profiles were scheduled using a different algorithm than any of those that were evaluated.

R. Moon: But they weren't within the USN no-stop limits, right, Paul?

P. Weathersby: No, they were decompression dives.

R. Moon: Right. That was the point that I wanted to make.

W. Gerth: It's on that basis that I would proscribe not allowing reverse dives on decompression dives because it's in that area where it looks like the algorithms that we're using, including all of the tables, where they might get us into a significant difference between forward and reverse dives. The reverse being significantly more risky under the algorithms that were used to schedule those dives.

Comment: What he is saying is that those dives that Paul presented were not based on conventional algorithms and that he's demonstrated that possibly there is an increased risk with reverse dives on unconventional algorithms.

P. Weathersby: They were scheduled appropriately.

R. Moon: Well, do you mean that there is an increased risk, or do you mean that you need shorter bottom times, which aren't the same thing.

W. Gerth: You need the right algorithm. The Navy algorithm that was used to schedule those dives is not yet available for everybody to use.

R. Vann: You ought to keep it simple.

G. Egstrom: Just one other issue. When you take a look at a document like this, one of its purposes is to provide sufficient information so that the people who read it can make some kind of an informed consent about whether or not they want to do this. I believe if you take all of the evidence that has been put out here in the last couple of days, you really ought to finish that off so that what you are doing is identifying the nature of the calculated risk. Diving is risky; it has always been risky. It is going to continue to be risky, and what we are trying to do is provide a better understanding of this issue so that people can approach it with more information than they've had, and permit them to do something that apparently they've been doing anyway for years.

A. Brubakk: I would suggest a totally different statement, saying that something along the lines that reverse dive profiles are generally not recommended. There is no convincing evidence that this rule shall be changed for the general diving population. However, for some divers, for instance, professional divers, divers whose activity is tightly controlled, procedures may be developed that apparently will not expose them to increased risk. I find none of the data presented here has convinced me and I agree with David. There is no way, with the present ways of looking at this, that we can demonstrate that we move from ten to the fourth or ten to the third. I mean that's simply not possible. We have to do totally different studies if we really want to know under what conditions these kind of profiles will be safer, equally safe, or more dangerous. That is a very complex issue and we need a lot of studies in order to document that. At the present I don't see any compelling reason why we should tell sports divers that you shouldn't follow the rules that they have followed for many years and I find some of the arguments that were made here earlier that make sense to go on. There is no good evidence to support that would change that, so let's just give it to people who need this kind of special thing. I see no reason to the let the general diving population have a relaxed rule in this matter. At least there are no data to support it.

R. Vann: You can't prove that it's unsafe. You're at a loss. You can never prove it's not safe.

E. Baker: I mean, we haven't shown anything.

R. Vann: We haven't shown that it is unsafe.

J. Lewis: I challenge that. You haven't shown us anything.

R. Vann: That's all we can say. We can't say that it's safe, but we're just saying that you can't say it's unsafe.

B. Wienke: We have no evidence to reject that hypothesis.

R. Vann: Right, that's exactly what we have.

J. Hardy: Good. Carry on that perspective. This is the way people are really behaving out there in the field. They do this. I've tried to convince you that they do it far more than we would like to admit to, but at the same time I am feeling kind of old in this whole thing. I've got my AARP card, by the way, and there are a few Jim Stewarts and Glen Egstroms here that remember back in 1978 when the then Undersea Medical Society got us all together as training associations and we debated at length the same thing on ascent training. That document that we amassed then has been very meaningful in the growth of our industry and how we train divers, and how we make ascents. The point I would like to make for perspective here is how we really want and deserve to come out of this with something meaningful. It is going to have significant implications for the training associations and how they implement it. It is going to have significant meaning for the Smithsonian et al, the entire scientific community. For those of us who serve as experts we are all going to use these documents either defending or prosecuting cases. I will lay you odds that this is going to be in the popular literature very soon. Whether you want it there or not, the recreational diver is going to be duly informed of the deliberations and what comes from this.

I want to give due credit, in 1979 PADI sponsored a workshop in Santa Ana, California where we talked about multi-level, diving decompression topics. We did multi-level ever shallower diving, and it worked. We weren't hurting anybody with that. That helped set the stage for computers and helped set the stage for the Orca Edge, which then was able to do that. PADI came back with DSAT, and again I want to praise, all the research that has produced the Recreational Dive Planner and the wheel. That made more multi-level diving possible.

In 1989, many of us got together in Catalina, for the AAUS Dive Computer Workshop, and that has significantly influenced what the manufacturers do. Add to the training associations and the scientific community and the legal cases in the popular literature, we also have the manufacturers who are going to look at this and they are going to change how they behave making their computers.

They've got a primary player like John Lewis sitting here and the fellows from Europe, who are going to go back to their companies and are going to do something with this. Now, to throw a little wrinkle into the whole thing, we are right on the verge of several things that Tom identified. What about all these other things, like dehydration and whether you are male or female? We are on the cusp of another change.

I will predict for you that recreational divers decompress all the time. They just don't do required stops. They come up slow, that's decompression. They do safety stops, that's decompression. Many of our modern dive computers force them to regularly decompress, so we have required stops on the computer that wouldn't exist otherwise. We're going to have to deal with the fact that recreational and scientific divers actually decompress even though our rules say they can't. I would like to say that something meaningful should come out of this. It should be concise, and we shouldn't just throw our hands up and say we can't do that.

R. Vann: I am going to play devil's advocate again. The last statement that we got form Alf I have an objection to that. If you are going to state that reverse dive profiles are generally recommended you are missing the why. I forgot to supply that. You have to explain your position here. The second statement that there is no evidence that this can be changed can be rewritten as is there evidence that it should not be changed. Where is that evidence?

A. Brubakk: In my opinion the reasonable evidence is there already. This is the theoretical discussion. From the theoretical point of view there have been arguments made in both directions. It is very difficult to judge from the data if it actually is or isn't a problem. I have a feeling that doing the deepest dive first, seems to be a sensible rule, as a general rule. I am not saying that it should be forbidden and do it the other way around.

J. Hardy: But that's the very point. If you are going to make a rule, you should have a strong case to do it. Basically, give us the freedom to do what we want to do, and give us rules that will prevent me from doing something seriously bad.

Comment: We have a rule that we are trying to do something about.

M. Lang: If we want to have a practical product from our theoretical discussions here, we have to put it in some layperson language that the divers are going to understand. Okay?

G. Smith: I would like to say that I am essentially agreeing with the first paragraph Dick Vann started, that there is no evidence to indicate that reverse dive profiles are either more or less likely to produce decompression sickness. Therefore, following a dive with a deeper dive should be allowed. However, there is more data on repetitive data when the deeper dive is done first, and this should remain the preferred procedure, especially for longer, deeper dives.

B. Wienke: We ought to make statements that are more scientifically based, and I think that Dick really summed it up quite well when he said that with the caveats and depth ranges, that the overwhelming suggestion is that we just don't think reverse dive profiles are anymore risky than forward dive profiles. We ought to preface it, and then make our caveats later. But if we suggest that reverse dive profiles are to be avoided, then we are already saying there is a reason for that. If you follow it by saying we don't have enough conclusive evidence, people are going to wonder what's going on here? They're saying one thing and they're saying something else. We need to be consistent. We don't know, but we do have some caveats about deeper diving.

M. Gernhardt: Each organization has its own procedures and constraints. If you look at the offshore diving community, the way they dive, they do reverse dive profiles, and they are quite successful. Why should they be limited if this got in to an argument of what is and isn't approved. Just say that reverse dive profiles are okay, within your organization's operations and how you operate safely, that's what the evidence here shows.

G. Egstrom: You're not saying reverse dive profiles are okay, you are saying that based on the evidence we have now, they are not unsafe. It's a critical difference.

M. Lang: We do need to keep a time marker on that, and that is with current decompression algorithms. As somebody comes up with another algorithm tomorrow and all of a sudden this whole issue is viewed very differently.

R. Vann: The evidence, if I understood it, appears largely to come from within the recreational dive and commercial diving envelope. It's not a bad idea to qualify this with a but, and to put the 130 foot and 40 foot limit in it just because we don't have evidence either way.

M. Lang: Since 130 ft is the recreational dive limit, does anybody have heartburn with leaving it at the recreational diver training level? That is already in all of the regulations and training standards? Granted, it's an arbitrary number.

P. Tikuisis: When we make a statement about a certain region, like less than 130 feet of sea water, we are not saying anything about other regions. They might also be safe. Our statement is limited to 130 feet because that's the region where we have some data. The statement is really simple. There's no convincing evidence that reverse dive profiles lead to a measurable increase in the risk of decompression sickness for no-stop diving to depths less than 130 feet. Somebody else may go to 150 feet, there's nothing wrong with that according to our statement, it's just that we are silent. We are silent about anything outside that range. Because we don't know much outside that range.

R. Moon: The data that we heard was not limited to 130 feet. We've heard data outside the 130 foot envelope. There's no reason to constrain the summary of what we heard to 130 feet. I would suggest that we come up with a definition that refers to reverse dive profiles. Does this refer to multiple dives in a single day only, with the second dive deeper than the first, or does this refer to a single dive profile with the last part of the dive deeper than the first part? Secondly, what is the minimum depth for the shallower dive?

K. Huggins: What we are looking at is range of 130 feet and first and second dive. Where would we place a risk gradient of this graph? Are we comfortable saying that reverse profile dives within this square are pretty much equal, or is there an increasing area in one of these areas because of the risk? We don't know. The best we can do as a group of experts is to look at a general mapping onto this of what we feel is appropriate and then make recommendations based on that. I don't think we can draw a straight line anywhere on this.

G. Beyerstein: During the course of this whole workshop we've said we don't have data over and over again. We're making recommendations and decisions now based on a consensus without any really supporting evidence just more or less like we feel this and we think that. Michael wants some definite statements and regardless of whether we make suggestions or not, we should include in here some statements that have come out of this workshop that I think are definite facts. For instance, the reverse dive profiles have been routinely performed in all aspects of diving, more in some areas that others. We can qualify that: recreational scientific, commercial and military. That appears to have been a fact that came out here, it's not in dispute. More facts: there's no historical prohibition against performing reverse dive profiles from the U.S.N. or the commercial sector. The origin of the prohibition of reverse dive profiles by the recreational training agencies cannot be traced to any definite body of evidence to indicate increased risk. Can we agree with that? Then also a statement that there's very little data to indicate that reverse dive profile have increased risk one way or the other.

R. Moon: I would like to reiterate that we still need a definition of a reverse dive profile.

J. Lewis: What we are talking about first of all, differential depths that are some number, bigger than one and less than 100. The second one is, I don't think people are talking about depths of a second dive that are shallow. We are talking about second dives that are 100 feet or more typically. The third parameter had to do with the surface interval, and I really don't know how to deal with that. It's probably best to avoid it. We just say dives within a 12 hour period, or something, because I don't know how to deal with it.

R. Moon: It would not be unreasonable to define a reverse dive profile as either two dives within 12 hours in which the second dive is deeper than the first, or a dive in which the latter portion of the dive is deeper than the earlier portion.

P. Mueller: In our definition of reverse dive profiles, do we constrict it to two dives? I can see quite a few situations where it could be more than two dives? One of the complaints I heard from training people is that they have to go down six or seven times a day.

E. Baker: We wrestled with this issue on the decompression list and based on what people said, a reverse dive can be defined as a deeper than the previous repetitive dive, a forward dive is therefore a shallower dive than the previous repetitive dive. Then we have to say what a repetitive dive is. A dive is considered to be repetitive when the surface interval between the second dive and it's predecessor is sufficiently short that the first dive can have some influence on the second dive.

M. Lang: What is wrong with the Navy's definition of repetitive dive?

M. Gernhardt: Could we just leave it as repetitive dive because that is defined differently with different modalities.

H. Van Liew: I don't agree with the third statement. I don't think it's true. Dennis Walder was mentioned as historic evidence. The whole idea that decompression sickness is caused by bubbles that always form because of gas nuclei says that there will be differences.

J. Lewis: But that's not evidence, that's hypothesis.

D. Yount: The evidence for the varying levels is pretty strong. You can see them with a microscope, you can predict results of experiments with that kind of evidence. We've heard about several bubble models.

T. Neuman: You are talking about the origin of proscription, the history.

G. Egstrom: I don't think that sentence is necessary. It doesn't buy us anything, and when Dennis Walder started us off on that direction, he was basing it on the idea that bubble formation is caused by nuclei.

B. Hamilton: I would propose that we suggest that the reason that there is a rule is that it was a practical one, that we got more bottom time by avoiding the reverse dive profile situation. That rule didn't come about because there wasn't any evidence. It came about because it was a practical issue.

M. Lang: That in and of itself is already a newsworthy item, because nobody knows that out there.

D. Richardson: The practical consideration was the penalty time factor, do the math. In 1972, a problem was run with the deeper dive first, the same criteria, reversed, deeper dive second, and the students would see that they got longer bottom time.

D. Scott: That's the whole deal. That should be explained.

T. Neuman: Let's not forget that we really need a definition of practical consideration for decreased bottom time.

M. Lang: Please hold on everybody, the light is shining at the end of the tunnel. Changing the word "proscription" to "prohibition" would make it a little more understandable.

J. Hardy: The word "routinely" was carefully chosen, because it separates that first statement from emergency which many of the decompression books now say that any decompression for recreational divers is an emergency. We're emphasizing that reverse dive profiles are not an unusual or a bad situation. It's not an emergency so it is well advised to write the word routine in there.

M. Lang: Do we feel that the delta peaked somewhere? Give them an inch and they'll take a mile. First it's 30 feet, then it's 40, 50, 60, then we have this 170 foot reverse! Every paper mentioned something about a pressure differential. Are we not going to mention anything at all?

Comment: How about using the word "significant?"

M. Lang: What are we going to flag when the dive log sheet comes in? A reverse dive with 30 ft delta P? No problem. 40 Foot? Maybe? 50 foot? What are we talking about?

T. Neuman: Notwithstanding Gary, no offense, the commercial evidence for the amount of reverse dive profiles is really pretty scant and the only thing we do have is considerably shallower than the entire range of air diving. Where we have the little bit of data is in the recreational arena and that's 130 feet. I would be loathe to make that air diving which is 190 feet military and who knows how deep it is in the commercial sector.

R. Moon: I still feel very strongly that we should take out no-stop air diving to depths of less than 130 feet because there was considerable data presented at other depths that showed no convincing evidence. I would say within normal air diving range is fine.

M. Lang: For the science community, it's 190 feet.

R. Moon: Right, but you mentioned all those bodies out in the front so they can apply that normal air diving range to each individual body and make their own conclusions.

T. Overland: I would disagree with the routinely at least on the commercial side because it's far less than 10 percent. Gary, I know you agree with that, and then you said all aspects of diving. Does that mean in saturation diving and Sur-D-O_2?

D. Richardson: Michael, can I make a comment? Can we spell out reverse dive profiles? That is important because we have an acronym called RDP (Recreational Dive Planner). All the papers say RDP in big captions. For 13 years ten million people have been trained that RDP is a Recreational Dive Planner, so diving does not need another mystery acronym.

M. Lang: The point is well taken. We'll spell it all out.

T. Neuman: Somebody keeps on saying eliminate no-stops, but the data that we have from decompression diving and reverse profiles is even skimpier than the data that we have on no-stop diving. I believe you are the only one who presented decompression reverse dive data.

J. Lewis: Excuse me, des Granges did it in 1957. 62 percent were reversed dives and the vast majority of those were decompression.

R. Moon: Tom, that's not true. Paul Weathersby, what percent of your dives were outside the no-stop limits and what about Dick Vann? Can you comment on that? How many of your profiles were outside the no-stop limits?

R. Vann: I have no idea. They were multi-level.

R. Moon: If you apply the U.S.N. algorithm to those dives? Have you done that?

K. Huggins: Why not just change it to risk of decompression sickness within the no-stop air limits.

G. Egstrom: The way it's stated does not exclude decompression diving. All it's saying is that we agree with this finding that there is no convincing evidence within no-stop diving. We don't all agree whether there is or isn't outside no-stop diving. We haven't excluded that.

R. Moon: But none of the statements we heard specifically address that.

K. Huggins: Other than the fact that we have had evidence presented that a lot of the decompression dives are no-stop dives being done by dive computer and are actually decompression dives.

M. Lang: These findings must be completed before we leave. We are not going to be together again as a group. Many of you have been through this drill with me several times before.

T. Neuman: What I am going to suggest is that it cannot be traced to any definite body of diving experience that indicates an increased risk of DCS.

D. Yount: Experience can be anything. Evidence indicates that it's a body like this that's evaluated something in a scientific manner. There is data outside of that which might disagree, but within the diving experience we don't have that evidence. So it needs to say something along the lines of body of diving evidence.

T. Neuman: ***Historically, neither the United States Navy nor the commercial sector have prohibited reverse dive profiles.***

M. Lang: Who does not agree with that? It is done. Number one is on the record.

T. Neuman: ***Reverse dive profiles are being performed in recreational, scientific, commercial and military diving.***

M. Lang: Who does not agree that that is a finding? Raise you hand. That's two in a row.

T. Neuman: The origin of the prohibition to conduct reverse dive profile by recreational training organizations cannot be traced to any definite diving experience that indicates an increased risk of decompression sickness, but rather, it appears to have been recommended based upon practical considerations of increased bottom time.

M. Lang: It's long, it's wordy, and it's awkward.

Comment: You can make it better by ending after DCS period.

Comment: Just say it appears to have arisen from practical considerations.

T. Neuman: The origin of the prohibition to conduct reverse dive profiles by recreational training organizations cannot be traced to any definite diving experience that indicates an increased rate of decompression sickness. It appears to have been based upon practical considerations of increased bottom time.

Comment: I'm suggesting saying the prohibition cannot be traced.

T. Neuman: We need somebody who does not have English as a native language to help with the right tenses and composition.

T. Neuman: The prohibition by recreational training organizations of reverse dive profiles cannot be traced to any definite diving experience that indicates an increased risk of decompression sickness. It appears to have been based upon practical considerations of increased bottom time.

Comment: Who really cares about who did it? The main thing is what did they do and it's shorter.

T. Neuman: It's times like these that remind us that a camel is a race horse.

Comment: It has virtually evolved to a prohibition.

Comment: That's why I had origin in there because it has been a prohibition.

M. Lang: Tom, would you please do a final read so we can move on to the next one? These are still the findings.

T. Neuman: The prohibition of reverse dive profiles by recreational training organizations cannot be traced to any definite diving experience that indicates an increased risk of decompression sickness. This prohibition - it should be this - this prohibition appears to have been based upon practical considerations of increased bottom time.

E. Flynn: I don't agree with the second sentence in that. Because in my early days as a scuba instructor there was always the safety issue. It was never an increase in bottom time issue. So, this does not ring true to me.

G. Egstrom: In the 1960's, this was routinely taught as a way to gain additional bottom time by diving your deep dive first. That point had nothing to do with safety.

E. Flynn: Well, I was a scuba instructor in the early 1960's, I recall this specifically as a safety issue. Because it regarded the shallow dive as part of the decompression stop. If you made your deep dive, you came up and were doing decompression; a second shallow dive was just more decompression. Why not strike that one sentence?

M. Lang: No, because it distinguishes that there's no physiological reasoning. It was based on a practical reason of increased available bottom time.

Comment: Does that matter if you said there's no physiological reason, or there's no diving data or experience?

T. Neuman: Agreed, because it's guessing what other people were thinking and therefore it's not a finding.

M. Lang: Tom, please, one last time?

T. Neuman: ***The prohibition of reverse dive profiles by recreational training organizations cannot be traced to any definite diving experience that indicates any increased risk of decompression sickness.***

M. Lang: No opposition? Okay, it's done.

T. Neuman: There is no convincing evidence reverse dive profiles lead to a measurable increase in the risk of decompression sickness using air within no decompression limits.

Comment: No convincing evidence was presented...

Comment: Why using air?

Comment: Because that's where the majority of the diving experiences are.

Comment: What about nitrogen-based diving?

M. Lang: Let's not introduce new data at this late stage. All we're doing here is recapping, in one-liners, what was presented. Did anybody present anything on nitrox that shows that there is no convincing evidence, yes or no?

T. Neuman: No.

G. Smith: NOAA surface interval oxygen was nitrox. That was 36 percent at 80 feet, 32 percent at 120 feet.

M. Lang: The proposition on the floor was we don't need "using air."

Comment: It's okay with helium. No, seriously, have we opened that door?

B. Hamilton: We have to put either air in, nitrox or nitrogen-oxygen to distinguish this from helium.

Comment: The key phrase, the descriptor, is no-decompression limits.

T. Neuman: No convincing evidence was presented that reverse dive profiles lead to a measurable increase in the risk of decompression sickness within no-decompression limits.

R. Moon: I would like to bring up the issue, within no-decompression limits, once again. That issue was not addressed by any of the speakers and if you're going to talk about no-decompression limits, you mean no-stop limits, in which case whose no-stop limits?

Comment: Everybody's.

R. Moon: I thought Ed Flynn made the point that no-decompression limits encompassed the computers as well as the tables. The implication of putting "within no-stop limits or no-decompression limits" is that if you require a stop, then all of the above doesn't hold.

B. Wienke: That's true and I don't think that's what we're trying to do.

T. Neuman: It's true as it stands and if we try to change it we'll have an argument.

Comment: It does not exclude decompression diving, it's speaking specifically to no-decompression, which we all appear comfortable with.

T. Neuman: ***No convincing evidence was presented that reverse dive profiles within the no-decompression limits lead to a measurable increase in the risk of decompression sickness.***

M. Lang: Who is opposed to this?

R. Moon: Within no-decompression limits is an ill-defined concept that is not on track within this workshop. I would just take out within no-decompression limits.

B. Wienke I wouldn't want to use any of these conventional algorithms to do heavy decompression diving, forward or reverse. If you take out no-decompression then you're stuck saying it's all fine, go have at it.

R. Moon: If you put in the caveat, within no-decompression limits, that implies that if you have to make a stop, then a reverse dive profile is more dangerous.

T. Neuman: No, it doesn't.

M. Lang: It is silent on the subject.

Comment: Could you change it to say available data indicates that reverse dive profiles within no-decompression limits would be safe?

M. Lang: Definitely not, don't go there.

Comment: How about a statement that indicates the preponderance of data considered at this workshop was in the no-decompression range and in that range, etc.

M. Lang: We should leave it because if the only objection really is that it implies something, that's not appropriate. This category is findings. If we're silent on a particular issue or don't particularly address something, then I think we should leave it. We may not have unanimity, that's already been pointed out. But if there is a mistake there or something that we did actually not find, then it needs to be changed. We're all happy with no-decompression limits in there, other than Richard? Let's grade this. Is it substantial or is it a minor thing?

Comment: Minor.

R. Moon: Well, I would just like to point out that if we come down a little harder on NoD limits during the recommendations, that most people could live with erasure of it here.

M. Lang: Well, what are we going to have? We're going to have findings, recommendations, a consensus statement and a definition?

Comment: I'm going to suggest that we have a statement and we don't try to divide it up into findings and consensus. This is our statement.

M. Lang: What does everyone feel? Is this it? Is this the take-home message?

Comment: Well, you need a definition.

M. Lang: What I originally sent out to all of you was to consider not just a reverse dive profile within a repetitive series, but also a deep portion after a shallow portion within a single excursion.

Comment: On a typical dive, you drop in ten feet and drift around in your gear for five minutes and then drop down to 110 feet. Is that a reverse dive profile?

M. Lang: The background of what we were trying to get at was the diver who was diving in 40 or 50 feet and found the anchor was stuck. They can't get it up and now they've got to spike back down to depth, and that's when problems occur. It could be due to a rapid ascent or other factors, but the fact is, they're diving shallow for a long time and then they're diving deep at the end.

Comment: There was little attention paid to that during this workshop and it may be a problem that we haven't really addressed.

Comment: Some data were presented to suggest that such an exercise would work against you in that scenario.

M. Lang: This is almost *ex post facto* because we're pretty much done with the workshop and now we're deciding what we actually talked about. Were we all talking about the same thing? This is a clarification, right, that's what this is for? I mean, we're not trying to introduce or say what we did or didn't talk about? This would be a clarification for those who were not here and are reading the proceedings and thinking, what is the definition of a reverse dive profile?

H. Van Liew: It seems to me that we really didn't talk about the second definition. A second definition that is commonly used is where the latter portion of a single dive is deeper than the initial portion, but that was not addressed.

Comment: It's very clear to me that that's part of it and figure three in my paper is that.

Comment: But did we hear any dive data about it? I didn't hear it.

P. Mueller: I guess nobody really excluded that second definition in their presentation, so why can't we assume that it was addressed and we didn't find any evidence.

D. Scott: But if you start off at 20 feet, at least if you're diving tables, and then you drop down to 60 feet, that's a different scenario versus where you come to the surface, get back in your boat, and then go back down and get your anchor. You've got ten minutes on the surface to decide to go back down and get your anchor.

M. Lang: Not according to dive computers. You don't even have to come to the surface. You can swim along at 40 feet on a coral reef and drop your Nikonos and it ends up in a crack at 90 ft. What are you going to do? Are you going to go get it?

D. Scott: But if you do that in a table's dive, then it changes your profile.

Comment: Either that or just state it's a single dive where the deepest portion of the dive does not occur at the beginning of the dive.

M. Lang: We're going to have to put a limit on this because we're running into logistical problems now. We have to really look at degrees of heartburn now, only major stuff please.

J. Lewis: The second half of that sentence should be struck. Make it a separate sentence. At the least, I would prefer you do that.

M. Gernhardt: It's a single dive where the deepest portion of the dive does not occur at the beginning. Or, the deepest depth of the dive does not occur at the beginning. And that could cover the scenario where you have a shallow dive and you drop down right at the end or a progressively deeper dive or any combination.

M. Lang: Okay, last time, are we going to take this? All those in favor, raise your hand. All those opposed, raise your hand. Okay, now we have more than we just had.

Comment: I'm going to suggest that we put this in front of our findings and that we call the whole thing, our statement.

M. Lang: Or, I can include what I sent out to all of you originally as a "working definition" and get rid of the definitions here. Okay, we'll delete the definitions.

M. Lang: Well, what do we do with our delta P and maximum depth?

Comment: Trash it, get rid of it.

Comment: We recommended a minimum delta P, a delta P not greater than 40 fsw.

Comment: Stay away from that.

M. Lang: That's absolutely nothing at this point. A diving instructor down the street says, "well what's a delta P?" Ten feet? 20 feet? We're back to the exact same question, which is why we came here in the first place. We should go with the findings, because the feeling is that there is no added value in coming up with something that's called a consensus. If the findings accurately describe our take-home message and what we did here, then fine. It's not as strong maybe as some of us would like, but there you have it.

Comment: Bruce, wasn't that exactly what you showed, that this is an essential part of it?

B. Wienke: The whole range of investigation for all the analyses was 130 feet of seawater and variable delta P's. We need to say something to the people who are going to read this about what the data was and where we looked. If we don't do that, we're leaving them a little short. Or, they can read it in the body of the paper, fat chance though.

M. Lang: That's exactly my point. If we have nothing to offer of operational practicality, then this effort is going to collect dust on a bookshelf. The diver is not going to go in and read Bruce's paper. But was that presented? Yes, it was, so perhaps it should be in the findings. But why do we negate what Bruce presented in his paper and what we discussed?

B. Wienke: That was the range of analysis for just about everybody's material.

Comment: What if you taught a resort course in the pool in the morning at ten feet and now you want to make a 100-foot dive?

B. Wienke: I still think you're talking about practical diving situations where people go out to open water. The pool is a *non-sequitur* here. You're talking about actual diving experience. They're talking about tables and dive computers. I don't know anybody who uses tables or computers in the pool. The range of analysis here was roughly 130 ft and you can argue about the delta P. But I still think we need to say that we looked and our findings were in that range for recreational diving, 130 feet.

Okay, now the issue is the diving instructor who doesn't know much says, oh, I can go to 130 feet. He reads the findings and sees, hey, there's no big deal about reverse dive profiles. I can do my training tomorrow, my first dive to 25 feet, then I'm going to go take these guys down to 130 ft on the second dive and have some fun. I don't think we want to do that. We need to limit that in some sense and if we specify a delta P, we're probably doing a service to the community at large.

T. Maney: If we can't state the delta P, do we have a point of fact that increasing delta P increases your risks? Is that reasonable?

B. Wienke: No, we don't know that.

M. Lang: We've got findings and we have not reached consensus. Is that what's going on?

T. Neuman: Can we work on it a little more? We should give the diving community something concrete. From the Undersea & Hyperbaric Medical Society's side of it, that's one of the eternal complaints of the diving community. I think we can temper it by saying that doesn't mean that in the future these numbers may not get deeper or shallower, but this appears to be conservative. We can waffle as much as we want, but I think we should come up with something like this and I personally think we ought to start conservatively. We can always get more liberal.

G. Beyerstein: Start in the commercial sector then, so we don't have to live with this?

T. Neuman: Well, that's part of the waffle, Gary.

T. Overland: Commercial diving is not going to pay any attention to this.

T. Neuman: This is within the scope of no-stop diving.

P. Weathersby: The findings are where we came closest to general agreement. Let's work from that if we've got a shred of hope in the next five minutes of being able to get anywhere. And if you get the findings back up there, see if we can agree on a final sentence like, participants were most comfortable with depth changes of less than 40 feet.

Comment: We ought to end at "the risk of DCS." Period. We could find no evidence for retention in the recreational diving community of a prohibition to perform reverse dives within the no-stop limits. That's the sense of what I follow and if we can't reach that sort of conclusion, then we really don't have any more to talk about.

D. Richardson: Right now we have outcomes based on prohibitions or behaviors. We know roughly what an incidence rate is. We're opening the door for something that's an unpredictable outcome in terms of diving patterns or behaviors.

M. Lang: Do you want to see the prohibition removed or not?

D. Richardson: Well, I don't know if I'm wrestling with what we're doing at this point here. I think we're just admitting reality.

D. Scott: I also thought the findings were very good.

B. Wienke: I like the findings. I thought the agencies could live with that.

M. Lang: How about that first sentence with no qualifiers? Is that a conclusion?

Comment: No, there are theoretical reasons to support prohibition of reverse dive profiles.

P. Weathersby: They are theoretical, they're not practical, they're not data-driven, but Wayne provided us with a theoretical reason to support the prohibition of reverse dive profiles within certain parameters.

Comment: So did David Yount.

Comment: Most people aren't doing them and they have a pretty good outcome.

G. Egstrom: I don't think you want to open the door and close the door. This strikes me as a baby and bath water situation.

M. Lang: Out goes the conclusion. So essentially what we have then are the four points that we agreed on in the findings and we're going to include the definition that I sent out prior to the workshop.

B. Wienke: We fought out those numbers in the findings. Now what we want to do is make a recommendation. We're comfortable about a certain range. That ought to be manifest in this conclusion. If we're not ready to do that as a group, then we should leave now.

T. Neuman: If we're all comfortable that it's safe to 40 feet of seawater, we could put in a statement that it may turn out to be as safe at 50, 60, 70 or 80 feet in the future, but right now at least we're liberalizing it a little bit. In a fashion that I think we can all live with and is not going to measurably increase the incidence of decompression sickness. If we start arguing about 70 feet, 80 feet, 90 feet, we're going to start getting into the arena where some of us feel that maybe it's not safe. But I think we'll all agree that at 40 feet of seawater it's safe, or acceptable. We should put something in to the effect that maybe 50 feet is okay too, maybe 60 feet is okay. But right now, we as a group, are all comfortable with 40 feet. Similarly, we as a group are all comfortable and then we have to find out what the maximum depth number is at 130 feet. We're doing a disservice to the diving community if we don't provide those parameters.

M. Lang: I agree with you. That's why we're still here.

Comment: But these statements here contravene the sense of the finding on the previous sheet. What do you want the reader to do with the findings? I thought we as a group had interpreted those findings and that there's no evidence to support the current prohibition. Are we ready to draw that conclusion from our own findings?

T. Neuman: We're admitting that the data are insufficient to allow a blanket relaxation of what has worked in the past. So what we're doing is being conservative in the relaxation of a set of rules that have historically worked. We could find no reason to retain the prohibition within these ranges.

B. Wienke: Let's interpret our findings for the reader, let's do them that service.

Comment: We recommend that the prohibition on reverse dive profiles be removed for depths of 130 feet of seawater and delta P of 40 fsw.

G. Beyerstein: Can't you use the word acceptable under certain conditions? You're not trying to take anything away from anybody, you're just saying that these are acceptable under these conditions.

A. Brubakk: But this depends on the culture you are coming from. If you come from a certain country, only things are allowed that are allowed. In this country, everything is allowed. So if it's not prohibited, it is allowed.

G. Egstrom: There is acceptable behavior and there is non-acceptable behavior. This is, I think, what the community is waiting for. Is this acceptable behavior or not?

M. Lang: We went back down this direction for the sole reason that we can pump out anything we want, but if we never give anything of practical value to the diving community, it's almost moot.

J. Lewis: Drew, do you want to leave it so the individual agencies can make their own decisions based upon the findings and just keep it simple?

D. Richardson: There was a lot of resistance to going with just the findings because of the implementation. I am delighted with the findings.

Comment: The people who are in public education are going to reconsider this. People who write these training guidelines. That's where the rubber hits the road with any of this stuff.

G. Egstrom: When we did the ascent rate workshop we came out with something and we didn't have a hard number for. What we came out with is a stop between ten and 30 feet, that's okay. We need to have some value here. If we don't have these items, the 40 feet and 130 feet, then we really don't have much. We have findings, but they don't give you any kind of practical use for the diver. If we have to have the recreational diver read through a fairly technical proceeding that's fairly thick, then we've wasted our time.

T. Neuman: I think we're all in agreement that we need something. The phrase "be reconsidered," really does soften it over here. Rather than the prohibition be lifted, we're just saying be reconsidered, that does give the agencies tremendous latitude and now we just have to agree with a set of parameters that we all agree are safe. We don't have to agree that that's the maximum, all we have to agree is that's the minimum safe number that we're dealing with. Safe being defined as not leading to a measurable increase in the risk for DCS.

Comment: The agencies do have that option and latitude.

B. Wienke: That's why we're here representing the agencies. The people in this room know about this stuff.

M. Lang: Raise your hand if you agree with this statement. Those who vehemently disagree, raise your hand. One, two, three.

Comment: You've got to give us the out.

M. Lang: My point is that we don't want to be limited.

G. Beyerstein: It's not prohibited in commercial diving.

T. Maney: The scientific air standard does not go to 130 feet, it goes to 190 feet.

Comment: Who is this recommendation aimed at? Is it aimed at the training organizations?

M. Lang: I'm going to use it at the Smithsonian. I'm comfortable with sending divers to the maximum of 130 feet with the 40-foot pressure differential. That's fine with me. Everybody seems comfortable with that.

S. Sellers: That doesn't mean you can't do your 190 foot dive, you just don't get a reverse profile for that.

M. Lang: We recommend the prohibition against reverse dive profiles by the recreational/scientific community be reconsidered for dives less than 130 foot seawater and pressure differentials less than 40 fsw.

Comment: Depth differential.

M. Lang: This is a recommendation. Do with it what you want, it's a recommendation. Tom, could you read it one more time please and then we'll wrap this up.

T. Neuman: We recommend the prohibition against reverse dive profiles by the recreational/scientific community be reconsidered for dives less than 130 feet of seawater and depth differentials less than 40 feet of seawater. Shouldn't we use 100 fsw limit that was up there before?

J. Hardy: Tom, you're just making that 100 fsw up. We've spent years establishing 130 fsw as the recreational diving limit. We're talking about at the reverse profile limit now.

T. Neuman: I'm talking about reverse dive profiles.

J. Hardy: Our scope, our envelope is 130 feet in the recreational community.

T. Neuman: I do understand that.

J. Hardy: If we change it to 100 fsw, it gets us in all kinds of tangles.

M. Lang: I have to agree with you, Jon, use 130 foot.

V. Flook: Okay, I'm not really good at English. If you put in the word, reconsidered, you're suggesting that somebody should hold a workshop to discuss this!

M. Lang: That's not quite true. What we're saying is that textbooks and the diving safety programs and regulations should reconsider for their own purposes.

V. Flook: It's not what you've said.

M. Lang: Okay, who's word was reconsider?

J. Lewis: That's Tom's word and I want it removed.

V. Flook: It should be reversed, removed.

Comment: We recommend that those two communities reconsider the prohibition against reverse dive profiles.

M. Lang: It needs to be stronger than that. The word "reconsidered" should be deleted, because that's not what our finding was. We found that there is no increased risk of DCS for reverse dive profiles versus forward profiles.

M. Gernhardt: People think that's too soft. How about we see no reason to prohibit reverse dive profiles in that range.

T. Neuman: We see no reason to prohibit reverse dive profiles by the recreational/scientific community.

M. Lang: We see no reason for the recreational/scientific community to prohibit reverse dive profiles.

S. Sellers: The biggest problem seems to be the recreational community. The scientific community was based on the results that we got back as far as who was doing reverse dive profiles, so people allowed it already. I don't think you should blanket scientific in there. I'd be happy if you struck scientific.

M. Lang: The dive computer guidelines that we came up with state that we shouldn't do deep repetitive dives for starters. So I'm perfectly happy with the 130 fsw, and striking scientific.

M. Gernhardt: If you say diving communities, I think everybody is happy. The commercial guys don't care, you're not threading the needle. We see no reason for the diving communities to prohibit reverse dive profiles.

M. Lang: Any other major problems with this?

T. Neuman: We find no reason for the diving communities to prohibit reverse dive profiles for dives less than 130 feet of seawater and depth differentials less than 40 feet of seawater.

Comment: Findings are facts, this is an opinion.

Comment: How about summary instead of finding?

Comment: How about conclusion?

M. Lang: Nobody had a problem with recommendation.

V. Flook: Michael, only one suggestion, that we express it in international units first and imperial second, if you want the world to pay attention to it.

Comment: Change it to conclusion.

Comment: We are drawing a conclusion from the workshop findings.

M. Lang: This is the ultimate reading of the conclusion, okay? Tom, last time, thank you.

T. Neuman: ***We find no reason for the diving communities to prohibit reverse dive profiles for no-decompression dives less than 40 msw (130 fsw) and depth differentials less than 12 msw (40fsw).***

M. Lang: Let me ask you this: Does this conclusion distill the findings down?

Comments all around: Yes.

M. Lang: Does it?

Comments all around: Yes.

M. Lang: All those in favor of this conclusion, raise your hands.

M. Lang: Those who are opposed to this conclusion, raise your hands.

M. Lang: It is done. Thank you very much.

Literature Cited

Yount, D.E., E.B. Maiken, and E.C. Baker. 2000. Implications of the Varying Permeability Model for Reverse Dive Profiles. *In:* Lang, M.A. and C.E. Lehner (eds.). Proceedings of the Reverse Dive Profiles Workshop. Smithsonian Institution, Washington, D.C. pp. 29-61.

Smithsonian Institution
Reverse Dive Profiles Workshop
October 29-30, 1999

Michael A. Lang and Charles E. Lehner, Co-Chairs

Findings

- Historically neither the U.S. Navy nor the commercial sector have prohibited reverse dive profiles.
- Reverse dive profiles are being performed in recreational, scientific, commercial, and military diving.
- The prohibition of reverse dive profiles by recreational training organizations cannot be traced to any definite diving experience that indicates an increased risk of DCS.
- No convincing evidence was presented that reverse dive profiles within the no-decompression limits lead to a measurable increase in the risk of DCS.

Conclusion

We find no reason for the diving communities to prohibit reverse dive profiles for no-decompression dives less than 40 msw (130 fsw) and depth differentials less than 12 msw (40 fsw).

Reverse Dive Profiles Workshop
October 29 and 30, 1999
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